Product Design for Manufacture and Assembly

Third Edition

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

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Product Design for Manufacture and Assembly

Third Edition

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Geoffrey Boothroyd
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Preface

This third edition of *Product Design for Manufacture and Assembly* includes updating of the data in all chapters of the book. In addition, a comprehensive set of problems and student assignments have been added to each chapter. This is because the book has been used in the past as the assigned text for university-level courses and the addition of these problem sets has made the new edition substantially more useful as a text book. The overall aim is to provide a text that can not only serve as a reference text for design and manufacturing engineers in industry, but will also serve as a basic text for courses in product design and design for manufacture. A comprehensive coverage of the factors that influence the ease of assembly and manufacture of products for a wide range of the basic processes used in industry is provided.

The introductory chapter has been updated to include more recent case studies of the application of design for manufacture and assembly (DFMA) techniques in industry, while still illustrating the effect that DFMA has had on U.S. industry as a whole. In Chapters 3 and 5, the extended versions of the classification schemes of the features of products that influence the difficulty of handling and insertion for manual, high-speed automatic and robot assembly have been added. This allows realistic student assignments to be added to these chapters. The chapter on printed circuit board assembly (Chapter 6) has been updated to reflect the changes in industry that have taken place since the previous edition, in particular the increased emphasis on the use of surface-mounted devices.

The remaining chapters on basic manufacturing processes have been updated with more recent data and comprehensive sets of problems and assignments added to each chapter. In Chapter 11 on design for powder metal processing, a discussion on design for powder injection molding has been added, as this technique has become more widely used in industry.

Each chapter includes some cost information on materials, labor, and machine operations. This information is representative of typical costs at the time of publication and does not necessarily indicate costs applicable at the current time. Costs obviously fluctuate over a period of time. The relative costs indicated in these data are probably suitable for a reasonable comparison between product designs and processing methods to be made.

As for the previous editions, we thank the various companies that have supported research on DFMA at the University of Rhode Island and the graduate students who have contributed to the research. The techniques developed from this research have become widely used in industry and have had a significant influence on the development of more competitive products that are both simpler in configuration and easier to manufacture with reduced overall costs.

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

Preface to the Second Edition

This second edition of *Product Design for Manufacture and Assembly* includes three new chapters, describing the processes of sand casting, investment casting, and hot forging. These chapters, combined with the chapters describing design for machining, injection molding, sheet metalworking, die casting, and powder metals, cover a wide range of the most basic forming processes used in industry.

In addition, substantial material has been added to the introductory chapter illustrating the effects that the application of design for manufacture and assembly (DFMA) has had on U.S. industry as a whole. Chapter 2, dealing with the selection of materials and processes for manufacture, now includes further material describing material selection specifically and the economic ranking of processes using a new software tool.

Chapter 3, dealing with product design for manual assembly, includes an updated special section dealing with the effect of design on product quality. Finally, additional material has been added to Chapter 15 discussing links between computer-aided design (CAD) solid models and design analysis tools.

As for the previous edition, we thank the various companies who have supported research on DFMA at the University of Rhode Island and the graduate students who have contributed to the research. We particularly acknowledge the help of Allyn Mackay, on whose work the new chapter on investment casting is largely based.

Finally, thanks are due to Shirley Boothroyd for typing much of the new material and to Kenneth Fournier for preparing some of the additional artwork.

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

Preface to the First Edition

We have been working in the area of product design for manufacture and assembly (DFMA) for over 20 years. The methods that have been developed have found wide application in industry—particularly U.S. industry. In fact, it can be said that the availability of these methods has created a revolution in the product design business and has helped to break down the barriers between design and manufacture; it has also allowed the development of concurrent or simultaneous engineering.

This book not only summarizes much of our work on DFMA, but also provides the details of DFMA methods for practicing and student engineers.

Much of the methodology involves analytical tools that allow designers and manufacturing engineers to estimate the manufacturing and assembly costs of a proposed product before detailed design has taken place. Unlike other texts on the subject, which are generally descriptive, this text provides the basic equations and data that allow manufacturing and assembly cost estimates to be made. Thus, for a limited range of materials and processes, the engineer or student can make cost estimates for real parts and assemblies and therefore, become familiar with the details of the methods employed and the assumptions made.

For practicing manufacturing engineers and designers, this book is not meant as a replacement for the DFMA software developed by Boothroyd Dewhurst, Inc., which contains more elaborate databases and algorithms, but rather provides a useful companion, allowing an understanding of the methods involved.

For engineering students, this book is suitable as a text on product design for manufacture and assembly and, in fact, is partially based on notes for a two-course sequence developed by the authors at the University of Rhode Island.

The original work on design for assembly was funded at the University of Massachusetts by the National Science Foundation. Professor K. G. Swift and Dr. A. H. Redford of the Universities of Hull and Salford, respectively, collaborated with G. Boothroyd in this early work and were supported by the British Science Research Council.

The research continued at the University of Rhode Island and was supported mainly by U.S. industry. We thank the following companies for their past and, in some cases, continuing support of the work: Allied, AMP, Digital Equipment, DuPont, EDS, Ford, General Electric, General Motors, Gillette, IBM, Instron, Loctite, Motorola, Navistar, Westinghouse, and Xerox.

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We would also like to thank our colleagues, the late Professor C. Reynolds who collaborated in the area of early cost estimating for manufactured parts, and Professor G. A. Russell who collaborated in the area of printed circuit board assembly.

Finally, thanks are due to Kenneth Fournier for preparing much of the artwork.

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

Authors

Geoffrey Boothroyd is emeritus professor of Industrial and Manufacturing Engineering at the University of Rhode Island, Kingston. Professor Boothroyd, the author or coauthor of more than 100 journal articles, is also the coauthor or coeditor of several books, including *Fundamentals of Machining and Machine Tools*, 3rd edition (with W. A. Knight) and *Automated Assembly and Product Design,* 2nd edition (published by Taylor & Francis), together with *Automatic Assembly* (with C. Poli and L. E. Murch), and *Applied Mechanics* (with C. Poli) (published by Marcel Dekker). Additionally, Professor Boothroyd has served as the coeditor of the Taylor & Francis series *Manufacturing Engineering and Materials Processing*. A Fellow of the Society of Manufacturing Engineers, he is a member of the National Academy of Engineers, among other professional societies. Professor Boothroyd received a PhD (1962) and DSc (1974) in Engineering from the University of London, England. His numerous honors and awards include the National Medal of Technology and the SME/ASME Merchant Medal.

Peter Dewhurst is a professor of Industrial Engineering and a professor of Mechanical Engineering at the University of Rhode Island, Kingston. During his career, he has made groundbreaking contributions in the areas of metal machining, metal deformation theory, design for manufacture, and the design of minimum weight structures. Since 2000, he has been the principal investigator for two research programs from the National Science Foundation, and one from Sandia National Laboratories. Awards in recognition of his work include the Sir Charles Reynold Fellowship, the F.W. Taylor Medal from the International College of Production Research, and the National Medal of Technology. He has taught senior and graduate classes in design for manufacture and assembly at URI for over two decades and was awarded the URI Carlotti Award twice for research excellence.

Winston A. Knight is emeritus professor of Industrial and Systems Engineering at the University of Rhode Island, Kingston. Dr. Knight, the author of over 120 professional papers and articles, is the coauthor of several textbooks including *Fundamentals of Machining and Machine Tools*, 3rd edition (with Geoffrey Boothroyd) published by Taylor & Francis. Dr. Knight's research interests have focused on various aspects of manufacturing engineering, including product design for manufacture, design for recycling and the environment, together with machine tool technology, group technology, and aspects of CAD/CAM. Dr. Knight is a Fellow of the Society of Manufacturing Engineers and Fellow of the International Academy of Product Research (CIRP). He received a BSc (1963) degree and PhD (1967) from the University of Birmingham, England and MA (1980) from Oxford University, England.

Nomenclature

A	area contained within perimeter; length of the rectangular envelope enclosing a nonrotational machined component
A_o	base time allowance for trim die manufacture
A_c	area of cavity plate; projected area of mold base; cross-sectional area of the undeformed chip
A_f	cavity surface area; average fault rate of insertions
A_H	area of through holes in forging
A_h	cross-sectional area of the hole
A_{hol}	hole-modified area = $A_h/3$
A_m	area of the machined surface
A_p	projected area of one part or pattern piece
A_{pb}	trim punch block area
A_{pl}	area of the sand casting pattern plate
A_s	area of the sheet metal used for each part; projected shot area
A_t	total area enclosed for all regions at a level in a powder metal part
A_{tb}	trim die block area
A_{tp}	total projected area of all parts or pattern pieces in the mold
A_u	usable die set plate area
A_0	part cross-sectional area before deep drawing
A_1	part cross-sectional area after deep drawing
a_d	depth of the groove to be machined
a_e	depth of the cut in horizontal milling; width of the cut in vertical milling
a_p	depth of the cut in turning, vertical milling, and grinding; width of the cut in horizontal milling
a_r	rough grinding stock on the radius of a rotational workpiece
a_t	total depth of the material to be removed
B	small batch size; width of the rectangular prismatic envelope enclosing a nonrotational machined component
B_o	basic bench standard value for forging dies
B_L	batch length in furnace
B_r	effective blow rate of forging equipment
B_s	batch size of parts
b	reduction exponent; index for the cavity milling standard equation
b_w	width of the surface to be machined
C	thickness of the rectangular prismatic envelope enclosing a nonrotational machined component
C_1	cost of one pair of cavity and core inserts
C_{1000}	cost per operation for a 1000 lb power hammer
C_{20}	tool accessory cost for 20 ton (178 kN) press for one-level part
C_{ab}	cost of mold base with custom work
C_{ac}	cost of standard mold components or actuators
C_{af}	cost of pattern assembly fixture
C_{ap}	programming cost per part in cents
C_{AP}	press capacity

C_b cost of the mold base; unit cost of the binder
C_{bo} cost per cluster for breakout
C_{box} cost of core box for sand casting
C_{bu} cost to apply backup coats
C_c cost of tungsten carbide per unit volume; grinding cost when recommended conditions are used; cost of the replacement component
C_{cl} cost of a single-cavity mold
C_{cf} operator cost per cluster for cutoff
C_{cl} cost per cluster for cleaning or leaching; sand casting cleaning cost
C_{cn} cost of the n-cavity mold
C_{co} cost per cluster for cutoff
C_{core} core processing cost
C_{csd} cost of core sand for one casting
C_D forging die cost per part
C_d mold cost
C_{db} coefficient for debinding
C_{DIE} total forging die cost
C_{dl} cost of single-cavity die; drilling cost per board
C_{dm} mold-making cost
C_{dman} forging-die manufacturing cost
C_{dmat} material cost for forging die block
C_{dn} cost of n-cavity die
C_{ds} cost of the die set
C_e cost of energy for melting metal
C_{en} furnace energy cost
C_f cost of feeding each part; cost of the induction melting unit; feedstock unit cost
C_F cost of the feeder
C_{fk} fixed furnace cost per weight of metal
C_{FL} furnace operating cost per unit time
C_{fp} cost of mold base fixed plates
C_{fs} cost of setup for cutoff
C_g production cost for a grinding operation
C_i cost of automatic insertion per part; cost per unit weight of the infiltrant material
C_{ip} process cost per pattern or core
C_{it} insertion cost
C_{lk} furnace labor cost per weight of metal
C_m cost of polymer material per part; material cost; cost of the metal ready to pour
C_{man} forging die manufacturing cost rate
C_{mat} cost of the part material
C_{mf} cost of furnace for alloy; cost of metal in finished sand casting
C_{mi} cost of the furnace for iron
C_{min} minimum production cost (minimum value of C_{pr})
C_{ml} cost of labor for melting metal
C_{mp} pouring cost; process cost for sand casting
C_{ms} total cost of metal at the furnace spout
C_n cost of n identical pairs of cavity and core inserts
C_{nh} operator cost per cluster for a pneumatic hammer
C_{ns} cost of setup for the pneumatic hammer
C_o cost per unit volume of impregnated oil; resin or polymer

C_{op} cost per operation of forging equipment
C_p cost of powder per unit weight; grinding cost when maximum power is used; processing cost of one part; cost of electricity
C_{pca} cost per part to assemble cluster
C_{pi} cost of the set of pattern impressions
C_{pm} cost of wax material; cost of pattern mounting plates
C_{po} production cost when maximum power is used
C_{pr} production cost per machined component; cost to apply primer coats to cluster; production cost per piece in forging; programming cost per component style
C_{pt} cost of the sand casting pattern
C_{px} complexity factor for sheet metal stamping
C_r relative feeder cost
C_{rm} cost of raw alloy; cost of raw material for sand casting
C_{rp} material cost of part
C_{rs} cost of a resink for forging dies
C_{ro} cost per operation of forging equipment relative to 1000 lb power hammer
C_{rwc} cost for reworking a faulty component
C_{rw} total cost for reworking faulty components
C_s setup cost per part type
C_{sb} processing cost per board
C_{set} setup cost per part for forging
C_{st} setup cost for a set of parts of the same package style
C_t cost of providing a new or freshly ground tool; cost of tool steel per unit weight; total handling and insertion cost per part
C_{tca} cost to assemble one cluster
C_{tl} cost of a single-aperture trim tool
C_{tn} cost of a multiaperture trim tool
C_{tp} total cost of the pattern piece
C_{tpa} pattern assembly cost
C_{trim} total cost of trimming tools
C_{trm} material cost for flash trimming tools
C_{tw} cost of cutoff tool wear per cluster
C_{vp} cost of mold base variable plates
C_w wheel wear and wheel changing costs in grinding
c dimensionless diametral clearance between peg and hole; "individual" reduction exponent
c_d average concentration of the remaining binder in the compact
c_f pattern clearance factor
c_h hand clearance
c_i initial concentration of the binder
D diameter of the hole; diameter of the circular cylinder enclosing a rotational machined component; part diameter; depth of the part
D_a probability of a defective product
D_{bar} equivalent bar diameter for forging
D_{bs} binder–solvent interdiffusional coefficient
D_c carbide insert diameter; cavity depth
D_d die case diameter
D_e equivalent part diameter
D_{eh} equivalent hole diameter

D_h hole diameter or circumscribing circle diameter for the hole
D_i average probability of assembly defects per operation
D_{li} circumscribing circle diameter for level i, $i = 1, 2, 3, \ldots$
D_o circumscribing circle diameter for the whole part
D_{pi} punch stock material diameter, punch $i = 1, 2, 3, \ldots$
D_{pm} density of the pattern material
D_0 blank diameter in deep drawing
D_1 cup diameter in deep drawing
d diameter of peg; depth
d_a outer diameter of the surface machined by facing
d_{ave} average cavity depth for forging
d_b inner diameter of the surface machined by facing
d_c cavity depth in forging
d_g grip size
d_m diameter of the machined surface
d_{max} maximum section diameter
d_t diameter of cutting tool
d_w diameter of the work surface
E orienting efficiency of a part
E_{ct} cost of electricity
E_f required energy capacity of forging equipment
E_m overall efficiency of machine-tool motor and drive systems; minimum energy for melting a metal
E_{ma} manual assembly efficiency
E_o equipment factory overhead ratio
e eccentricity of force on peg; strain in sheet metal forming
F press force; maximum separating force
F_c profile complexity factor
F_{fc} fixed furnace cost per volume of metal; forging complexity factor
F_{ff} furnace efficiency
F_{ins} benchwork factor for forging dies
F_{lck} trim punch lock factor
F_{lw} plan area correction factor
F_m maximum feed rate for standard feeder
F_{PWB} basic cost factor for printed circuit boards
F_{trm} load required for flash removal by trimming press
F_r required feed rate
f displacement of the tool relative to the workpiece, in the direction of feed motion per stroke or per revolution of the workpiece or tool; separating force on die or mold; factor increase in output; press force
f_d die plate thickness correction factor
f_p parting surface adjustment factor
G_f gate factor for sand casting pattern
H height of feature; specific heat capacity
H_b specific heat capacity of the binder
H_f latent heat of fusion; feedstock specific heat capacity
H_F height of the furnace opening
H_p specific heat capacity of powder material
H_s specific heat

H_{st} the maximum stack height
H_t heat-transfer coefficient
h wall thickness or gage thickness
h_{cl} minimum clearance
h_{cm} section thickness
h_d die plate thickness; depth of the part or pattern piece
h_f fill height of the powder
h_{fp} thickness of ejector, riser, and stripper plates
h_{max} maximum wall thickness
h_p combined thickness of core and cavity plates
h_{pt} height or thickness of the mold base
K compaction pressure correction factor; distance traveled by a point on the tool cutting edge relative to the workpiece during the machining time; coefficient for cavity milling standard equation
K_v volumetric expansion factor
k thermal conductivity
k_b binder thermal conductivity
k_f feedstock thermal conductivity
k_1 constant representing wheel wear and wheel-changing costs per unit metal removal rate in grinding; coefficient of machine hourly rate
k_2 constant representing rough grinding time multiplied by the metal removal rate
k_p powder material thermal conductivity
k_r powder compression ratio
L length of the part or feature; length of the peg in a section in the hole; depth of insertion; length of the circular cylinder enclosing a rotational machined component
L_{blk} length of the forging die block
L_b total length of bend lines
L_D total life for forging dies
L_e equivalent part length
L_{FL} furnace overall length
L_h length of the hole machined by EDM
L_{HT} sintering zone length of the furnace
L_i lower punch length for punch i, $i = 1, 2, 3, \ldots$
L_{plt} platter length for forging
L_s clamp stroke
L_{tbas} basic trimming tool life quantity
L_{trm} trimming tool life quantity
LV life volume
L_w length of the wire
l overall length of the part in the direction of feeding
l_b printed circuit board length
l_f life of a tool element
l_p length of pathway between machine tools; powder loss during PM processing; printed circuit board panel length
l_{rd} distance forklift truck travels to respond to request
l_s section length
l_t length of the broach
l_w length of the machined surface

M	total machine tool and operator rate; equipment operating cost per unit time
M_1	manufacturing hours to make one item
$M_{1,n}$	average manufacturing hours to make each of n items
M_{bu}	machine and operator rate for backup coat application
M_{cp}	pattern or core material cost
M_{dl}	operating cost of the drilling machine in \$/h
M_{ds}	equivalent manufacturing hours for die set
M_e	manufacturing point score or hours for the ejector pin system
M_f	mass of feedstock material
M_i	machine and operator rate
M_m	mass of feedstock in cavity
M_{me}	minimum melt energy
M_n	total manufacturing hours for making n items
M_p	sheet metal die manufacturing points; block area factor for trimming die
M_{pc}	manufacturing points for custom punches
M_{pn}	manufacturing die points for number and length of bends
M_{po}	basic sheet metal die manufacturing points; manufacturing hours for part or pattern piece size
M_{pr}	machine and operator rate for primer coat application
M_{ps}	manufacturing points for standard punches
M_{px}	manufacturing points for geometrical complexity
M_r	mass of feedstock material in runners
M_s	manufacturing hours for nonflat parting surface; surface patches per unit projected area for forging dies
M_{sl}	operational cost in \$/h
M_t	manufacturing points for the trim tool
M_{to}	basic manufacturing points for the trim tool
M_{tot}	total manufacturing hours for mold making
M_x	manufacturing hours for geometrical complexity
m	multicavity cost index, usually 0.7
m_l	coefficient of machine hourly rate
m_{rc}	cutoff rate
N_1	normal force at point 1
N_2	normal force at point 2
N_b	number of bends to be formed in one die; number of blows or strokes required for a forging
N_c	number of contacts in a connector; number of impressions or cavities in sand casting; number of identical forgings produced per cycle
N_d	number of different punch shapes or sizes; number of assembly errors in one product
N_e	number of ejector pins
N_{fl}	number of fuller dies for a forging
N_{fw}	number of parts across furnace width
N_h	number of hits with turret press
N_{hd}	number of holes or depressions
N_{imp}	number of forging impressions
N_{min}	theoretical minimum number of parts
N_{mw}	number of line workers for sand casting
N_{op}	number of operations required for a forging

N_p number of custom punches
N_{pi} number of identical impressions on the pattern plate
N_r number of replacement tool items
N_{tp} number of different components of the package style
N_{rs} number of resinks possible for forging dies
N_{sp} number of surface patches to be machined
N_{st} number of stitches in the lacing of a wire harness
N_t number of part types
N_w number of wires assembled simultaneously onto a wire harness jig
n number of workpieces; number of cavities; Taylor tool life index (or exponent) in machining; number of assembly operations
n_{bd} indicator for bending die required (1 or 0)
n_{bk} indicator for blocker die required (1 or 0)
n_c number of cores per pattern piece
n_{cb} number of backup coats
n_{cl} number of clearances required
n_{cp} number of primer coats
n_e efficiency of induction furnace
n_{edg} indicator for edger die required (1 or 0)
n_{fin} indicator for finishing die required (1 or 0)
n_{fl1} indicator for first fuller die required (1 or 0)
n_{fl2} indicator for second fuller die required (1 or 0)
n_{gp} number of gates per casting
n_l number of lifters per pattern piece; number of leads
n_{lp} number of boards per panel length
n_L number of printed circuit board layers
n_p number of boards per panel
n_{pa} number of pieces per pattern
n_{pc} number of parts per cluster
n_{pd} number of patterns (cavities) per mold
n_{pl} number of core and cavity plates
n_r frequency of cutting strokes
n_{ps} number of panels per stack
n_{rs} number of resinks required for forging dies
n_s number of surface patches on the part or pattern piece
n_{sb} indicator for scale-breaking die required (1 or 0)
n_{sf} indicator for semifinishing die required (1 or 0)
n_{sm} number of printed circuit board sides processed
n_{so} number of supplemental cuts per cluster
n_{sp} number of side pulls per pattern piece
n_t rotational speed of the cutting tool
n_{ud} number of unscrewing devices per pattern piece
n_w rotational speed of the workpiece on the worktable
n_{wp} number of boards in the printed circuit board panel width
P compaction pressure; force on peg; perimeter length to be sheared on sheet metal part
P_b payback period
P_{cm} core production rate for sand casting
P_e electrical power required for machining

P_{ff}	sand casting plant efficiency
P_i	recommended injection pressure; uncorrected compaction pressure
P_j	injection power
P_l	metal loss rate
P_m	power required in machining
P_{mp}	sand casting production rate
P_p	perimeter of custom punches; packing pressure
P_{psr}	pattern piece setup rate
P_r	perimeter of the projected area
P_{rv}	proportion of runner volume
P_s	specific cutting energy—power required to remove unit volume of material in unit time
P_v	production volume
P_w	perimeter of through holes in forging
Q	hole machining factor
Q	flow rate
Q_{lv}	life production volume for forgings
Q_{mx}	maximum wax injection flow rate
Q_{rb}	basic resink quantity for forging dies
Q_{rs}	resink quantity for forging dies
q_c	proportion by weight of the infiltrant material
q_o	proportion by volume of the impregnated oil
R_1	batch furnace heating rate
R_2	batch furnace cooling rate
R_a	arithmetical mean surface roughness
R_{cl}	worker rate for cleaning sand castings
R_{co}	operator rate for cutoff
R_{ds}	mold-making rate
R_f	cost of using feeding equipment
R_i	cost of using an automatic workhead per part
R_{mp}	worker rate for the sand casting line
R_{nh}	operator rate for breakout
R_p	production rate (parts per unit time); number of repeats
R_t	tool making rate for sand casting
r	inside bend radius; tool profile radius; average time for a factor increase in output divided by the time for the first output expressed as a percentage
r_c	cutting tool corner radius
S	profile cutting speed
S_a	volume shrinkage for metal
S_{bw}	bench standard for forging dies
S_c	cavity standard for forging dies
S_{ca}	setup time for cluster assembly
S_{co}	setup time for cutoff
S_d	cavity spacing in forging
S_{ds}	time to set up the mold on the injection machine
S_e	cavity edge distance in forging
S_{lk}	die lock standard for forging dies
S_g	percentage of scrap for sand castings
S_m	scrap rate for sand casting

S_{ml}	milling standard for forging dies
S_n	number of shifts worked per day
S_{nh}	setup time for the pneumatic hammer
S_{pa}	setup time for pattern assembly
S_{sl}	scale loss in forging (%)
S_z	capacity of the furnace
s_b	spacing between boards in a printed circuit board panel
s_e	edge spacing in printed circuit board panel
T	part thickness; die thickness; temperature
T_1	time of production for the first unit
$T_{1,100}$	assumed basic DFA time value
$T_{1,B}$	adjusted DFA time for batch size B
$T_{1,x}$	average time of production for x units
T_B	burn-off time
T_{blk}	thickness of the forging die block
T_{bt}	base time for forging die block preparation time
T_{bw}	bench-working time for forging dies
T_{cav}	cavity time for forging dies
T_{cl}	sand casting cleaning time
T_{dl}	dowel machining time for forging dies
T_{edg}	edger machining time for forging dies
T_f	flash land thickness in hot forging
T_{fl}	flash gutter time for forging dies
T_{int}	initial time allowance for trim die manufacture
T_i	injection temperature; insertion time per part
T_{lay}	forging die layout time
T_{lk}	additional time for trimming die manufacture for locked dies
T_{lp}	time to load and unload each panel
T_m	mold temperature
T_{mill}	cavity milling time for forging dies
T_{pl}	block planning time for forging dies
T_{pol}	cavity polishing time for forging dies
T_{prep}	forging die block preparation time
T_{rm}	unsoldering or removal time
T_{rs}	time to solder the replacement component
T_s	sintering time
T_{set}	setup time for forging equipment
T_{sm}	processing time per board side in seconds
T_{tp}	time to manufacture a flash trimming punch
T_{trd}	manufacturing time for a flash trimming die
T_w	web thickness in forging
T_x	ejection temperature; time to produce the xth unit
t	machine cycle time; part thickness; tool life (machining time between regrinds or between cutting edge replacements); binder extraction time
t_a	basic assembly time for one part
t_b	basic time to insert a peg through the stack of parts; board thickness.
t_c	nonproductive time in grinding including wheel dressing time and time to load and unload the workpiece; tool life giving minimum cost machining; cooling time

t_{cl} time for applying the first primer coat
t_{ca} time for assembling the cluster
t_{cb} time for applying one backup coat
t_{cg} time for cutting through a single gate
t_{cl} time for loading the cluster for cutoff
t_{co} time for cutting off all parts from the cluster
t_{cp} time for applying each subsequent primer coat
t_{ct} tool changing time
t_{d} time to dress a wire; dry cycle time
t_{dc} solvent debinding time
t_{enl} entry film layer thickness for hole drilling
t_{enl} exit film layer thickness for hole drilling
t_{f} mold fill time; transportation time for a roundtrip by a forklift truck
t_{FB} batch furnace batch sintering time
t_{FL} furnace throughput time per part
t_{gc} grinding time for recommended conditions
t_{gf} finish grinding time
t_{gp} grinding time when maximum power is used; time to reposition the cluster from one gate to next
t'_{gp} corrected value of t_{gp} to allow for wheel costs
t_{gr} time for rough grinding
t_{h} basic time for handling a "light" part
t_{i} manual insertion time for a peg into the hole; average assembly time per operation; injection time
t_{l} nonproductive time incurred each time the workpiece is clamped and undamped or loaded and unloaded in the machine tool
t_{m} machining time—time between engagement and disengagement of feed motion; time to assemble N_w wires attached to a connector onto a wire harness jig
t_{ma} total assembly time for the product
t_{mc} machining time when cutting speed for minimum cost is used
t_{mp} machining time when maximum power is used
t_{n} time for assembling N_w wires simultaneously onto a wire harness jig
t_{nh} breakout cycle time for the pneumatic hammer
t_{oc} open and close time
t_{p} time penalty for insertion of a peg through the stack of parts; time for assembling wires with crimped contacts into a connector; packing time
t_{pa} time for pattern assembly
t_{pw} additional part handling time due to weight
t_{r} total reset time; tool life for a cutting speed of v_r
t_{s} spark-out time in grinding; time for assembling a connector having soldered contacts
t_{sc} time for supplemental cut through runner or sprue
t_{so} time for repositioning cluster for supplemental cuts
t_{st} time for lacing a wire harness
t_{t} total cycle time
t_{tr} transportation time per workpiece
t_{0} minimum debinding cycle time
U ultimate tensile strength
U_{i} upper punch length; punch i, $i = 1, 2, 3, \ldots$

V	part volume; required production volume
V_c	cavity volume
V_{fc}	volume of metal in finished casting
V_{fl}	volume of flash per unit length of the flash line
V_m	volume of material to be removed by machining
V_p	part volume
V_r	volume of material in runners
V_s	shot size
V_{sc}	value of scrap
V_{trd}	material volume for the flash trimming die
V_{trp}	material volume for the flash trimming punch
υ	cutting speed—relative velocity of the tool relative to the workpiece
υ_{av}	average cutting speed
υ_c	cutting speed giving minimum cost machining; press closing speed
υ_f	feed speed in milling
υ_F	belt or feed speed for furnace
υ_{max}	maximum cutting speed
υ_o	press opening speed
υ_{po}	cutting speed giving maximum power
υ_r	cutting speed for a tool life of t_r
υ_{trav}	traverse speed in grinding
W	weight of the part; width of the part or feature
$\dot{W}$	heat flow rate
W_a	manual operator rate
W_{blk}	width of forging die block
W_c	workhead cost
W_f	width of the flash land in hot forging
W_{max}	maximum weight per unit area for the furnace
W_p	poured weight of casting
W_{pa}	operator rate for pattern assembly
W_{plt}	platter width for hot forging
W_{pr}	weight of material poured into a single mold
W_r	relative workhead cost
W_{sm}	dry weight of the shell mold
W	thickness of the gate
w_1	width of the chamfer on the peg
w_2	width of the chamfer on the hole
w_b	printed circuit board width
w_p	printed circuit board panel width
w_F	belt or feeder width for furnace
w_s	section width
w_t	width of the grinding wheel
X_i	inner complexity value
X_o	outer complexity value
x	number of identical units
Y_1	yield stress after 1.0 percent strain
Y_d	casting yield
X_p	profile complexity value
Y_s	equivalent shear yield stress of the material

Y_{sm}	shell mold yield
Z_{pw}	metal removal rate when maximum power is used in grinding
Z_w	metal removal rate
Z_{wc}	metal removal rate for recommended conditions in grinding
Z_{wmax}	maximum metal removal rate
α	thermal diffusivity; alpha symmetry of a part
α_m	material load factor for hot forging
α_s	shape load factor for forging
β	beta symmetry of a part; limiting deep-drawing ratio
β_m	material die life factor for hot forging
β_s	shape die life factor for hot forging
θ	angle of force on the peg; angle of bend of the sheet metal part
θ_b	burn-off temperature
θ_s	sintering temperature
θ_1	semiconical angle of chamfer on the peg
θ_2	semiconical angle of chamfer on the hole
μ	coefficient of friction
ρ	part density
ρ_a	density of alloy; powder apparent density
ρ_f	feedstock theoretic density
ρ_i	density of iron; infiltrant material wrought density
ρ_o	density of the impregnated oil
ρ_p	part density, including infiltrant
ρ_t	density of the tool steel
ρ_w	equivalent wrought density of the material
Φ_c	critical solids loading of feedstock
Φ_m	mass-based solids loading
Φ_v	volumetric powder loading
Ψ_{fl}	angle of fuller dies on the die block

1

Introduction

1.1 What Is Design for Manufacture and Assembly?

In this chapter we shall assume that "to manufacture" refers to the manufacturing of the individual component parts of a product or assembly and "to assemble" refers to the addition or joining of parts to form the completed product. Hence, the term "design for manufacture" (or DFM) means the design for the ease of manufacture of the collection of parts that form the product after assembly and "design for assembly" (or DFA) means the design of the product for the ease of assembly. Design for manufacture and assembly (DFMA) is a combination of DFA and DFM.

DFMA is used for three main activities:

1. As the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure to reduce manufacturing and assembly costs, and to quantify the improvements.
2. As a benchmarking tool to study competitors' products and quantify manufacturing and assembly difficulties.
3. As a should-cost tool to help control costs and to help negotiate suppliers contracts.

1.2 History

For many years, "design for ease of manufacture," also referred to as "manufacturability" or "producibility," has been considered important. However, until the 1970s no quantitative measures of the manufacturability of a product and its component parts were readily available to the designer without waiting for supplier estimates.

That designers should give more attention to possible manufacturing problems has been advocated for many years. A competent designer should be familiar with manufacturing processes to avoid adding unnecessarily to manufacturing costs during design. Traditionally, it was expected that engineering students should take "shop" courses which gave some familiarity with manufacturing processes. Unfortunately, in the 1960s, shop courses disappeared from university curricula in the United States; they were not considered suitable for academic credit. Now, engineering graduates joining design departments often have little knowledge of manufacturing processes.

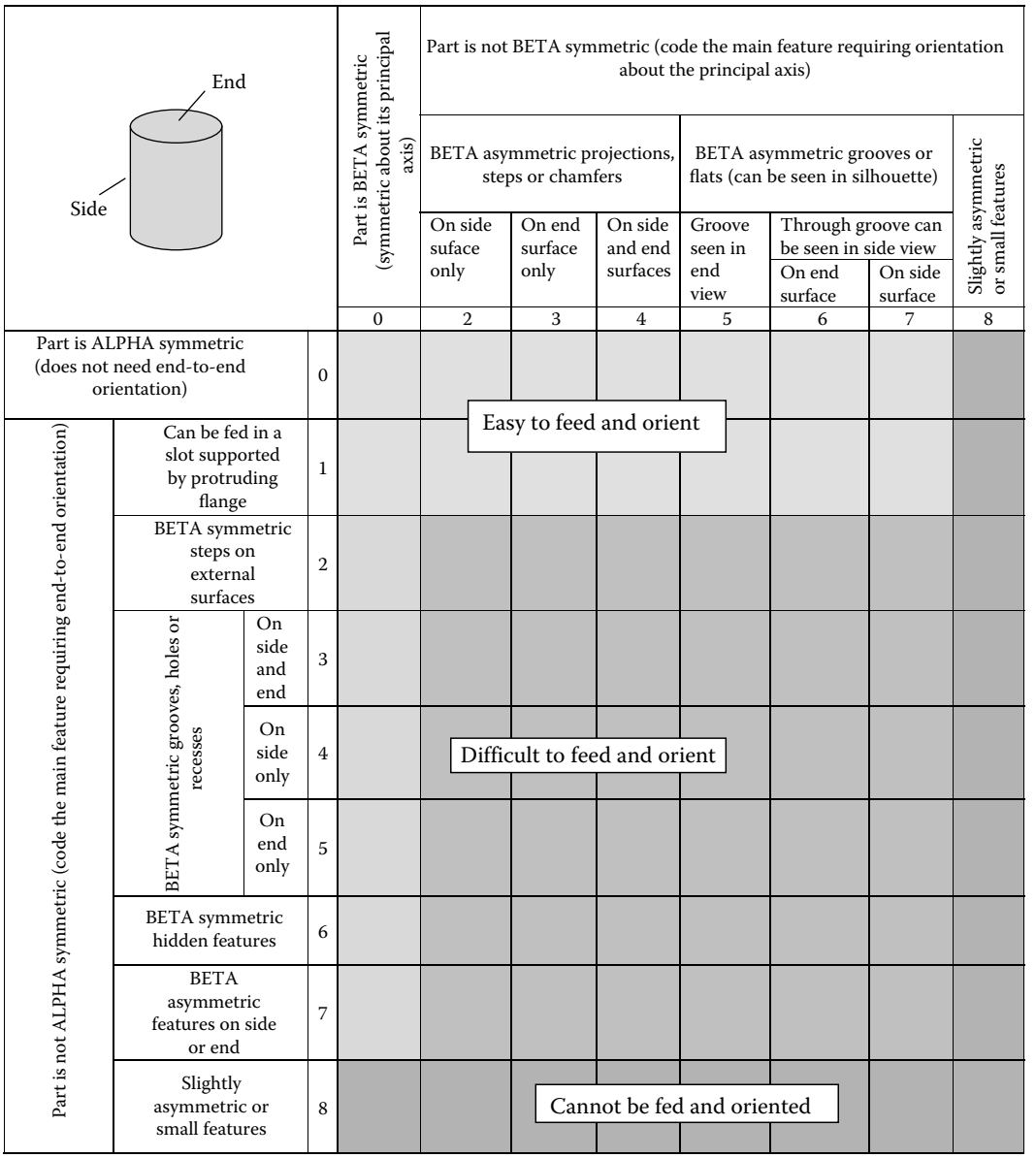

FIGURE 1.1
Coding system for the automatic feeding and orienting of small rotational parts. (Adapted from Boothroyd, G. *Assembly Automation and Product Design*, 2nd Ed., CRC Press, Boca Raton, FL, 2005.)

The development of DFMA started with research into automatic assembly. In the early 1970s, a handbook [1], which catalogs feeding and orienting techniques for small parts, was published at the University of Massachusetts (UMass). This handbook was the culmination of research started at Salford University in England in 1963 by Geoff Boothroyd and his graduate student Alan Redford and further pursued at UMass by Geoff Boothroyd and his colleagues Corrado Poli and Laurence Murch. A part coding system based on group technology was devised for the handbook in order to catalog the various solutions

to feeding and orienting techniques (Figure 1.1) of which one of Boothroyd's graduate students, C. Ho was the primary contributor [2]. The numerical codes not only showed which pages in the handbook illustrated automatic feeding solutions but also showed which parts would be easy to feed and orient, which parts would be relatively difficult to feed and orient, and which parts could not normally be fed and oriented automatically.

It seemed that product designers might use the coding system to avoid part shapes that were difficult to feed and orient or to provide part features that facilitated feeding and orienting. Using a combination of the coding system and the data developed in the research, a systematic method was devised to provide designers with a technique to quantify product designs for the ease of automatic assembly.

Thus, the efforts of numerous undergraduate and graduate students, visiting scholars, and summer exchange students who built and tested some 140 feeding and orienting systems led to the development of the Design for Automatic Assembly methodology.

Later, Boothroyd and his colleague at UMass, Bill Wilson, believed that they could make a significant contribution to the broader subject of Product Design for Ease of Manufacture. Boothroyd and Wilson visited the NSF to present a proposal and received funding in 1978 for a 3-year research program to study Design for Manufacturability [3].

As his responsibility in the research program, Boothroyd pursued his interest in DFA based on the results of the feeding and orienting studies. For the automatic insertion of parts, he collaborated with his colleagues in England, Alan Redford and Ken Swift who had obtained a grant for a study of product design for automatic assembly. As part of the study in England, various designs of domestic gas flow meters were compared. These meters all worked on the same principle and had the same basic components. However, it was found that their manufacturability varied widely and that the least manufacturable design had six times the labor content of the best design.

Figure 1.2 shows five different solutions for the same attachment problem taken from the gas flow meters studied. It can be seen that, on the left, the simplest method for securing a housing consisted of a simple snap fit. In the examples on the right, not only does the assembly time increase, but also both the number and cost of parts increases. This illustrates the two basic principles of design for the ease of assembly of a product: reduce the number of assembly operations by reducing the number of parts and make the assembly operations easier to perform.

Boothroyd and his students developed the analysis method for Design for Manual Assembly in order that manufacturing engineers could make justifications for automation proposals.

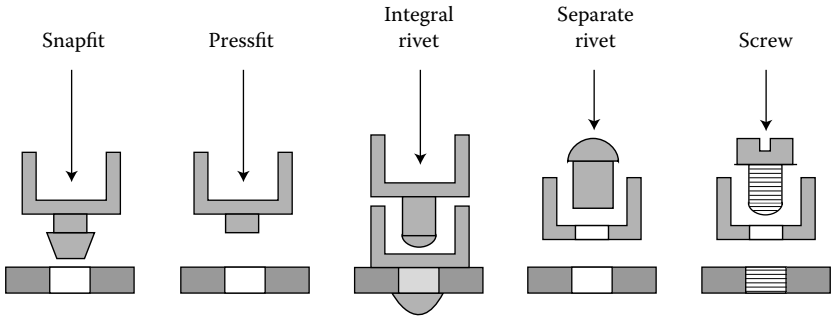

FIGURE 1.2
Examples of design features affecting assembly.

Bill Wilson's contribution to the research program was his study of the initial Selection of Materials and Processes for the manufacture of parts which dealt with important decisions made by designers in the initial stages of product design [4].

The third area of research was DFM of the parts. In this, we were fortunate to have Winston Knight from Oxford University spend his sabbatical at UMass working with Poli on the research program. Knight's contributions, specifically in the area of Design for Forging, continued as he spent subsequent summers at UMass.

Thus, DFA and DFM were born, later to become DFMA.

The original objectives of the entire research program were to develop analytical methods to guide designers in their work. The general idea was to design products for the ease of assembly and to design their component parts for the ease of manufacture (often referred to as producibility). However, these objectives were soon found to be conflicting. Producibility rules have led to suggestions that component parts be divided into simple shapes. However, as will be illustrated, this is rarely a good idea. In fact, *reduction* of the number of separate component parts in a product not only reduces the cost of assembly but generally reduces the total cost of the parts.

In the work on DFA, three simple criteria were developed to determine whether a component part should be considered for elimination. It was the application of these criteria that held the key to simplification of the product structure with the resulting cost benefits [5].

The DFA methodology for both automatic and manual assembly was published at UMass in the form of a loose-leaf handbook [6] made available to industry for a small subscription. Over a period of only 4 years, 2000 subscriptions were obtained and used to supplement the work on DFA.

Soon after the DFA Handbook was made available, several studies were undertaken at the Diablo Printer Division of the Xerox Corporation. These studies, of small electromechanical assemblies, generated redesigns of assemblies where significant savings were made in the total manufacturing cost, most of which arose from a reduction in the number of separate parts.

Major companies, such as Xerox, General Electric, Westinghouse Electric, IBM, and Digital Equipment, were quick to implement DFA in order to simplify product designs. As an example, it was estimated by Sydney Liebson of Xerox, that full implementation of the DFA methodology would result in annual savings for the Company in hundreds of millions of dollars [5]. Sydney Liebson, who was the corporate manager of manufacturing at Xerox, was an enthusiastic supporter of the original NSF proposal on Design for Manufacturability.

The results of all of the research on automatic assembly and on DFA are presented in detail in the companion text "Automatic Assembly and Design for Assembly" [7].

1.3 Implementation of Design for Assembly

The objective of DFMA was to produce tools which could be used by product designers. These tools guide the designers or design team to where the problems in a proposed design lie. However, it is one thing to develop design tools but quite another to get designers to use them.

Peter Dewhurst joined Boothroyd in 1980 at UMass. They quickly collaborated in developing a computer version of the DFA handbook [8]. They used the latest personal computer

(PC), the Apple II Plus, and released a software package "Design for Automatic and Manual Assembly." It appeared that, unlike their European or Japanese counterparts, the U.S. designers preferred to use the new computers rather than perform hand calculations to analyze their designs for ease of assembly. Both IBM and Digital Equipment funded translation efforts so that the code would run on their own computers—in the case of IBM on their new PC. It is clear that the availability of computer software for DFA analysis contributed significantly to successful implementation in U.S. industry.

This work led to the incorporation of Boothroyd Dewhurst Inc. in 1981. The company has continued to develop software for DFA and for the estimation of manufacturing costs for a variety of processes (DFM Concurrent Costing).

A major breakthrough in DFA implementation was made in 1988 when Ford Motor Company reported that DFA software had helped them save billions of dollars on their Taurus line of automobiles. Later, General Motors (GM) made comparisons between its assembly plant at Fairfax, Kansas, which made the Pontiac Grand Prix, and Ford's assembly plant for its Taurus and Mercury Sable models near Atlanta [9]. GM found a large productivity gap and concluded that 41% of the gap could be traced to the manufacturability of the two designs. For example, the Ford car had fewer parts—10 in its front bumper compared with 100 in the GM Pontiac—and the Ford parts fit together more easily.

1.4 Design for Manufacture

Research on early cost estimating for a variety of manufacturing processes was pursued at UMass and then, from 1985 to 1996 at the University of Rhode Island (URI) by Geoff Boothroyd, Peter Dewhurst, and Winston Knight. Knight joined Boothroyd and Dewhurst on the faculty at URI in 1986. The present text describes much of this work.

It should be pointed out that the commercial software developments were all based on the research. Much of the support for this research came from industrial gifts which were mainly used to fund graduate students—many of whom went on to apply the results in the supporter companies. The results of the research were made freely available to industry in the form of 22 research reports from UMass and over 100 research reports from URI.

1.5 Producibility Guidelines

In the 1960s, there was much talk about designing products so they could be manufactured more easily. Recommendations commonly known as producibility guidelines were developed. Figure 1.3 shows a typical design guideline published in 1971 that emphasized simplifying the individual parts [10]. The authors of this guideline mistakenly assumed that several simple-shaped parts are inherently less expensive to manufacture than a single complex part and that any assembly cost is more than offset by the savings in part costs. They were wrong on both counts, as the results in Table 1.1 show. Even ignoring assembly costs, the two parts in the "right" design are significantly more expensive than the single part in the "wrong" design—even the piece part costs (neglecting tooling costs) are more expensive. Taking assembly costs into account and ignoring

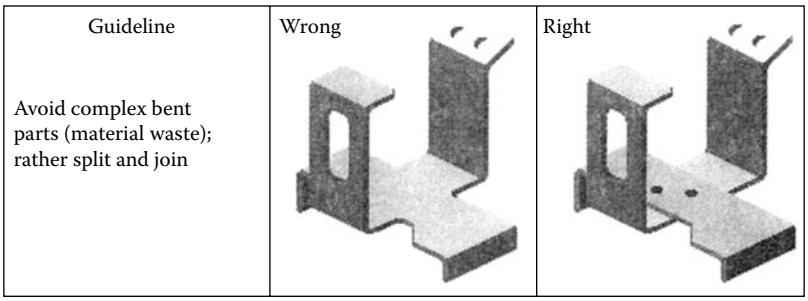

FIGURE 1.3
Misleading producibility guideline for the design of sheet metal parts. (From Pahl, G. and Beitz, W. *Engineering Design*, English Edition, The Design Council, London, 1984. With permission.)

storage, handling, quality, and paperwork costs, the "right" design is 50% more costly than the "wrong" design!

Once methods for analyzing assembly difficulties were developed in the 1970s, it became recognized that there was a conflict between producibility and assembly. It was found that the simplification of products by reducing the number of separate parts through DFA—on the order of 50% on average—could easily achieve substantial reductions in assembly costs. Much more important, however, was the fact that even greater savings could be achieved in the cost of the parts. The ability to estimate both assembly and part manufacturing costs at the earliest stages of product design is the essence of DFMA. The authors of this text have carried out numerous research programs over the past two decades on the subject of DFMA. A primary objective of this work has been to develop economic models of manufacturing processes, based on product design information, and which require a minimum of manufacturing knowledge [11–13].

The simple example in Figure 1.3 and Table 1.1 illustrates this. If the "right" design were subject to a DFA analysis, the designer would be challenged as to why the subassembly could not be manufactured as a single part, thereby eliminating an assembly cost of $0.20. Further analysis would show an additional saving of $0.17 in part costs.

Of course, the word "design" has many different meanings. To some it means the esthetic design of a product such as the external shape of a car or the color, texture, and shape of the casing of a can opener. In fact, in some university curricula this is what would be meant by a course in "product design." On the other hand, design can mean establishing

TABLE 1.1

Estimated Costs in Dollars for the Two Examples in Figure 1.3 if 100,000 are Made

	Wrong	**Right**
Setup	0.015	0.023
Process	0.535	0.683
Material	0.036	0.025
Piece part	0.586	0.731
Tooling	0.092	0.119
Total manufacture	0.678	0.850
Assembly	0.000	0.200
Total	0.678	1.050

the basic parameters of a system. For example, before considering any detail, the design of a power plant might mean establishing the characteristics of the various units such as generators, pumps, boilers, connecting pipes, and so on.

Yet another interpretation of the word "design" would be detailing of the materials, shapes, and tolerance of the individual parts of a product. This is the aspect of product design mainly considered in this text. It is an activity that starts with sketches of parts and assemblies; it then progresses to the computer-aided design (CAD) workstation, where assembly drawings and detailed part drawings are produced. These drawings are then passed to the manufacturing and assembly engineers whose job it is to optimize the processes used to produce the final product. Frequently, it is at this stage that manufacturing and assembly problems are encountered and requests are made for design changes. Sometimes these design changes are large in number and result in considerable delay in the final product release. In addition, the later in the product design and development cycle changes occur, the more expensive they become. Therefore, not only is it important to take manufacture and assembly into account during product design, but also these considerations must occur as early as possible in the design cycle.

This is illustrated qualitatively by the chart in Figure 1.4 showing that extra time spent early in the design process is more than compensated for by savings in time when prototyping takes place. Thus, in addition to reducing product costs, the application of DFMA shortens the time to bring the product to market. As an example, Ingersoll–Rand Company reported [14] that the use of DFMA software from Boothroyd Dewhurst, Inc., slashed product development time from two years to one. In addition, the simultaneous engineering team reduced the number of parts in a portable compressor radiator and oil-cooler assembly from 80 to 29, decreased the number of fasteners from 38 to 20, trimmed the number of assembly operations from 159 to 40, and reduced assembly time from 18.5 to 6.5 min. Developed in June 1989, the new design went into full production in February 1990.

Another reason why careful consideration of manufacture and assembly should be taken into account early in the design cycle is because it is now widely accepted that over 70% of the final product costs are determined during design [15]. This is illustrated in Figure 1.5.

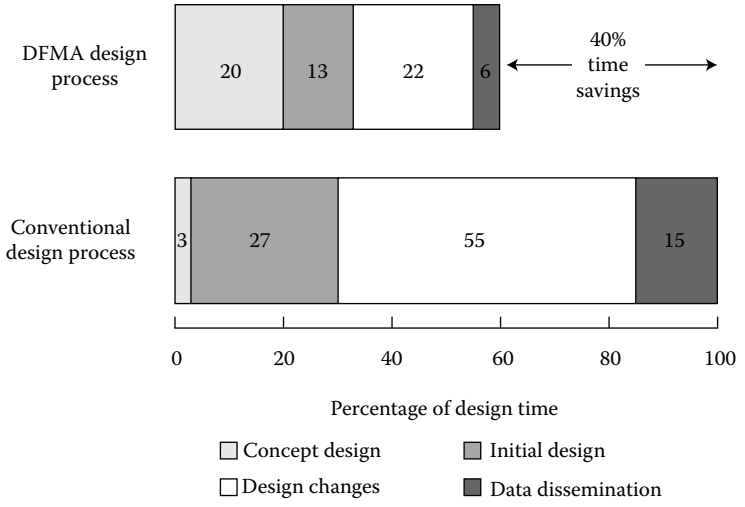

FIGURE 1.4
DFMA shortens the design process. (Adapted from Bauer, L. *Team Design Cuts Time, Cost, Welding Design Fabrication,* September, 1990, p. 35.)

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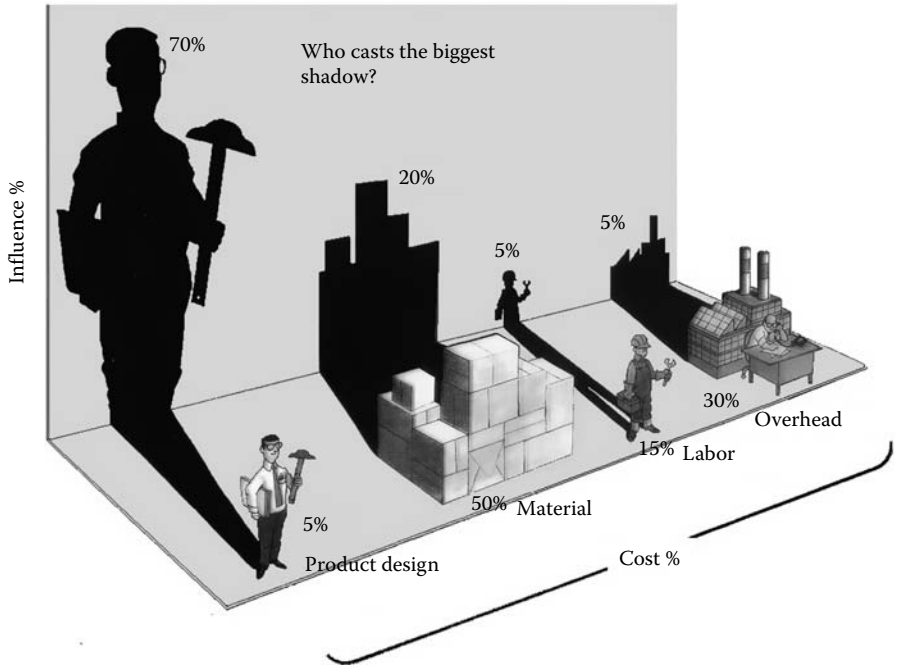

FIGURE 1.5
Who casts the biggest shadow? (Adapted from Munro and Associates, Inc.)

Traditionally, the attitude of designers has been "we design it, you build it." This has now been termed the "over-the-wall approach" where the designer sits on one side of the wall and throws designs over the wall (Figure 1.6) to the manufacturing engineers, who then have to deal with the various manufacturing problems arising because they were not involved in the design effort. One means of overcoming this problem is to consult the manufacturing engineers at the design stage. The resulting teamwork avoids many problems. However, these teams, now called simultaneous engineering or concurrent engineering teams, require analysis tools to help them study proposed designs and evaluate them from the point of view of manufacturing difficulty and cost.

By way of illustration we see that DFMA efforts at Hewlett Packard Loveland [16] started in the mid-1980s with the redesign of existing products and continued with application to new product design. During these studies, which proved increasingly successful, product development involved one to three manufacturing engineers interacting frequently with the R&D team members. Eventually, by 1992, HP Loveland had incorporated DFMA into a formal concurrent engineering approach. The gradual improvements in their product manufacturing and assembly costs are shown in Figure 1.7.

1.6 How Does DFMA Work?

Let us follow an example from the conceptual design stage. Figure 1.8 shows the original design of a motor drive assembly that is required to sense and control its position on two

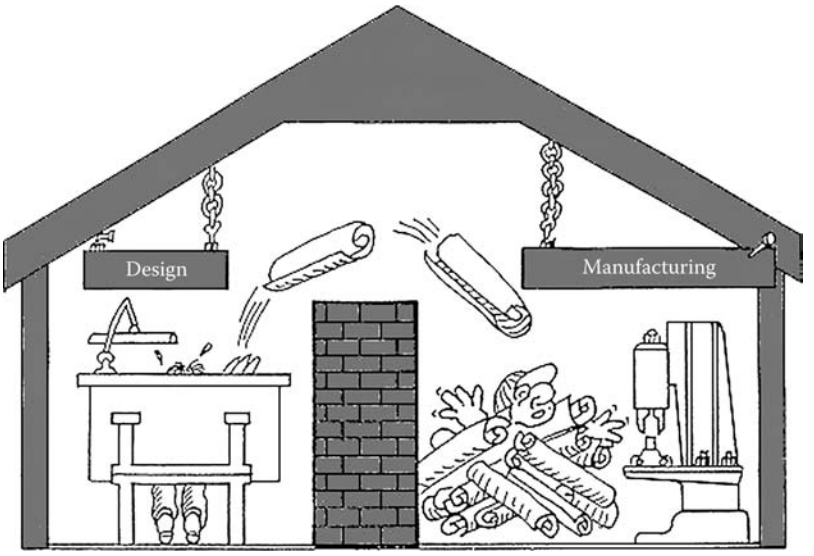

FIGURE 1.6
"Over-the-wall" design, historically the way of doing business. (Adapted from Munro and Associates, Inc.)

steel guide rails. The motor must be fully enclosed for esthetic reasons and have a removable cover to provide access to adjustment of the position sensor. The principle requirements are a rigid base designed to slide up and down the guide rails and both support the motor and locate the sensor. The motor and sensor have wires connecting to a power supply and control unit, respectively.

The base is provided with two bushings to provide suitable friction and wear characteristics. The motor is secured to the base with two screws; a hole accepts the cylindrical

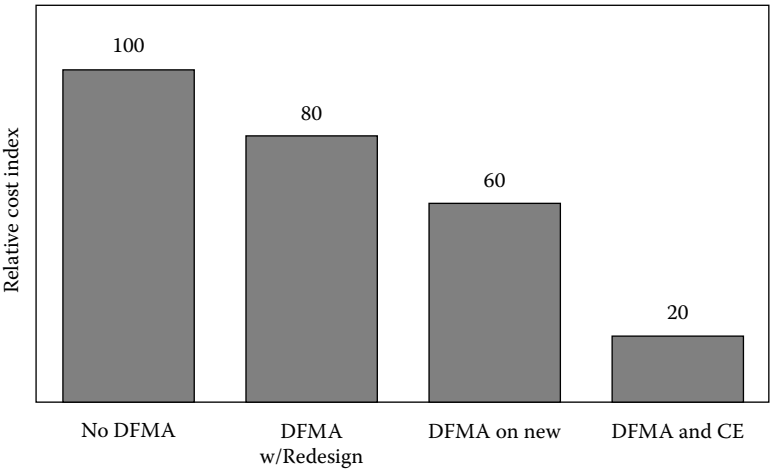

FIGURE 1.7
Effects of DFMA and CE on product cost at Hewlett Packard. (Adapted from Williams, R.A. *Successful Implementation of Engineering Products and Processes*. Van Nostrand, New York, 1994.)

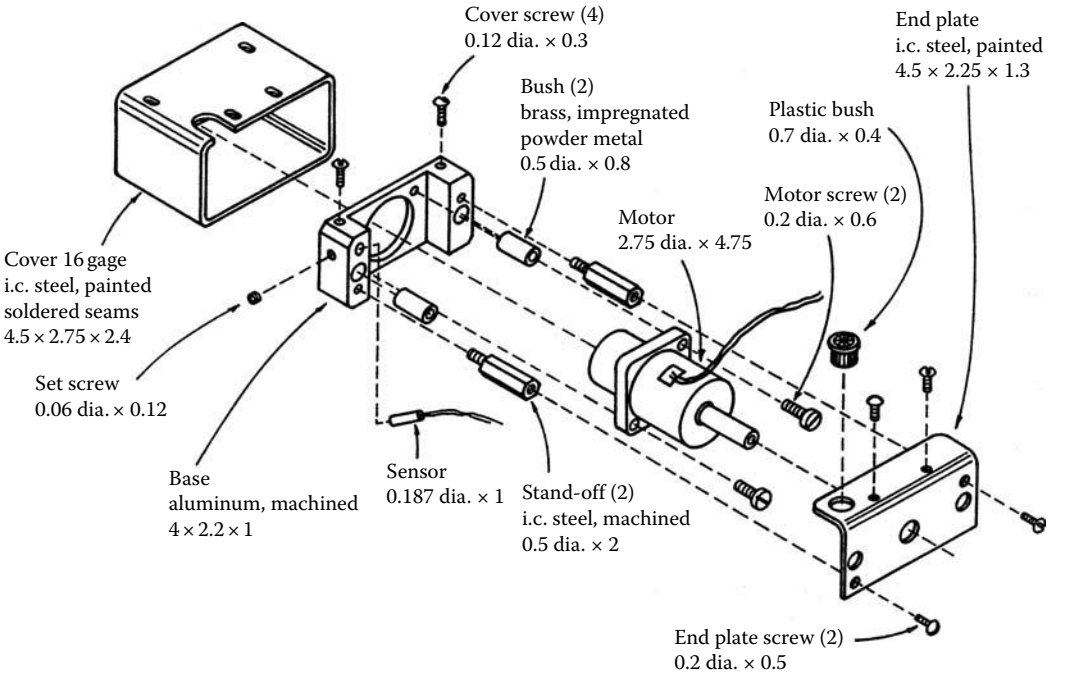

FIGURE 1.8
Original design of the motor drive assembly (dimensions in inches).

sensor, which is held in place with a set screw. The motor base and sensor are the only items necessary for the operation of the device. To provide the required covers, an end plate is screwed to two standoffs which are screwed into the base. This end plate is fitted with a plastic bushing through which the connecting wires pass. Finally, a box-shaped cover slides over the whole assembly from below the base and is held in place by four screws, two passing into the base and two into the end cover.

There are two subassemblies, the motor and the sensor, which are required items, and, in this initial design, there are eight additional main parts and nine screws making a total of nineteen items to be assembled.

When DFA began to be taken seriously in the early 1980s and the consequent benefits were appreciated, it became apparent that the greatest improvements arose from simplification of the product by reducing the number of separate parts. In order to give guidance to the designer in reducing the part count, the DFA methodology [5] provides three criteria against which each part must be examined as it is added to the product during assembly.

1. During operation of the product, does the part move relative to all other parts already assembled. Only gross motion should be considered—small motions that can be accommodated by integral elastic elements, for example, are not sufficient for a positive answer.
2. Must the part be of a different material or be isolated from all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.

3. Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible.

Application of these criteria to the original design (Figure 1.8) during assembly would proceed as follows:

1. *Base:* Since this is the first part to be assembled, there are no other parts with which it can be combined, and so it is a theoretically necessary part.
2. *Bushings (2):* These do not satisfy the criteria because, theoretically, the base and bushings could be of the same material.
3. *Motor:* The motor is a standard subassembly of parts that, in this case, is purchased from a supplier. Thus, the criteria cannot be applied and the motor is a necessary separate item.
4. *Motor screws (2):* Invariably, separate fasteners do not meet the criteria, because an integral fastening arrangement is always theoretically possible.
5. *Sensor:* This is another standard subassembly and will be considered as a necessary separate item.
6. *Set screw:* Theoretically not necessary.
7. *Standoffs (2):* These do not meet the criteria; they could be incorporated into the base.
8. *End plate:* Must be separate for reasons of assembly of necessary items.
9. *End plate screws (2):* Theoretically not necessary.
10. *Plastic bushing:* Could be of the same material as, and therefore combined with, the end plate.
11. *Cover:* Could be combined with the end plate.
12. *Cover screws (4):* Theoretically not necessary.

From this analysis, it can be seen that if the motor and sensor subassemblies could be arranged to snap or screw into the base and a plastic cover designed to snap on, only four separate items would be needed instead of 19. These four items represent the theoretical minimum number needed to satisfy the requirements of the product design without considering practical limitations.

It is now necessary for the designer or design team to justify the existence of those parts that did not satisfy the criteria. Justification may arise from practical or technical considerations or from economic considerations. In this example, it could be argued that two screws are needed to secure the motor and one set screw is needed to hold the sensor, because any alternative would be impractical for a low-volume product such as this. However, the design of these screws could be improved by providing them with pilot points to facilitate assembly.

It could be argued that the two powder metal bushings are unnecessary, because the part could be machined from an alternative material, such as nylon, having the necessary frictional characteristics. Finally, it is difficult to justify the separate standoffs, end plate, cover, plastic bushing, and six screws.

Now, before an alternative design can be considered, it is necessary to have estimates of the assembly times and costs so that any possible savings can be taken into account when considering design alternatives. Using the techniques described in this text, it is possible

TABLE 1.2

Results of DFA Analysis for the Motor Drive Assembly Original Design (Figure 1.8)

	No.	Theoretical Part Count	Assembly Time (s)	Assembly Cost (¢)[a]
Base	1	1	3.5	2.9
Bushing	2	0	12.3	10.2
Motor subassembly	1	1	9.5	7.9
Motor screw	2	0	21.0	17.5
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	10.6	8.8
Standoff	2	0	16.0	13.3
End plate	1	1	8.4	7.0
End plate screw	2	0	16.6	13.8
Plastic bushing	1	0	3.5	2.9
Thread leads	—	—	5.0	4.2
Reorient	—	—	4.5	3.8
Cover	1	0	9.4	7.9
Cover screw	4	0	31.2	26.0
Totals	19	4	160.0	133

$$\text{Assembly index} = \frac{4 \times 3}{160} = 7.5\%$$

[a] For a labor rate of $30 per h.

to make estimates of assembly costs, and later estimate the cost of the parts and associated tooling, without having final detail drawings of the part available.

Table 1.2 presents the results of an assembly analysis for the original motor drive assembly where it can be seen that an assembly index of 7.5% is given. This figure is obtained by comparing the estimated assembly time of 160 s with a theoretical minimum time obtained by multiplying the theoretical minimum part count of four by a minimum time of assembly for each part of 3 s. It should be noted that for this analysis, standard subassemblies are counted as parts.

Considering first the parts with zeros in the theoretical part count column, it can be seen that those parts that did not meet the criteria for minimum part count involved a total assembly time of 120.6 s. This figure should be compared with the total assembly time for all 19 parts of 160 s. It can also be seen that parts involving screw-fastening operations resulted in the largest assembly times. It has already been suggested that the elimination of the motor screws and the set screw would probably be impractical. However, elimination of the remaining parts not meeting the criteria would result in the redesign concept shown in Figure 1.9 where the bushings are combined with the base and the standoffs, end plate, cover, plastic bushing, and six screws are replaced by one snap-on plastic cover. The eliminated items involved an assembly time of 97.4 s. The new cover would take only 4 s to assemble and would avoid the need for a reorientation. In addition, screws with pilot points would be used and the base redesigned so that the motor is self-aligning.

Table 1.3 presents the results of an assembly analysis of the new design where it can be seen that the new assembly time is only 46 s—less than one-third of the original assembly time. The assembly index is now 26%, a figure that approaches the range found from the experience to be the representative of good designs of small electromechanical devices produced in a relatively low volume.

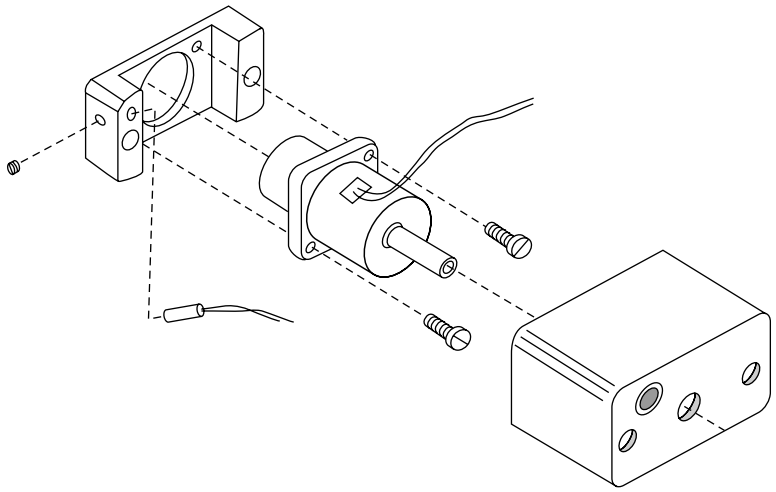

FIGURE 1.9
Redesign of the motor drive assembly following DFA analysis.

Table 1.4 compares the cost of the parts for the two designs showing a savings of $15 in parts cost. However, the tooling for the new cover is estimated to be $6307—an investment that would have to be made at the outset. The parts' cost and tooling cost estimates were made using the techniques described in this text.

Thus, the outcome of this study is a second design concept representing a total savings of $15.95, of which only 95 cents represents the savings in assembly time. In addition, the assembly index has been improved by about 250%.

It is interesting to note that the redesign suggestions arose through the application of the minimum part count criteria during the DFA analysis—the final cost comparison being made after assembly cost and parts cost estimates were considered.

The second step in an analysis is DFM. This means estimating the cost of the manufactured parts in order to quantify the effects of any design improvements suggested by the initial DFA analysis. In the present example, the DFM analysis of the base revealed the cost of providing each set of features by machining. Interestingly, it was found that elimination

TABLE 1.3

Results of DFA Analysis for the Motor Drive Assembly Redesign (Figure 1.9)

	No.	Theoretical Part Count	Assembly Time (s)	Assembly Cost (¢)[a]
Base	1	1	3.5	2.9
Motor subassembly	1	1	4.5	3.8
Motor screw	2	0	12.0	10.0
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	8.5	7.1
Thread leads	—	—	5.0	4.2
Plastic cover	1	1	4.0	3.3
Totals	6	4	46.0	38.4

$$\text{Assembly index} = \frac{4 \times 3}{46.0} = 26\%$$

[a] For a labor rate of $30 per h.

TABLE 1.4

Comparison of Parts Cost for the Motor Drive Assembly Original Design and Redesign (Purchased Motor and Sensor Subassemblies not Included)

(a) Original Design		(b) Redesign	
Item	**Cost ($)**	**Item**	**Cost ($)**
Base (aluminum)	12.91	Base (nylon)	13.43
Ushing (2)	2.40[a]	Motor screw (2)	0.20[a]
Motor screw (2)	0.20[a]	Set screw	0.10[a]
Set screw	0.10[a]	Plastic cover	6.71
Standoff (2)	5.19	(includes tooling)	
End plate	5.89		
End plate screw (2)	0.20[a]	Total	20.44
Plastic bushing	0.10[a]		
Cover	8.05	Tooling cost for plastic cover, $6307	
Cover screw (4)	0.40[a]		
Total	35.44		

[a] Purchased in quantity.

of the two drilled and tapped screw holes in the side of the base and the two drilled and tapped holes provided for the standoffs would reduce the total machining cost by $1.14. Thus, these changes would save more than the total possible savings in an assembly cost of 95 cents. This is an indication that it is important not only to know the total estimated manufacturing cost of an item but, more importantly, to know the cost of providing the various features. This case study is typical in the sense that although DFA means design for assembly, the results of improving assemblability usually manifest themselves in significant reductions in part manufacturing costs.

Figure 1.10 summarizes the steps taken when using DFMA during design. The DFA analysis is first conducted leading to a simplification of the product structure. Then,

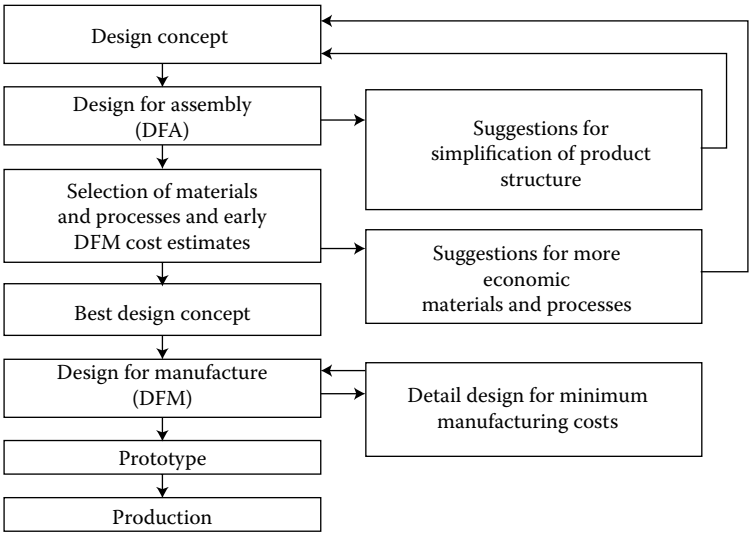

FIGURE 1.10
Typical steps taken in a DFMA study using the DFMA software.

using DFM, early cost estimates for the parts are obtained for both the original design and the new design in order to make trade-off decisions. During this process the best materials and processes to be used for the various parts are considered. In the example, would it be better to manufacture the cover in the new design from sheet metal? Once the final selection of materials and processes has occurred, a more thorough analysis for DFM can be carried out for the detailed design of parts. All these steps are considered in the following chapters.

1.7 Falsely Claimed Reasons for Not Implementing DFMA

1.7.1 No Time

In making presentations and conducting workshops on DFMA, the authors have found that the most common complaint among designers is that they are not allowed sufficient time to carry out their work. Designers are usually constrained by the urgent need to minimize the design-to-manufacture time for a new product. Unfortunately, as was illustrated earlier (Figure 1.4), more time spent in the initial stages of design reaps benefits later in terms of reduced engineering changes after the design has been released to manufacturing. Company executives and managers must be made to realize that the early stages of design are critical in determining not only manufacturing costs, but also the overall design-to-manufacturing cycle time.

1.7.2 Not Invented Here

Enormous resistance can be encountered when new techniques are proposed to designers. Ideally, any proposal to implement DFMA should come from the designers themselves. However, more frequently it is the managers or executives who have heard of the successes resulting from DFMA and who wish their own designers to implement the philosophy. Under these circumstances, great care must be taken to involve the designers in the decision to implement these new techniques. Only then will the designers support the idea of applying DFMA. If they do not support DFMA, it will not be successfully applied.

1.7.3 Ugly Baby Syndrome

Even greater difficulties can exist when an outside group or a separate group within the company undertakes to analyze current designs for the ease of manufacture and assembly. Commonly, it is found that significant improvements could be made to the current design, and when these improvements are brought to the attention of those who produced the design this can result in extreme resistance. Telling a designer that their designs could be improved is much like telling a mother that her baby is ugly! It is important, therefore, to involve the designers in the analysis and provide them with the incentive to produce better designs. If they perform the analysis, they are less likely to take as criticism any problem that may be highlighted.

1.7.4 Low Assembly Costs

The earlier description of the application of DFMA showed that the first step is a DFA analysis of the product or subassembly. Quite frequently, it is suggested that since

assembly costs for a particular product form only a small proportion of the total manufacturing costs, there is no point in performing a DFA analysis. Figure 1.11 shows the results of an analysis where the assembly costs were extremely small compared with material and manufacturing costs. However, DFA analysis would suggest a replacement of the complete assembly with, say, a machined casting. This would reduce total manufacturing costs by at least 50%.

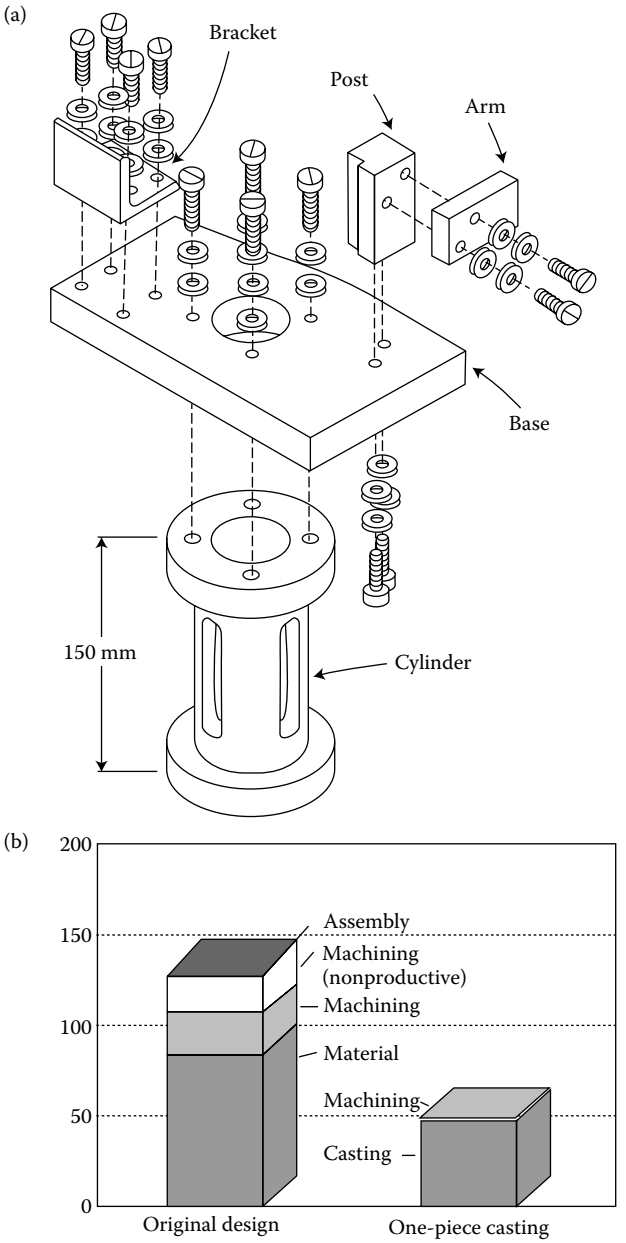

FIGURE 1.11
DFA analysis can reduce total costs significantly even though assembly costs are small.

1.7.5 Low Volume

The view is often expressed that DFMA is worthwhile only when the product is manufactured in large quantities. It could be argued, though, that the use of the DFMA philosophy is even more important when the production quantities are small. This is because, commonly, reconsideration of an initial design is usually not carried out for low-volume production. Figure 1.11 is an example of this where the assembly was designed to be built from items machined from stock as if the product were one-of-a-kind. The prototype then became the production model. Applying the philosophy "do it right the first time" becomes even more important, therefore, when production quantities are small. In fact, the opportunities for parts consolidation are usually greater under these circumstances, because it is not usually a consideration during design.

1.7.6 We Have Been Doing It for Years

When this claim is made, it usually means that some procedure for "design for producibility" has been in use in the company. However, design for producibility usually means a detailed design of individual parts for the ease of manufacture. It was made clear earlier that such a process should occur only at the end of the design cycle; it can be regarded as a "fine tuning" of the design. The important decisions affecting total manufacturing costs would already have been made. In fact, there is great danger in implementing the design for producibility in this way. It has been found that the design of individual parts for the ease of manufacture can mean, for example, limiting the number of bends in a sheet metal part. Again, experience has shown that it is important to combine as many features in one part as possible. In this way, full use is made of the abilities of the various manufacturing processes.

1.7.7 It Is Only Value Analysis

It is true that the objectives of DFMA and value analysis are the same. However, it should be realized that DFMA is meant to be applied early in the design cycle and that value analysis does not give proper attention to the structure of the product and its possible simplification. DFMA has the advantage that it is a systematic step-by-step procedure that can be applied at all stages of design and challenges the designer or design team to justify the existence of all the parts and to consider alternative designs. Experience has shown that DFMA still makes significant improvements of the existing products even after value analysis has been carried out.

1.7.8 DFMA Is Only One among Many Techniques

Since the introduction of DFMA, many other techniques have been proposed, for example, design for quality (DFQ), design for competitiveness (DFC), design for reliability, and many more. Many have even suggested that the design for performance is just as important as DFMA. One cannot argue against this. However, DFMA is the subject that has been neglected over the years, while adequate consideration has generally been given to the design of products for performance, appearance, and so on.

The other factors, such as quality, reliability, and so on, will follow when proper consideration is given to the manufacture and assembly of the product. In fact, Figure 1.12 shows

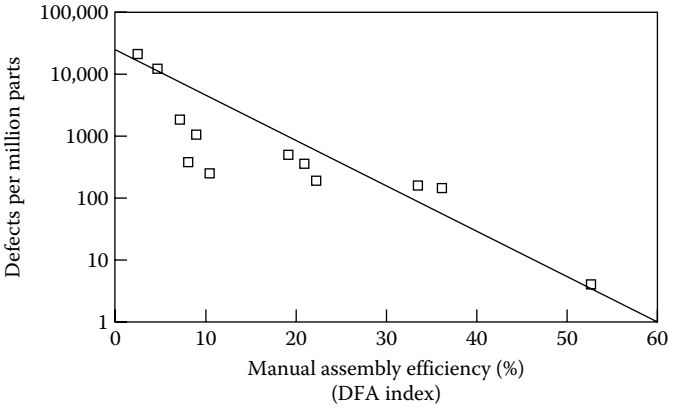

FIGURE 1.12
Improved assembly efficiency results in increased reliability. (Adapted from Branan, W. Six-Sigma quality and DFA *DFMA insight*, Boothroyd Dewhurst Inc., 2(1), winter 1991, 1–3.)

a relationship between the quality of a design measured by the assembly index obtained during DFA and the resulting product quality measured in defects per million parts assembled. Each data point on this graph represents a different product designed and manufactured by Motorola. It clearly shows that if DFA is carried out leading to simplified designs, then improved quality will follow.

1.7.9 DFMA Leads to Products that are more Difficult to Service

This is absolute nonsense. Experience shows that a product that is easy to assemble is usually easier to disassemble and reassemble. In fact, products that need continual service involving the removal of inspection covers and the replacement of various items should have DFMA applied even more rigorously during the design stage. How many times have we seen an inspection cover fitted with numerous screws, only to find that after the first inspection only two are replaced?

1.7.10 I Prefer Design Rules

There is a danger in using design rules, because they can guide the designer in the wrong direction. Generally, rules attempt to force the designer to think of simpler-shaped parts that are easier to manufacture. In an earlier example, it was pointed out that this can lead to more complicated product structures and a resulting increase in the total product cost. In addition, in considering novel designs of parts that perform several functions, the designer needs to know what penalties are associated when the rules are not followed. For these reasons, the systematic procedures used in DFMA that guide the designer to simpler product structures and provide quantitative data on the effect of any design changes or suggestions are found to be the best approach.

1.7.11 I Refuse to Use DFMA

Although a designer will not say this, if the individual does not have the incentive to adopt this philosophy and use the tools available, then no matter how useful the tools or how simple they are to apply, the individual will see to it that they do not work. Therefore, it is

imperative that the designer or the design team be given the incentive and the necessary facilities to incorporate considerations of assembly and manufacture during design.

1.8 What Are the Advantages of Applying DFMA during Product Design?

DFMA provides a systematic procedure for analyzing a proposed design from the point of view of assembly and manufacture. This procedure results in simpler and more reliable products that are less expensive to assemble and manufacture. In addition, any reduction in the number of parts in an assembly produces a snowball effect on cost reduction because of the drawings and specifications that are no longer needed, the vendors that are no longer needed, and the inventory that is eliminated. All these factors have an important effect on overheads, which, in many cases, form the largest proportion of the total cost of the product.

DFMA tools also encourage dialogue between designers and the manufacturing engineers and any other individuals who play a part in determining final product costs during the early stages of design. This means that teamwork is encouraged and the benefits of simultaneous or concurrent engineering can be achieved.

A recent example [17] comes from the International Gaming Technology (IGT). IGT is a global Fortune 500 company involved in the design, manufacture, and marketing of electromechanical gaming equipment. When the current economic crisis impacted on their customers and the gaming industry worldwide, their engineers were challenged to seek new opportunities for cost reductions, alongside innovative design and development.

About 4 years ago, Sam Mikhail, who had previous experience with DFMA, raised the possibility of using DFMA in IGT for cost reduction. This proposal was met with the attitude that DFMA implementation was not necessary within the company and that the prevailing processes in the company had already incorporated any potential cost reduction. Typical responses included: "Why? we have no time for this," "we don't need it," and "we have always been doing it this way"

Initially, the engineers believed that DFMA is a time-consuming practice with unknown benefits and that the size of the company would make it challenging to implement. There were also a number of engineers who believed that they had been, or were, working with DFMA principles and therefore had nothing to gain by formally introducing DFMA in the company.

Eventually, Sam was successful in introducing DFMA through a pilot workshop. When the selected participants for the workshops were invited to attend, reluctance was expected. This was reflected in the results of a preworkshop questionnaire (Figure 1.13).

As the workshop progressed, the participants' enthusiasm grew significantly as they applied DFMA techniques to their existing designs, and ultimately welcomed the challenge to improve the designs. Pushing design boundaries beyond the status quo and with open communication between the manufacturing, mechanical, and electrical disciplines resulted in innovative approaches to solving design challenges. After the workshop, another survey was conducted. The results (Figure 1.14) indicated a complete change in attitude on the part of the participants.

Following the success of the workshop in June 2008, the management approved an ongoing DFMA program with training for the engineers. As a result, cost savings in excess of 1 million had been achieved by June 2009 and more savings were expected.

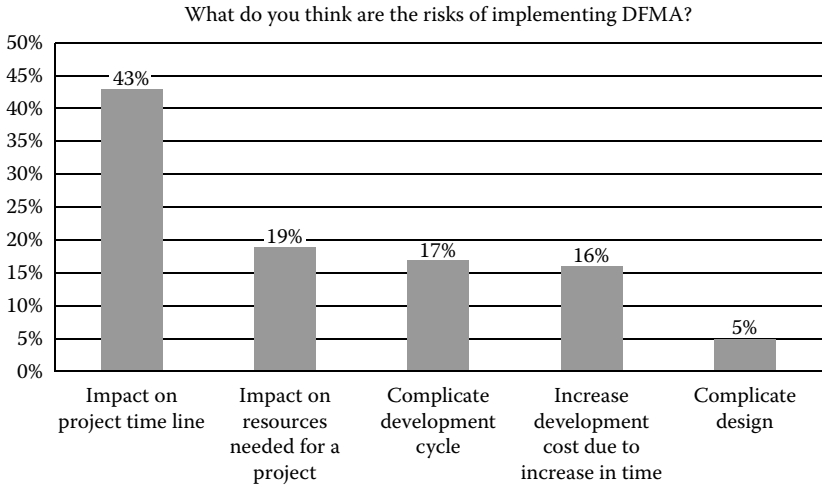

FIGURE 1.13
Responses to a questionnaire presented to IGT engineers prior to the introduction of DFMA. (Adapted from Mikhail, S. *Decision-making Process for Implementing DFMA at IGT*, International Forum on DFMA, Providence, RI, June 2009.)

Another recent example is from Aztalan Engineering; a precision machining company providing quality components for the American industry [18]. However, as General Manager Jim Hale points out "all this precision cutting and milling requires careful planning and tracking." During the course of a day's work, technicians assemble "to analyze proposed designs of parts for their manufacturability, establish process controls for parts being manufactured, and communicate with customers and the supply chain."

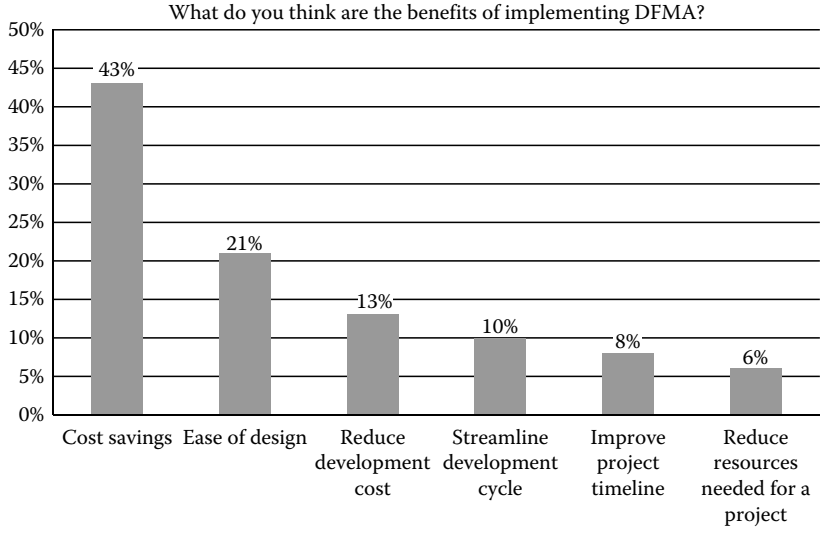

FIGURE 1.14
Responses to a questionnaire presented to IGT engineers following the pilot workshop on DFMA. (Adapted from Mikhail, S. *Decision-making Process for Implementing DFMA at IGT*, International Forum on DFMA, Providence, RI, June 2009.)

In 2008 Jim Hale found a valued ally to help him execute these tasks more efficiently, namely the DFMA software. According to Jim, the company uses this software in a number of ways.

Quoting. "When a customer sends a CAD model of a proposed new part, we transfer the geometry from CAD into DFMA. Based on the geometry, the material, and the initial machining process selected for manufacturing the part, the software can identify significant blocks of machining time, part handling and fixturing time, tooling costs and secondary process costs."

Design review. Sometimes, it is not the process but the design of the part that affects costs. In that case, Aztalan shares its design analysis with the design engineer. "Often, we are addressing a series of questions that come from our analysis" Hale says. "Is the part complex? Can it be made simpler, maybe more machine-friendly?"

"Are the specified tolerances overly tight? Is there a way to reduce the number of secondary operations, or can we reduce costs by making the part from a different material?" The answers to these questions can help engineers design costs out of a part while preserving its functionality.

Alternative manufacturing processes. After establishing a benchmark, Aztalan can study different methods of manufacturing the part to see if one is potentially less expensive. Here the process library in DFMA is especially helpful. "We are expert machinists" Hale points out, "but we can't be experts in every single process out there—Investment casting, or forging for instance." At this stage, the software provides valuable guidance—first in exploring which processes can manufacture the current design of the part, then in providing initial time and cost estimates including the cost of any tooling. "Once we have determined which are viable, affordable processes, we can consult experts in those processes for more information" says Hale "but the software helps us to focus our exploration."

The savings in manufacturing costs obtained by many companies who have implemented DFMA are astounding. As mentioned earlier, Ford Motor Company has reported savings in billions of dollars as a result of applying DFMA to the original Ford Taurus line of automobiles [19]. This is a high-volume product. At the other end of the spectrum, where production quantities are low, Brown & Sharpe were able, through DFMA, to introduce their revolutionary coordinate-measuring machine, the MicroVal, at half the cost of their competitors, resulting in a multimillion dollar business for the company [20].

QSTAR is a mass spectrometer manufactured by MDS Sciex. Mass spectrometers are large, sophisticated instruments produced in low volumes. The manufacturing team recognized that the ease of assembly would largely determine the cost, manufacturing efficiency, and field performance for the product. As originally constructed, the prototype was difficult to assemble and needed days of testing and tweaking. QSTAR engineers used the DFA software to analyze the existing design and to spark innovative ways to consolidate parts and eliminate assembly difficulties [21].

The DFA software flagged the number of fasteners connecting a stack of resistors and metal rings. In the initial concept, each of the 32 resistors were secured with four screws, which contributed heavily toward the 8-h assembly time. As an alternative, they designed a connection that allows a technician to press the resistors into the metal base.

In the end, the QSTAR team designed one reflector subassembly that can be put together in only 45 min and can be removed and serviced without disrupting the rest of the instrument. Whereas the prototype reflector contained 289 parts with 26 unique components, the final reflector module contains 144 parts with 21 unique components. Only three screws and three nuts hold all 144 parts together.

DFA practices saved money in other ways too. By reducing the part count, QSTAR engineers cut material costs by $35,000 per unit and reduced opportunities for design and manufacturing errors.

Most importantly, DFA helped shorten the development cycle by 20%. MDS SCIEX management calculates that getting to market in 14 months increased revenue by $20 million and allowed QSTAR to capture one-fifth of the global market in the first year of sales.

The next case illustrates that DFMA reduces service time as well as assembly time.

At Dell Corporation, the redesign of the Optiframe® chassis for PCs, saved Dell an estimated $32.5 million in reduced direct labor costs [22]. The company saved millions more by increasing throughput and thus postponing facility relocations that otherwise would have been required to boost manufacturing capability. The savings in material costs from chassis integration and the related supply chain optimization program was $11.6 million for 1998 and was predicted to be $35 million in 1999.

Mechanical assembly time was reduced by an average of 32%.

Purchased part count was reduced by 50%.

Screw type count was reduced by 67%.

Screw min/max count was reduced by 55%.

Average service time was reduced by 44%.

These reductions resulted in substantial gains in productivity for Dell. Throughput per hour per square foot in the factories showed a 78% improvement. Operator productivity increased from 1.67 units per hour per operator to 3.07 units, an 84% improvement.

1.9 Overall Impact of DFMA on U.S. Industry

The preceding case studies describe a few of the successes resulting from the application of DFMA software. A summary of the results of published case studies from various companies is presented in Table 1.5, which shows that the average part count reduction

TABLE 1.5

Results of 123 Published Case Studies Showing Improvements from the Application of the DFMA Software

	Average Reduction (%)	Number of Cases
Labor costs	42	8
Part count	53	103
Separate fasteners	57	21
Weight	22	21
Assembly time	59	68
Assembly cost	45	20
Assembly operations	54	25
Product development cycle	45	2
Total cost	50	32

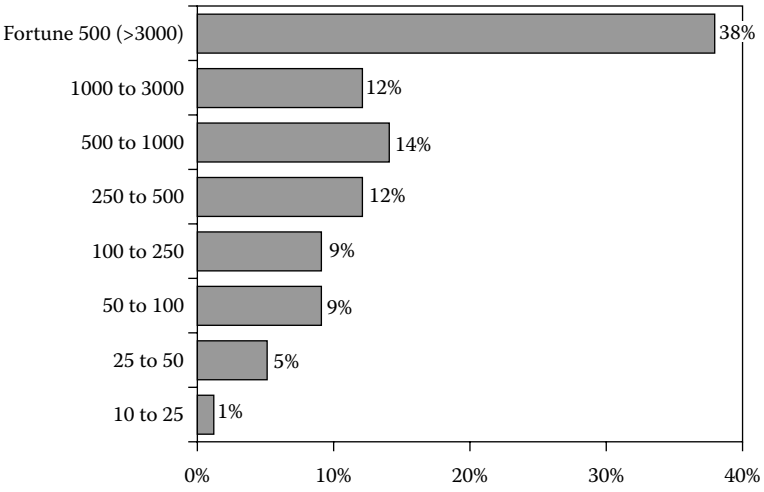

FIGURE 1.15
Percentage distribution of DFMA software users by company annual revenue.

is around 53%. The table also shows other improvements due to DFMA applications mentioned in the case studies. For example, 32 studies reported an average 50% reduction in the product cost.

According to our records, over 800 different U.S. companies have implemented the DFMA software since 1990. Of course, this figure does not indicate the number of individual users. The largest company, GM, reportedly has 1500 users, whereas others have only one. No other similar design methodology has had a significant impact on the U.S. industry as a whole. In the early 1980s, the Hitachi Assembly Evaluation Method (AEM) was licensed by a few major manufacturers; almost all now use DFMA instead.

Of course, not all the successful applications of DFMA are publicized. Companies are often reluctant to reveal their developments—certainly not before the product in question appears on the market. Thus, the published case studies form only a small proportion of the successes resulting from DFMA applications.

Of the Fortune 500 companies (those with annual revenues greater than about $3 billion) that are manufacturers, 60% have divisions or own companies that have licensed DFMA software. These represent about 38% of the licensed manufacturers (Figure 1.15).

The incentive to implement DFMA or concurrent engineering often arises because a company is under pressure to reduce manufacturing costs, improve time to market, and so on, because of competitive pressures. This was certainly true of the U.S. computer equipment and transportation industries 20 years ago. More recently, the U.S. aerospace and defense industries have been under pressure to become more competitive. It is not surprising that these developments are reflected in the industries using the DFMA software (Figure 1.16).

1.10 Conclusions

It is clear that the use of the DFMA software has a tremendous impact when properly applied in a concurrent engineering environment. Our experience in running DFMA

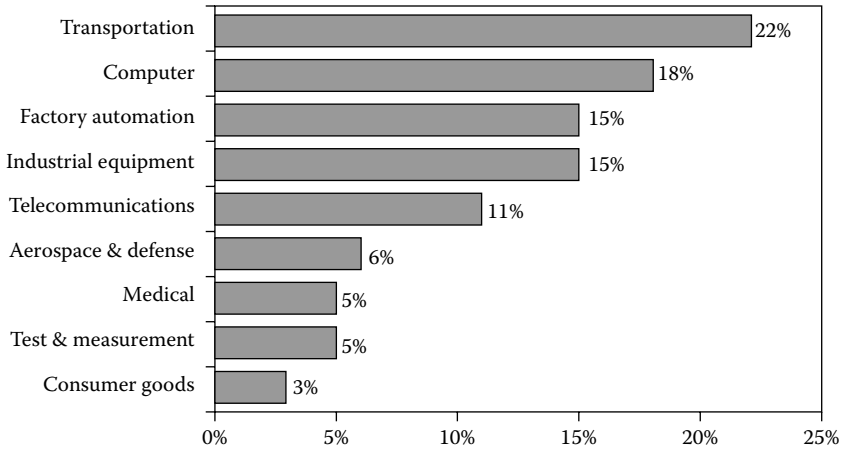

FIGURE 1.16
Percentage distribution of DFMA software users by industry.

design workshops has shown that significant ideas for design improvements can invariably be made in the space of only a few hours. Unfortunately, small manufacturers have not been able to take advantage of the huge potential of DFMA; they do not have the manpower or the necessary experience. Even with large companies, proven successes in one division do not necessarily spread to other divisions without management support and commitment. However, we remain encouraged by the continuing reports of substantial product improvements and often staggering cost savings obtained by both high- and low-volume manufacturers in the United States.

It should be noted that in all the published case studies mentioned, a systematic step-by-step DFMA analysis and quantification procedure was used. However, as pointed out earlier, it is still claimed by some that design rules or guidelines (sometimes called producibility rules) by themselves can give similar results. This is not so. In fact, guidelines or the qualitative procedures cart lead to increased product complexity, because they are usually aimed at simplifying the individual component parts, resulting in a design that has a large number of parts and poor quality and involves greater overheads, due to larger inventory, more suppliers, and more record keeping. Rather, the objective should be to utilize the capabilities of the individual manufacturing processes to the fullest extent in order to keep the product structure as simple as possible.

In spite of all the success stories, the major barrier to DFMA implementation continues to be human nature. People resist new ideas and unfamiliar tools, or claim that they have always taken manufacturing into consideration during design. The DFMA methodology challenges the conventional product design hierarchy. Designers are traditionally under great pressure to produce results as quickly as possible and often perceive DFMA as yet another time delay.

In fact, it has been established that the overall design development cycle is shortened through use of early manufacturing analysis tools, because designers can receive rapid feedback on the consequences of their design decisions where it counts—at the conceptual stage.

In conclusion, it appears that in order to remain competitive in the future, almost every manufacturing organization has to adopt the DFMA philosophy and apply cost quantification tools at the early stages of product design.

PROBLEMS

1. For each example in Figure 1.17, determine the theoretical minimum part count. Also, establish the part count when practical considerations are taken into account. In example b, assume both box and cover are die castings and, in example c, assume that the purpose is to cover the hole in the base plate.
2. Estimate the theoretical minimum part count for the Latch Mechanism shown in Figure 1.18.
3. Figure 1.3 shows a design recommendation which is shown to be misleading under a wide range of conditions. List the circumstances where the design recommendation might lead to a lower total manufacturing cost.
4. Perform a literature search to uncover reports where the applications of DFA or DFMA-type studies have resulted in product simplification or reductions in manufacturing costs. For each report give the reference and a brief summary of the findings.

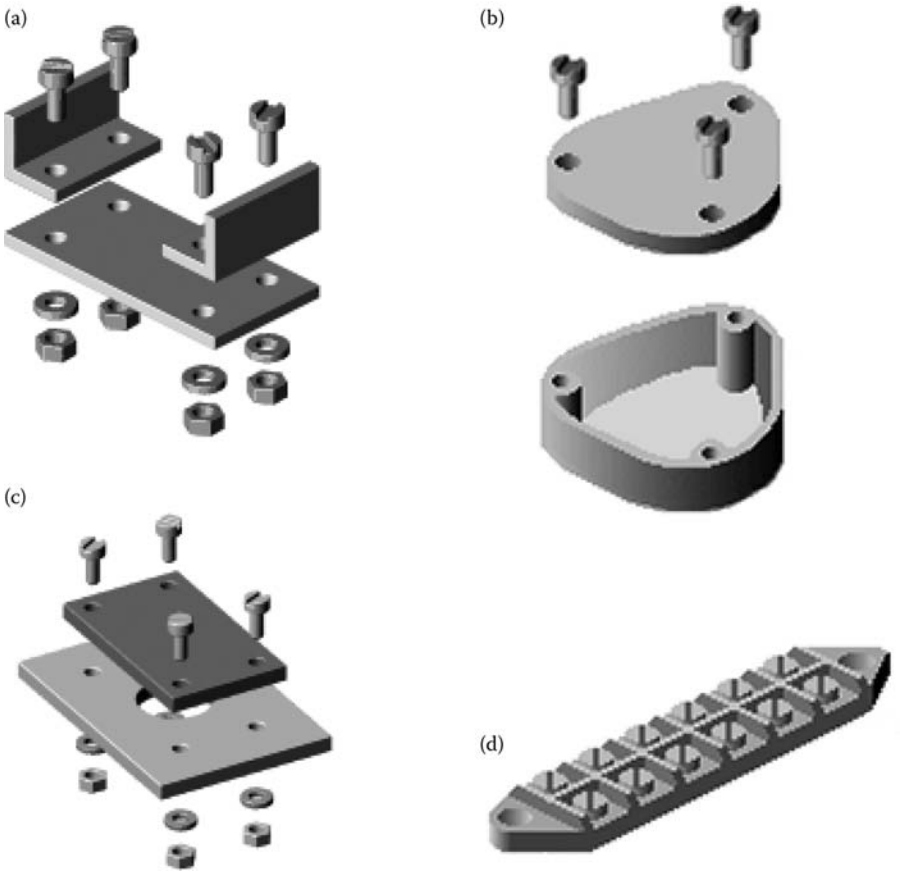

FIGURE 1.17
Examples of Problem 1.

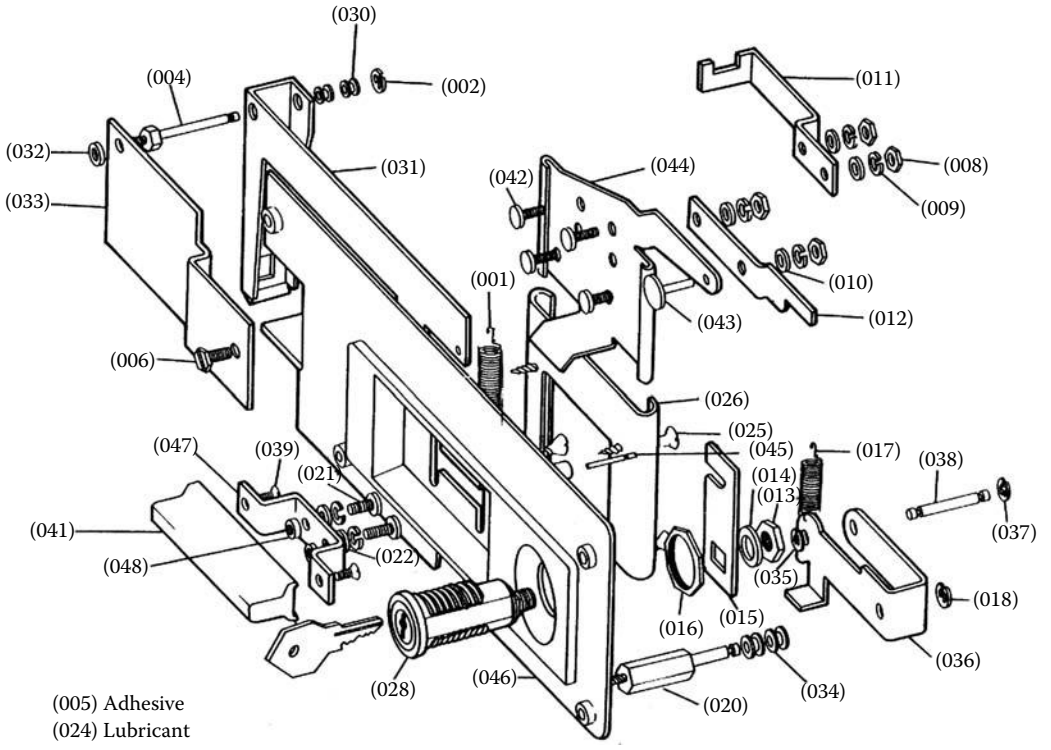

FIGURE 1.18
Latch mechanism.

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2

Selection of Materials and Processes

2.1 Introduction

An integral part of design for manufacture is the early selection of material and process combinations for the manufacture of parts, which can then be ranked according to various criteria. Unfortunately, designers tend to conceive parts in terms of the processes and materials with which they are most familiar, and they may, as a consequence, exclude from consideration processes and process/material combinations that might have proved to be more economic. Opportunities for major manufacturing improvements may be lost through such limited selections of manufacturing processes and the associated materials in the early stages of product design. This can be well illustrated by the results of a survey of designers' knowledge of manufacturing processes and materials carried out in Britain [1]. This survey covered a wide range of design offices in various sectors of industry. For manufacturing processes (Figure 2.1), more than half of those surveyed professed little or no knowledge of metal extrusion, two-third knew little about glass-reinforced molding, and over three quarters were uninformed about plastic extrusion, sintering, and the use of thermoset polymer fiber-reinforced sheet-molding compounds (SMC) and bulk-molding compounds (BMC). For less common processes, such as hot isostatic pressing, outsert molding, and superplastic forming, the percentage of designers claiming some process knowledge was only 6, 7, and 8, respectively. Similar results were found for materials, and Figure 2.2 illustrates designers' knowledge about a range of polymeric materials. This again shows a surprising lack of familiarity with some commonly used materials. The overall implication of these findings is that because material and process combinations are likely to be chosen from those with which designers are most comfortable, the possibilities of using other processes that may be much more cost-effective may be missed.

2.2 General Requirements for Early Materials and Process Selection

In order to be of real design value, the information on which the initial selection of material/process combinations and their ranking is to be based should be available at the early concept design stage of a new product. Such information might include, for example:

- Product life volume
- Permissible tooling expenditure levels
- Possible part shape categories and complexity levels

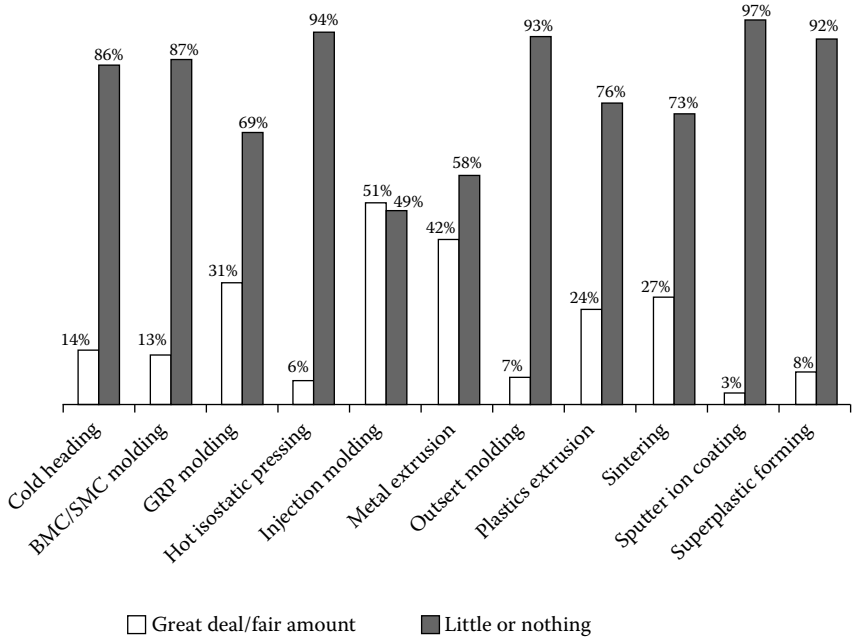

FIGURE 2.1
Survey of designers' knowledge of manufacturing processes. (Adapted from Bishop, R. *Huge Gaps in Designers' Knowledge Revealed*, Eureka, October 1985.)

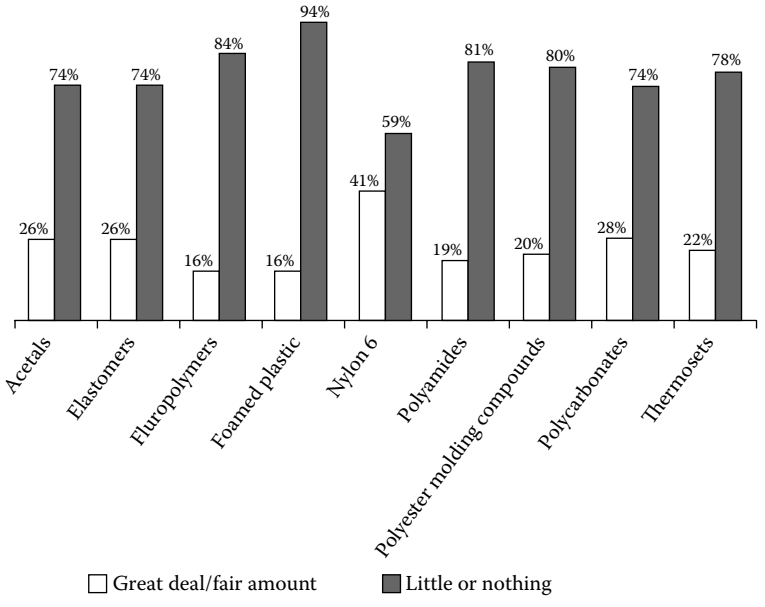

FIGURE 2.2
Survey of designers' knowledge of polymer materials. (Adapted from Bishop, R. *Huge Gaps in Designers' Knowledge Revealed*, Eureka, October 1985.)

- Service or environment requirements
- Appearance factors
- Accuracy factors

It is important to realize that for many processes the product and process are so intimately related that the product design must use an anticipated process as a starting point. In other words, many design details of a part cannot be defined without a consideration of processing. For this reason, it is crucial that an economic evaluation of competing processes be performed while the product is still at the conceptual stage. Such an early evaluation ensures that every economically feasible process is investigated further before the product design evolves to a level where it becomes process-specific.

As a design progresses from the conceptual stage to production, different methods can be used to perform the cost modeling of the product. At the conceptual stage, rough comparisons of the costs of products of similar size and complexity may be sufficient. While this procedure contains a certain degree of uncertainty, it only requires conceptual design information and is useful for the purpose of early economic comparison. As the design progresses and specific materials and processes are selected, more advanced cost modeling methods may be employed. These may be particularly useful in establishing the relationship between design features and manufacturing costs for the chosen process. The basis of several cost-estimation procedures for different processes is outlined in later chapters.

2.2.1 Relationship to Process and Operations Planning

There is an obvious relationship between the initial selection of process/material combinations and process planning. During process planning, the detailed elements of the sequence of manufacturing operations and machines are determined. It is at this stage that the final detailed cost estimates for the manufacture of the part are determined. Considerable work has been done in the area of computer-aided process planning (CAPP) systems [2–4], although closer examination shows that the majority of this work has been devoted to machining processes only. These systems are utilized after a detailed design of the part has been carried out, and the manufacturing processes are evident. The initial decision on the material and process combination to be used for the part is most important, as this determines the majority of subsequent manufacturing costs. The goal of systematic early material and process selection is to influence this initial decision on which combination to use, before a detailed design of the part is carried out and before detailed process planning is attempted.

2.3 Selection of Manufacturing Processes

The selection of appropriate processes for the manufacture of a particular part is based on a matching of the required attributes of the part and the various process capabilities. Once the overall function of a part is determined, a list can be formulated giving the essential geometrical features, material properties, and other attributes that are required. This represents a "shopping list" that must be filled by the material properties and process capabilities. The attributes on the "shopping list" are related to the final function of the part and are determined by geometric and service conditions.

Most component parts are not produced by a single process, but require a sequence of different processes to achieve all the required attributes of the final part. This is particularly the case when forming or shaping processes are used as the initial process, and material removal and finishing processes are required to produce some of the final part features. Even when using molding or casting processes, which can produce extremely complex geometries, there may be a number of features that are impossible to form and require subsequent machining operations. In other cases some of the features may be assigned to separate machining operations, because otherwise the die or mold may be uneconomically expensive. However, one of the goals of DFMA analysis is product structure simplification and parts consolidation. Experience shows that it is generally most economical to make best use of the capabilities of the initial manufacturing process in order to provide as many of the required attributes of a part as possible. As discussed in the introduction, the alternative approach of following guidelines to ensure that individual parts are as easy as possible to manufacture typically leads to an unnecessarily large number of separate parts, some of which add little value to the product.

There are hundreds of processes and thousands of individual materials. Moreover, new processes and materials are being developed continually. Fortunately, the following observations help to simplify the overall selection problem:

1. Many combinations of processes and materials are not possible. Figure 2.3 shows a compatibility matrix for a selected range of processes and material types.
2. Many combinations of processes are not possible and, therefore, do not appear in any processing sequences.
3. Some processes affect only one attribute of the part, particularly surface treatment and heat-treatment processes.
4. Sequences of processes have a natural order of shape generation, followed by feature addition or refinement by material removal and then material property or surface enhancement.

Processes can be categorized as:

- Primary processes
- Primary/secondary processes
- Tertiary processes

Some texts refer to primary processes as those used for producing the raw materials for manufacturing such as flat rolling, tube sinking, and wire drawing. In the context of producing component parts in this text, the term primary process refers to the main shape-generating process, assuming that the material has been purchased in the appropriate stock form (wire, tube, sheet, etc.). Such processes should be selected to produce as many of the required attributes of the part as possible and usually appear first in a sequence of operations. Casting, forging, and injection molding are examples of primary shape-generating processes.

Primary/secondary processes, on the other hand, can generate the main shape of the part, form features on the part, or refine features on the part. These processes appear at the start or later in a sequence of processes. This category includes material removal processes such as machining, grinding, and broaching.

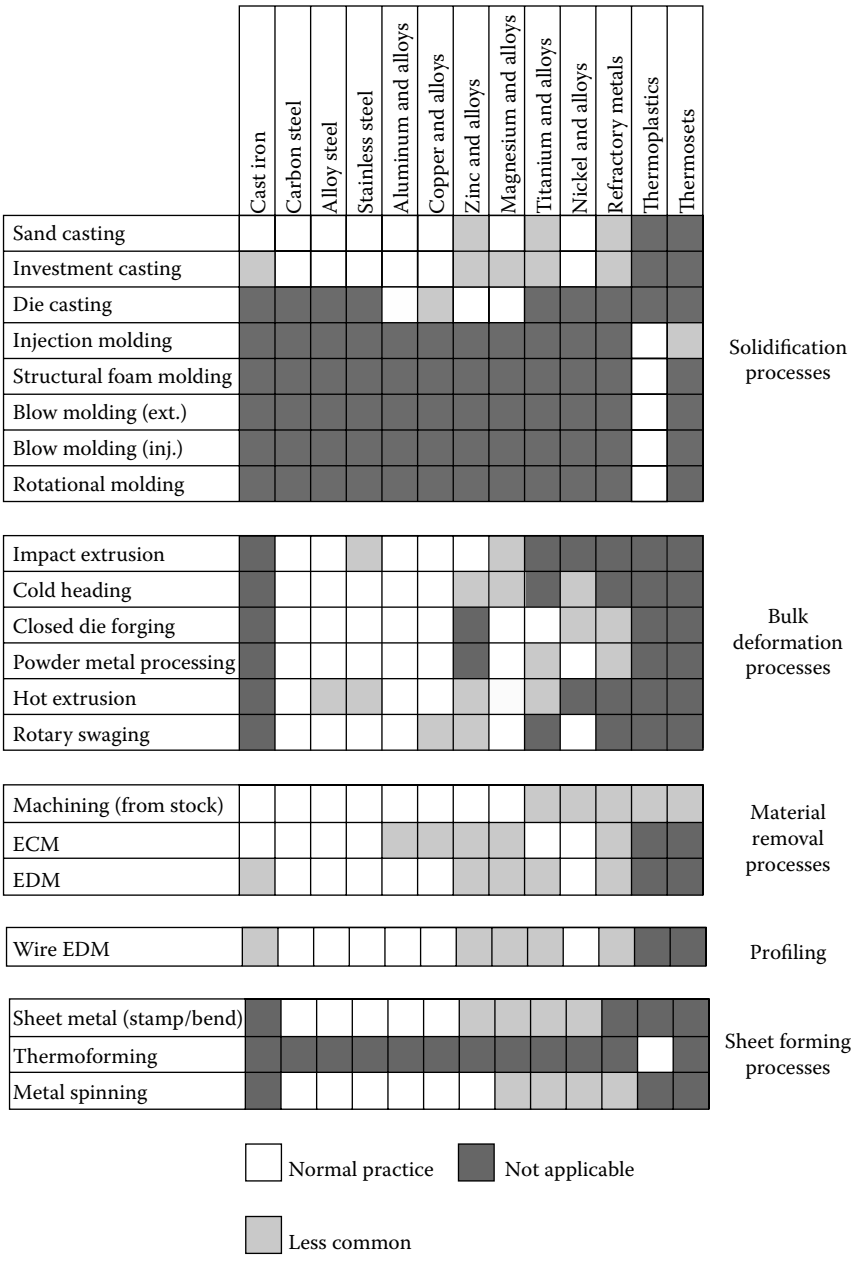

FIGURE 2.3
Compatibility between processes and materials.

Tertiary processes do not affect the geometry of the part and always appear after primary and primary/secondary processes. This category consists of finishing processes such as surface treatments and heat treatments. The selection of tertiary processes is simplified, because many tertiary processes only affect a single attribute of the part. For instance, lapping is employed to achieve a very good surface finish, and plating is often used to improve the appearance or corrosion resistance.

2.4 Process Capabilities

A great deal of general information is available on manufacturing processes in a wide range of textbooks, handbooks, and so on. Each process can be analyzed to determine the range of its capabilities in terms of attributes of the parts that can be produced. Included in these capabilities are shape features that can be produced, natural tolerance ranges, surface roughness capabilities, and so on. These capabilities determine whether a process can be used to produce the corresponding part attributes. Table 2.1 shows some of the general capabilities of a range of commonly used processes that can be used as a guide to selection.

The shape-generating capabilities of the range of the processes characterized in Table 2.1 are shown in Table 2.2, with the various terms used in this table defined as follows.

2.4.1 General Shape Attributes

Depressions (Depress): The ability to form recesses or grooves in the surfaces of the part. The first column entry refers to the possibility of forming depressions in a single direction, while the second entry refers to the possibility of forming depressions in more than one direction. These two entries refer to depressions in the direction of tooling motion and those in other directions. The following are some examples of tooling motion directions.

Processes with split molds—the direction of mold opening.

Processes that generate continuous profiles—normal to the direction of extrusion or normal to the axis of the cutting medium.

Forging (impact) processes—the direction of impact of the tooling onto the part.

Uniform wall (UniWall): Uniform wall thickness. Any nonuniformity arising from the natural tendency of the process, such as material stretching or buildup behind projections in centrifugal processes is ignored, and the wall is still considered uniform.

Uniform cross-section (UniSect): Parts where any cross-sections normal to a part axis are identical, excluding draft (slight taper) in the axial direction for die or mold release if required.

Axis of rotation (AxisRot): Parts whose shapes can be generated by rotation about a single axis: a solid of revolution.

Regular cross-section (RegXSec): Cross-sections normal to the part's axis contain a regular pattern (e.g., a hexagonal or splined shaft). Changes in shape that maintain a regular pattern are permissible (e.g., a splined shaft with a hexagonal head).

Captured cavities (CaptCav): The ability to form cavities with reentrant surfaces (e.g., a bottle).

Enclosed (Enclosed): Parts that are hollow and completely enclosed.

Draft-free surfaces (NoDraft): The capability of producing constant cross-sections in the direction of tooling motion. Many processes can approach this capability when less than ideal draft allowances are specified, but this designation is reserved for processes where this capability is a basic characteristic and no draft can be obtained without cost penalty.

2.4.2 DFA Compatibility Attributes

Manufacturing processes have varying levels of compatibility with the basic goals of the DFA of simplified product structure and ease of assembly. This relative compatibility in Table 2.2 is measured in the following key areas.

Part consolidation (PConsol): The ability to incorporate several functional requirements into a single piece, eliminating the need for multipart assemblies.

Alignment features (Alignmt): The ease of incorporating in the part positive alignment or location features that aid in the assembly of mating parts.

Integral fasteners (IntFast): The cost-effectiveness and scope of fastening elements that can be designed into the part. The ability to incorporate features such as threads, which generally involve separate fasteners, is not given as much consideration as elements such as snap features.

2.5 Selection of Materials

The systematic selection of specific materials to meet required properties is given considerable attention. Numerous textbooks and handbooks have been devoted to this topic [5–8]. Comprehensive procedures have been developed in the past for material selection, such as, for example, the detailed handbook system of the Fulmer Research Institute in the United Kingdom [9]. Today online databases of material properties are available, such as the Alloy Center from the American Society of Metals [10], the MatWeb system of 69,000 datasheets [11], and the Cambridge University material selection and processing resource [12]. In addition, most of the major polymer manufacturers have online resources for material selection and detailed material properties. Special mention should be made of the comprehensive commercial material selection software offered by Granta Design [13], which is based on the powerful graphical material selection procedure developed by Ashby [8]. All these procedures are valuable for the systematic selection of materials in product design. However, their usefulness at the very early stages of product design, when initial decisions on materials and processes are made, is restricted for several reasons, including:

1. With the exception of the Granta Design system, these procedures are aimed at the selection of specific materials based on detailed material property specifications that may not be available early in the design process. At this stage only general ranges of properties may have been decided upon.
2. The material selection is considered independent from the manufacturing processes that may be used, whereas compatibility between processes and materials is important. Several approaches can be adopted to rationalize the search for suitable materials for application during early product design, as discussed in the following sections.

2.5.1 Grouping of Materials into Process Compatible Classes

Rather than using a single comprehensive materials database, it is preferable to divide the material databases into classes related to the principal shape-generating processes used in

TABLE 2.1

Capabilities of a Range of Manufacturing Processes

Process	Part Size	Tolerances[a]	Surface Finish	Shapes Produced Competitively[b]
Sand casting	Weight: 0.2 lb–450 ton Minimum wall: 0.125 in.	General: ±0.02 (1 in.), ±0.1 (24 in.) For dimensions across parting line add ±0.03 (50 in.^{2}), ±0.04 (200 in.^{2})	500–1000 µin.	Large parts with walls and internal passages of complex geometry requiring good vibration damping characteristics
Investment casting	Weight: 1 oz–110 1b Major dimension: To 50 in. Minimum wall: 0.025 (ferrous), 0.060 (nonferrous)	General: ±0.002 (1 in.) ±0.004 (6 in.)	63–25 µin.	Small intricate parts requiring good finish, good dimensional control, and high strength
Die casting	Minimum wall (in.): 0.025 (Zn), 0.05 (Al, Mg) Minimum hole diameter (in.): 0.04 (Zn), 0.08 (Mg), 0.1 (Al) Maximum weight (lb): 35 (Zn), 20 (Al), 10 (Mg)	General: ±0.002 (1 in.) ±0.005 (6 in.) (Zinc) ±0.003 (1 in.), ±0.006 (6 in.) (Alum, Mg) Add ±0.004 across parting line or moving core	32–85 µin.	Similar to injection molding
Injection molding (thermo-plastics)	Envelope: 0.01 in.^{3}–80 ft^3 Wall: 0.03–0.250 in.	General ±0.003 (1 in.), ±0.008 (6 in.) Hole diameter: ±0.001 (1), ±0.002 (1 diameter) Flatness: ±0.002 in. per in. Increase tolerance 5% for each additional mold cavity Increase tolerance: ±0.004 for dimensions across parting line	8–25 µin.	Small-to-medium sized parts with intricate detail and good surface finish
Structural foam molding	Weight: 25–50 lb Wall: 0.09–2.0 in.	Approximately that of injection molding	Poor; paint generally required properties	Large, somewhat intricate parts, requiring high stiffness and/or thermal or acoustical insulating properties
Blow molding (extrusion and injection)	Envelope: Up to 800 gal containers (105 ft^3) Wall: 0.015–0.125 in.	General: ±0.02 (1 in.), ±0.04 (6 in.) Wall: ±50% of nominal wall Neck: ±0.004 (injection only)	250–500 µin.	Hollow, well-rounded thin- walled parts with low degree of asymmetry
Rotational molding	Envelope: Up to 5000 gal containers (670 ft^3) Wall: 0.06–0.40 in.	General: ±0.025 (1 in.) ±0.05 (6 in.), ±0.01 (24) Wall: ±0.015	Poor; parts generally textured	Large containers with minimal detail
Impact extrusion (forward and backward)	Diameter: 0.075–2.5 in. Length: 3–4 in.	Outer diameter (O.D.): ±0.002 (0.5 in) Inner diameter (I.D.): ±0.003 (5 in.) Bottom diameter: ±0.005 (5 in.) Tolerances approximately 50% greater for rectangular parts	20–63 µin.	Approximately, 1–2 in. diameter Part with a closed end thicker than side walls (backward) Headed parts with large L/D ratio and zero draft (forward extrusion) Combination of forward/ backward common
Cold heading	Shank diameter: 0.03–2.0 in. Length: 0.6–9.0 in.	Head height: ±0.006 (0.025 shank diameter) ±0.008 (0.50 shank diameter) Head diameter ±0.01 (0.25 shank diameter, ±0.018 (0.50 shank diameter) Length: ±0.03 (1 in.)	32–85 µin.	Small symmetrical, or near symmetrical, headed cylindrical parts, with shank length greater than shank diameter
Hot forging (closed die)	Weight: 0.1–500 lb	Perpendicular to die motion: ± 0.7% of dimension Parallel to die motion: ±0.03 (10 in.^{2} area), ±0.12 (100 in.^{2} area)	125–250 µin.	Parts of moderate complexity, in a wide range of sizes, whose failure in service would be catastrophic

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Process Limitations	Typical Application	Mat'ls[c]	Comments
Secondary machining usually required Production rates often lower than that for other casting processes Tolerances, surface finish coarser than other casting processes Requires generous draft (approximately 3 deg) and radii (approximately equal to thickness)	Engine blocks Engine manifolds Machine bases Gears pulleys	1, 2, 3 4, 5, 6 7[d], 8, 12	Very flexible manufacturing process in terms of possible geometries, part size, and possible materials Pattern in reusable and mold expendable
Most investment castings are less than 12 in. long and less than 10 1b L/D ratio of through or blind holes less than 4:1 and 1:1, respectively Tooling cost and lead time generally greater than for other casting processes except die casting	Turbine blades Burner nozzles Armament components Lock components Sewing machine components Industrial handtools bodies	2, 3, 4[d] 5, 6, 8 9[d], 12	Expendable pattern and mold Greater flexibility in material choices or part geometry than die casting, but much higher production costs Less susceptible to porosity than most casting process Multiple parts may be cast simultaneously around central sprue
Trimming operations required for flash and overflow removal Porosity can be present Die life limited to approximately 200 k shots in Al or Mg or 1 million in Zn	Similar to injection molding in part geometry, but particularly suited where higher mechanical properties or the absence of creep are required	5, 6[d], 7, 8	Produces thin-set walls of all casting process Production rate approximately 100 parts per h in alum and approximately 200 parts per h in zinc Tooling cost and lead time similar to that for injection molding but trimming and surface treatment can make process less economic
Tooling is costly and requires greater lead time than most alternative processes Poor design can result in high levels of molded-in stress, resulting in warpage or failure	Numerous applications, often replacing the die casting or sheet metal assemblies	10, 11	Typical cycle time 20–40 s Details such as living hinges, insert molding, and snap features allow significant opportunity for part consolidation Injection molding of thermoset materials also possible: Longer cycle time, no reprocessing of waste, generally harder, more brittle, but more stable material which can be used at higher service temperatures
Details as sharp as those of injection molding not possible Cycle time is long (2–3 min)	Pallets, housing, drawers, TV cabinets, fan shrouds	10	Tooling approximately 20% less than for injection molding Solid skin approximately 0.03–0.8 in. thick; entire wall cross section has densities between 50% and 90% of solid weight Process generates a low level of internal stress RIM is a similar foaming process utilizing thermosets (generally polyurethane)
With extrusion blow molding, some geometries produce a high level of material scrap Integral handles possible with extrusion blow molding only Poor control of wall thickness	Most polymer containers to 5 gal Toys Auto heater ducting	10	Injection blow molding: Smaller parts, more accurate necks Extrusion blow molding: More asymmetrical parts, less costly tooling High production rates, particular for injection blow molding (as low as 10 s per cycle)
Abrupt wall changes, long, thin projections, and small separations between opposing part surfaces not possible	Toys Containers	10	Cycle time 8–20 min Inserts for securing or stiffening are possible Less detail possible than with blow molding
Flat inner bottom requires additional operation Tooling costs are high Maximum L/D ratio for backward extrusion is 10 (in some aluminum alloys) L/D ratio almost unlimited in forward extrusion Tolerances not as good as machining	Fasteners Sockets for socket wrench Gear blanks with shank	2, 3[d], 5 6, 7, 8	Generally chosen over screw machined part if material savings are significant (approximately 25% or more) Significant improvement in mechanical properties due to cold working, allowing further material reduction Limited asymmetry possible
Seldom used for diameters greater than 1.25 in. Must allow much more generous radii than with machining Significant asymmetry difficult	Nails Fasteners Spark plug pot Ball Joint Shafts	2, 3, 4[d] 5, 6, 12[d]	Minimization of shank diameter and upset volume important Production rates 35–120 parts per min Process can also be carried out warm (800–1200°F)
Holes may not be produced directly Flash must be removed and secondary machining is often required Die wear and die mismatch can be significant Generous draft angles and radii are suggested	Crankshafts Airframe components Tools Nuclear components Agricultural components	2, 3, 4 5, 6, 8 9, 12[d]	By controlling material flow, grain structure may be applied with the direction of principal stress Closed die forgings nearly always pass through series of impressions before completion In decreasing order of forgability: A1, Mg, steel, St Steel, titanium, high-temperature

continued

TABLE 2.1 (continued)

Capabilities of a Range of Manufacturing Processes

Process	Part Size	Tolerances[a]	Surface Finish	Shaped Produced Competitively[b]
Pressing and sintering (power metal parts)	Minimum wall: 0.06 in. Minimum hole diameter: 0.06 in. Maximum length (in direction of press): 4.0 in. Maximum projected area: 40 in.^{2}	Perpendicular to press direction: ±0.15% of dimension (±0.05% if repressed) Parallel to press direction: ±0.30% of dimension	8–50 µin.	Small parts of uniform height with parallel, but fairly intricate walls
Rotary swaging	Diameter: 0.01–5.0 in. (bar), 14 in. (tubing)	Diameter: ±0.003 (1 in.)	20% of original stock finish (five-fold improvement)	Tapered cylindrical rod or tubing
Hot extrusion	Cross-sectional area: 0.1–225 in.^{2} (Alum), 0.5–4.0 in.^{2} (LC steel) Minimum wall: 1.5% OF circumscribed diameter	General: ±0.01 (1 in.) ±0.03 (6 in.) (±0.005 if cold drawn after extrusion) Angles ±2 deg. Twist: 1° per foot for width less than 2 in. Flatness: 0.004 in. per in.	63 µin. (Alum), 125 Micro-includes (LC steel)	Straight part with constant cross section that is fairly complex, but balanced, without extreme change in wall thickness
Machining (from stock)	Limited only by machine capability	Turning ±0.001, boring ±0.0005, Milling ±0.002, Drilling ±0.008–0.002, Broaching ±0.005, Grinding +0.002 (diameter); ±0.008 (surface), Reaming, ±0.001 (all for dimensions of 1 in.)	Turning 63–125 Boring 32–125 Milling 63–125 Drilling 63–250 Grinding 8–32 Reaming 63	Rotational: Axisymmetrical part with L/D ratio of 3 or less and major diameter of 2 in. or less Nonrotational: Rectangular part with all feature parallel and open in the same direction
Electrochemical machining (ECM)	Minimum hole diameter: 0.01 in Maximum hole depth: 50 × diameter	General: ±0.001	8–63 µin.	Highly accurate complex, or finely detailed shapes in hardened materials or those susceptible to damage due to heat build-up Production of high aspect or bur-free holes and processing of flimsy materials
Electrical discharge machining (EDM)	Minimum hole diameter: 0.002 Minimum slot width: 0.002 in.	General ±0.001	8–250 µin. (dependent on removal rate)	Same as ECM
Sheet metal stamping/ bending	Material thickness 0.001–0.75 in. (normally 0.050–0.375 in.) Area: 80 ft^2 with turret press and press brake, 10 ft^2 with die sets	Punching or stamping: ±10% of material thickness (2.0 in.) Press brake: ±2° On bend, ±0.015 in. hole-to-bend	For cold rolled sheet or coil: 32–125 µin.	Moderate complexity parts of constant material thickness with flanges in a single direction
Thermoforming	Area: 1 in.^{2}–300 ft^2	General: ±0.05% of dimension Wall: ±20% of nominal	60–120 µin.	Large, shallow, thin wall parts with generous radii
Metal spinning	Diameter: 25 in.–26 ft Material thickness: (Alum), 0.004–1.5 (LC steel), (0.025–0.05 in. most common)	Diameter: ±0.01 (1 in.), ±0.03 (24 in.) Angle: ±3 deg	32–65 µin.	Thin-walled conical shape with diameter greater than twice depth

Process Limitations	Typical Application	Mat'ls[c]	Comments
Generally lower mechanical properties than wrought metals Undercuts, off-axis holes, and threads cannot be produced directly Thin sections and feature edges should be avoided Maximum L/D ratio approximately 3	Small gears Lock mechanisms components Small arms parts Filters Bearings	1, 2, 3 4, 5, 6 9[d], 12[d]	Production rates approximately 700 parts per h Impregnation with lubricants gives self- lubrication properties Density range 75%–95% (compared to raw material) Maximum compression ratio (powder volume before and after pressing and sintering) approximately 2.5:1
Tapper should be 6° or less included angle for manual feeding and up to 14° for power feed Shoulders perpendicular to part axis not possible	Tube: Gold club shafts, table legs, exhaust pipes Bar: Punches, screwdriver blades	2, 3, 4 5, 6, 7[d] 8[d], 12	Tooling costs are generally less than those for cold extrusion or cold heading Noncylindrical part can be swaged in stationaly die machines Production rates can range from 100–3000 parts per h Shapes like splines can be produced by swaging tubing over an internal former called a mandrel
Dimensional accuracy and part-to-part consistency generally not an high as competing processes. Warp and twist can be troublesome Use of materials other than aluminum and copper alloys can cause some shape restrictions Avoid knife edges and long, unsupported projections	Heatsinks Structural corner and edge members Decorative trim	2, 3[d], 4[d] 5, 6, 7[d] 8, 9[d]	Plastic working produces favorable grain structure Maximum extrusion ratios are 40: 1 (Alum), 5: 1 (LC steel) Shorter setup time than rolling, but a lower production rate (1–8 ips) crossover point at approximately 50,000 ft Low tooling costs, therefore short runs can often be justified if part consolidation and integral fastening is considered.
Little opportunity for part consolidation Most parts produced by a sequence of several operations and machines Need for multiple operations can impact part quality Tool wear is significant	Widely varied applications	1, 2, 3 4, 5, 6 7[d], 8, 9[d] 10[d], 11[d] 12[d]	Closer to true CAD/CAM link than most other processes Most flexible of manufacturing processes
Some taper of walls Minimum radius of 0.002 all around Material most be electrically conductive	Various jet engine parts	1[d], 3, 6[d] 9, 12	Material removal rates much greater than EDM (approximately 5 in. 3 per min.) although tooling, equipment, and energy costs are much higher Surface finish not nearly as closely tied to removal rates as with EDM Generally more cost-effective than precision machining and grinding for all but the most easily machined materials
Electrode wear impacts accuracy and requires periodic replacement Material removal rate is extremely slow (0.01–0.5 in. 3 per h) Additional limitations identical to ECM	Due to low production rates, EDM is generally used in toolmaking rather than part production, or for deburring, where other methods are not satisfactory	2[d], 3[d] 5[d], 6, 9[d] 12[d]	A very different variation of conventional EDM, wire EDM is used to cut highly accurate, and sometimes complex profiles in hardened materials up to 6 in. thick These components are often used in drawing, extruding, or stamping dies
Holes with diameter lest than stock thickness need to be drilled Since 1/2–2/3 of material thickness is fractured, rather than sheared, secondary operation or fineblanking is needed for good edge finish or parallel sides Finishing and material scrap costs are often substantial	Numerous consumer and industrial applications	2, 3, 4 5, 6, 7[d] 8[d], 12[d]	Mechanical reciprocating presses operate at 35–500 strokes per min. CNC Turret presses achieve 55–265 hits per min. at 1 in. centers Often when the cost of dies exceeds the total cost of parts, die sets are no longer cost-effective (approximately 20,000 pcs for common geometries) Progressive dies can often be justified if they can save two or more secondary operations on individual die sets
Low degree of part complexity Low dimensional accuracy Minimal opportunity for integral fasteners or attachment points	Various consumer packaging Bus, aircraft interior panels Refrigerator linings Signs Boat hulls	10	Tooling less expensive than other plastic processing, methods High production rates possible (drinking cups: 2000–3000 pcs.min.) Material properties can be improved due to molecular orientation Reinforcing fibers may also be added to improve strength Of several processes available (vacuum, pressure, drape), vacuum is most popular
Stiffening beads should be formed externally rather than internally Cylindrical sections and reentrant angles are possible but more costly Minimal radius 1.5 × thickness Maximum thickness for hand spinning: 0.25 in. (A1), 0.187 (LC steel), 0.125 (S steel)	Cooking utensils Lamp bases Nose cones Reflectors	2, 3[d], 4 5, 6, 7[d] 8[d], 12[d]	Conventional spinning and displacement spinning differ in that displacement spinning moves material back along forming member refining grain structure in direction of flow Tooling costs are much less than for stamping or deep-drawing, very small quantities may be economically produced Tube spinning reduced I.D., O.D., or lengthens tubes or performs

Source: Boothroyd Dewhurst, Inc., Wakefield, Rhode Island.

[a] Limits shown represent fine tolerances. More stringent requirements will significantly increase cost.

[b] Part types that can be produced cost effectively in comparison to other processes.

[c] Materials.

[d] Used on a limited basis: 1, cast iron; 2, carbon steel; 3, alloy steel; 4, stainless steel; 5, aluminum and alloys; 6, copper and alloys; 7, zinc and alloys; 8, magnesium and alloys; 9, titanium; 10, thermoplastics; 11, thermosets; 12, nickel and alloys.

TABLE 2.2

Shape Generation Capabilities of Processes

	Depress		UniWall	UniSect	AxisRot	RegXSec	CaptCav	Enclosed	NoDraft	PConsol	Alignmt	IntFast	
Sand casting	Y	Y	Y	Y	Y	Y	Y	N	N	4	3	1	Solidification processes
Investment casting	Y	Y	Y	Y	Y	Y	Y	N	N	5	5	2	
Die casting	Y	Y[a]	Y	Y	Y	Y	N	N	N	4	5	3	
Injection molding	Y	Y[a]	Y	Y	Y	Y	N[b]	N	N	5	5	5	
Structural foam	Y	Y[a]	Y	Y	Y	Y	N	N	N	4	4	3	
Blow molding (extr)	Y	Y[a]	M	N	Y	Y	M	Y	N	3	4	3	
Blow molding (inj)	Y	Y[a]	M	N	Y	Y	M	N	N	3	4	3	
Rotational molding	Y	Y[a]	M	N	Y	Y	N	M	N	2	2	1	
Impact extrusion	Y	N	Y	N	Y	Y	N	N	Y	3	3	1	Bulk deformation
Cold heading	Y	N	Y	N	Y	Y	N	N	Y	3	3	1	processes
Closed die forging	Y	Y[a]	Y	Y	Y	Y	N	N	N	3	2	1	
Power metal parts	Y	N	Y	Y	Y	Y	N	N	Y	3	3	1	
Hot extrusion	Y[d]	N	Y	M	Y	Y	N	N	Y	2	2	3	
Rotary swaging	N[c]	N	N	N	M	N[c]	N	N	N	1	1	1	
Machining (from stock)	Y	Y	Y	Y	Y	Y	Y	N	Y	2	3	2	Material removal
ECM	Y	Y[c]	Y	Y	Y	Y	N	N	N	3	4	1	processes
EDM	Y	Y[c]	Y	Y	Y	Y	N	N	N	3	4	1	
Wire-EDM	Y[d]	N	Y	Y	Y	Y	N	N	Y	2	2	3	Profile generating
Sheetmetal stamp/bend	Y	Y	M	Y	Y	Y	N	N	N	4	3	4	processes
Thermoforming	Y	Y[a]	M	N	Y	Y	N	N	N	3	3	3	Sheet forming
Metal spinning	N	N	M	N	M	N	Y	N	N	1	1	1	processes

Note: Y—process is capable of producing parts with this characteristic; N—process is not capable of producing parts with this characteristic; M—parts produced with this process must have this characteristic; an underline entry indicates that parts using this process as easier to form with this characteristic.

[a] Possible at higher cost.

[b] Shallow undercuts are possible without significant cost penalty.

[c] Possible with more specialized machine and tooling.

[d] Only continuous, open-ended possible.

The last three columns refer to DFA guidelines and are rates on a scale of 1–5, with 5 assigned to processes most capable of incorporating the respective guidelines.

discrete parts manufacture. This is necessary because of the incompatibility between some processes and materials and because, generally, the selection of processes and materials must be considered together. The processes used for producing material forms for other shape-generating processes need not be included, since the manufacture of discrete parts starts with materials that have already undergone this primary processing. Thus, the separate material databases should include, for example, standard metal stockforms (wire, rod, etc.), sand and permanent mold-casting alloys, die-casting alloys, metal powders, thermoplastic granules, thermoplastic sheets and extruded stockforms, and so on.

During an initial search phase when a rapid response to changes in input is essential, it is perhaps inappropriate to search for extensive material databases in order to identify precise metal alloys, polymer specifications, powder mixes, and so on. This leads to unacceptably slow search procedures and provides information largely irrelevant to the early process/material decision-making. For example, listing all the thermoplastic resins that satisfy the specified performance requirements would clearly be premature in early discussions of the relative merits of alternative processes, their required tooling investments, the likely size and shape capabilities, and so on. A more efficient procedure is to have, for each process, an associated supermaterial specification that comprises the best attainable properties of all the materials in the corresponding category. If a new alloy is added, say, to the die-casting material database, its properties are compared with the die-casting supermaterial specification, which is then updated as necessary.

The approach to preliminary process selection through supermaterial specification is compatible with the trade-off and compromise decisions that are part of early design work. A typical scenario might involve the specification of possible shape attributes, size, and one or more production and performance parameters. The next step would be to change the input specifications or add to the specification list, or to investigate a process further for acceptable associated materials.

2.5.2 Material Selection by Membership Function Modification

One challenge of designing a system so that appropriate materials are chosen at the early stages of design lies in modeling ambiguous or vague material constraints. For instance, a designer may want to use a material with a yield stress of "about" 2000 psi and a service temperature "in the neighborhood of" 90°C. A conventional database search for materials with properties greater than those specified would unnecessarily exclude materials with properties close to the desired values, but not in the range specified.

Some material selection systems have attempted to model vague designer specifications by breaking the material property values into discrete ranges. However, an alternative approach is to model such vague qualifiers as "about" and "in the neighborhood of" using aspects of fuzzy logic. Fuzzy logic relies on the concept of a membership function to determine how well an object fits into a defined set.

Ambiguity in the material constraints specified by the designer is modeled by providing the designer with different levels of accuracy to further describe the material constraints specified. These levels could correspond, for example, to the qualifiers "approximately," "close to," and "more or less." These levels of precision are illustrated in Figure 2.4. The ability to assign different levels of accuracy or precision to each constraint is an advantage of fuzzy logic.

A simple example may help to illustrate the advantages and flexibility of this approach (Figure 2.5). For instance, if pressing and sintering has been selected as a candidate primary

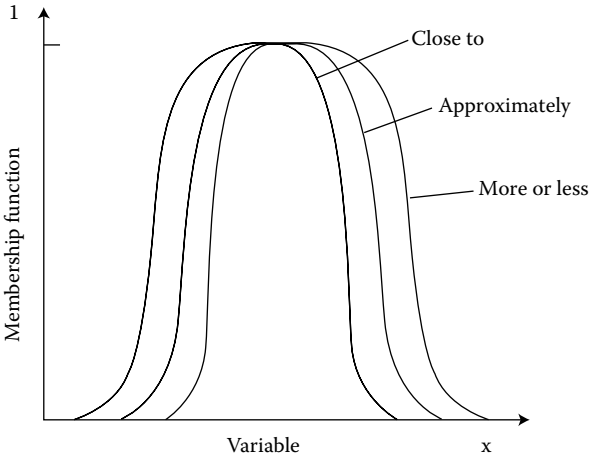

FIGURE 2.4
Membership functions for material and process selection.

process and the user has restricted the material to one with an ultimate tensile strength between 25 and 30 kpsi, then a conventional search of a small database that contains 102 entries would yield 15 candidate materials. A fuzzy search with the qualifier "close to" would yield 29 candidate materials with ultimate tensile strengths between 21 and 29 kpsi. The qualifier "approximately" produces 38 materials with ultimate tensile strengths from 19 to 36 kpsi. In all, 17 additional materials with tensile strengths between 16 and 39 kpsi

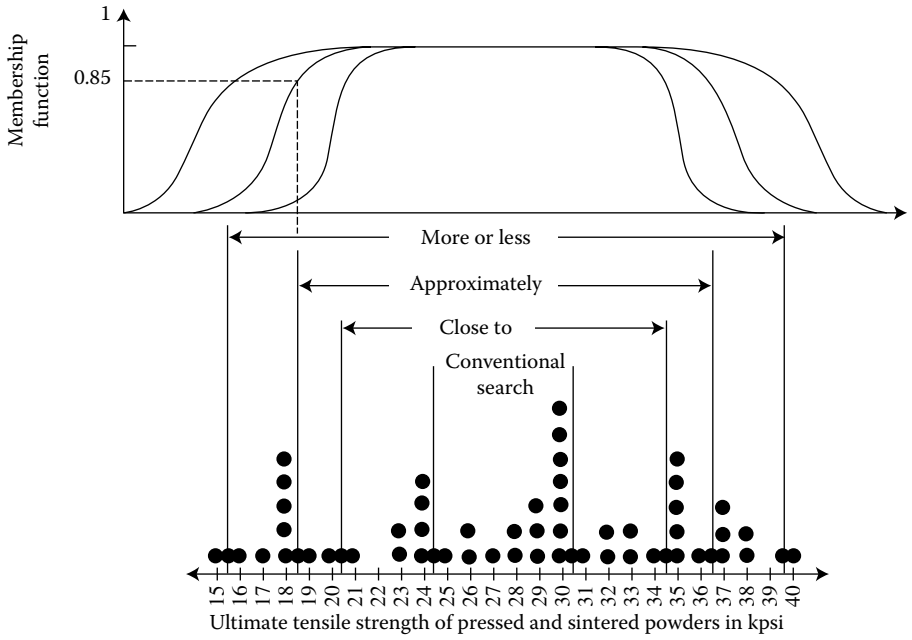

FIGURE 2.5
Selection of sintered powder materials by membership function modification. (Adapted from Farris, J. *Selection of Processing Sequences and Materials During Early Product Design*, Ph.D. Thesis, RI, 1992.)

are chosen when the qualifier "more or less" is used. The additional materials selected by the modified membership function may become increasingly important as other material constraints eliminate many materials from consideration.

2.5.3 Material Selection by Dimensionless Ranking

An aspect of material selection, which is a great source of difficulty, is the distinction between the fundamental material properties, which are given in material databases, and the actual design requirements, which are usually based on a combination of different property values. For the present purposes, material cost per unit weight is included as a property of the material, so that economic constraints on design can be considered in just the same manner as weight constraints, strength constraints, and so on. Thus, for a structural member in an aerospace product, the designers may be interested in the maximum stiffness per unit weight, while for a high-volume consumer product, the maximum stiffness per unit material cost may be more important. In the first case, the materials would be compared on the basis of a function of Young's modulus and density, and in the second case a combination of Young's modulus, density, and cost per unit weight would be used for comparison purposes. Derived parameters, which are commonly used in mechanical design, have been established in the literature [8,15]. In this section, we are concerned with establishing a simple procedure for comparing materials based on either single fundamental properties, or the general form of derived parameters. Such material comparisons may typically be required on the basis of total performance, best performance per unit weight, or best performance per unit cost. A procedure is established later in this section for making these comparisons on a dimensionless scale from 0 to 100.

Before proceeding with the establishment of a general material comparison system, it is useful to consider two examples in mechanical design. First, the simplest case of the design of a tie bar is considered to illustrate the steps to be taken with respect to performance, weight, and material cost. The second case is concerned with the stiffness of thin-walled components, which has major implications for material and process selection of such parts.

For a tie bar, the design specification may include the length, l, and the maximum force, F, to be supported. The design requirement may be to meet the specifications with the smallest possible part cross-sectional area, and hence occupy the smallest volume, V. In this case, we require maximum possible performance per volume from the material. If the yield or failure stress level in tension is denoted Y_t, and the cross-sectional area is A, then we can write

$$V = Al \tag{2.1}$$

and

$$F = AY_t \tag{2.2}$$

The fact that the cross-sectional area changes with different material selections, at this concept stage of design we wish to avoid specifying its value. Thus, we eliminate A between Equations 2.1 and 2.2 giving

$$\frac{V}{F} = (l)\left(\frac{1}{Y_t}\right) \tag{2.3}$$

The form of this equation is important. The goal is to represent the design intent, in this case the minimum volume for the required force, as a product of two terms. The first term, contains only those parameters which are fixed by the design specification and do not change with different material selections, and the second term contains only fundamental material properties. Optimizing the design intent thus involves taking the maximum or minimum of the second term. Thus, from Equation 2.3, for minimum volume to support the required force we require the minimum value of $(1/Y_t)$ or the maximum value of (Y_t) This is obviously true, but in other cases the criteria which emerge from this procedure may comprise several material properties and are certainly not self-evident.

If material density is represented by ρ, and the design requirement is minimum weight to support the given force, then we replace Equation 2.1 with the expression for part weight,

$$W = Al\rho \tag{2.4}$$

and again eliminate A. This gives

$$\frac{W}{F} = (l)\left(\frac{\rho}{Y_t}\right) \tag{2.5}$$

and our criterion for material selection is the maximum possible value of (Y_t/ρ).

Finally, if this is a large component, for which material cost is a primary concern, our focus changes to include the cost of material per unit weight, C_m. In this case, we replace component weight, W, with component material cost, C, and write

$$C = Al\rho C_m \tag{2.6}$$

and again eliminate A to obtain

$$\frac{C}{F} = (l)\left(\frac{\rho C_m}{Y_t}\right) \tag{2.7}$$

Now, the material selection requirement is the maximum value of $Y_t/(\rho C_m)$.

The general procedure for determining derived parameters for particular design requirements can be recognized from the simple example of the tie bar. The first step is to find or establish the equation, or set of equations, which define the design intent. The next step is to decide on a single design parameter which changes when one material is substituted for another. This is most typically the section thickness or cross-sectional area. This design parameter must be eliminated by substitution, since we require a derived parameter which can be used prior to deciding on the parameter's value. Occasionally this parameter can be eliminated between the equations which describe the design intent. In this case the derived parameter represents absolute performance. Most often, however, it is necessary to introduce an additional equation for the component volume and eliminate the material-variable design parameter with the volume equation to establish the derived parameter for maximum possible performance. If, alternatively, maximum performance per weight or per material cost is desired, then expressions for component weight or component material cost must, of course, be introduced into the parameter elimination procedure.

For thin-walled components, a primary design requirement is often the stiffness of the wall. This may arise from an engineering requirement concerning wall deflections in

product use, or it may be a customer perception issue that, for example, a plastic-molded product housing must feel as durable as a competing sheet metal housing. If we review engineering formulae for the deflection of plates, shells, or beams [8] we find that for a given applied force, F, wall thickness, h, and Young's modulus, E, the deflection, δ, of any region of the wall of a thin part depends upon the shape of the region and its boundary. However, the expression can typically be reduced to the form

$$\delta = \frac{C_0 F}{(Eh^3)} \tag{2.8}$$

where C_0 is a constant for a particular design.

Equation 2.8 has quite profound implications for the design of polymer components. For example, if two materials A and B are to provide the same wall stiffness for the same component design, then we require

$$E_A h_A^3 = E_B h_B^3 \tag{2.9}$$

Alternatively, if we require to replace material A with material B, then the new component wall thickness for an equivalent stiffness is

$$h_B = h_A \left(\frac{E_A}{E_B} \right)^{1/3} \tag{2.10}$$

This simple expression explains why it has been possible to replace the use of sheet metal fabrications in consumer products with molded thermoplastic parts, despite the extreme difference in the elastic modulus between these two classes of materials. For example, assume that the new design of a product replaces a fabricated 1 mm thick aluminum alloy cover with an injection-molded snap-fit cover. The aluminum alloy has an elastic modulus of 70 GN/m^2 and the proposed glass-reinforced polycarbonate replacement has a modulus of 5.5 GN/m^2; only 8% of the aluminum alloy value. Nevertheless, substitution into Equation 2.10 shows that a thickness of 2.5 mm provides the required equivalent stiffness. The addition of ribs to the inside of plastic-molded parts can increase the stiffness and allow even thinner main walls in a design, but in many cases their use is limited for space reasons or the surface imperfections they produce through shrinkage.

Returning to Equation 2.8 to obtain the desired derived parameter for material selection, we need to introduce an expression for part volume, weight, or material cost, and then eliminate wall thickness by substitution. Assuming that we are interested in producing a light-weight stiff component, we write an expression for weight in terms of wall thickness, h, in the form

$$W = C_1 h \rho \tag{2.11}$$

Substituting for h from Equation 2.8 gives

$$W = \left(\frac{C_1 (C_0 F)^{1/3}}{\delta^{1/3}} \right) \left(\frac{\rho}{E^{1/3}} \right) \tag{2.12}$$

where C_1 is constant for a given part geometry.

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In Equation 2.12 the expression, as in Equation 2.7, is divided into the product of parameters fixed by the design specification and fundamental material properties. Since we wish to minimize weight, we require the maximum value of $(E^{1/3}/\rho)$ which is our derived performance parameter.

The authors, in their work on computer-aided material and process selection, have observed that material properties tend to be distributed approximately uniformly when presented on logarithmic scales. This fact can be seen clearly in the work by Ashby [8], in which material properties are plotted on a variety of combinations of logarithmic scales, such as yield strength plotted against density, coefficient of expansion against thermal conductivity, and so on. In all cases, the properties of groups of materials represented as bubbles are seen to spread out in an approximately uniform manner across the logarithmic scales. For example, Figure 2.6 shows the spread of elastic modulus for the different classes of materials when presented on a linear scale. It can be seen that there is a crowding of materials at the beginning of the scale with poor discrimination between material properties in that region because of the coarse scale. Figure 2.7 shows the same data represented on a logarithmic scale, which spreads out the material classes across the wide range of property values. Similar approximately uniform spread of materials across logarithmic property scales is found to apply also to derived material properties. This can be seen by viewing the spread of materials along the inclined lines in the Ashby plots [8], which represent a wide variety of derived parameters.

Property distributions of the form shown in Figure 2.6 can be changed to a log-linear scale through a transformation of the form

$$P = \alpha 10^{\beta N} \tag{2.13}$$

where

P = the actual property value
N = the log-linear scale value
α, β = constants for a particular material property.

We are interested in using Equation 2.13 to develop look-up tables or spreadsheets in which fixed upper and lower values provide benchmarks for the comparison of material properties. These fixed values, for the material properties, are set at zero for the least value in the material database and 100 for the highest value. The database is updated

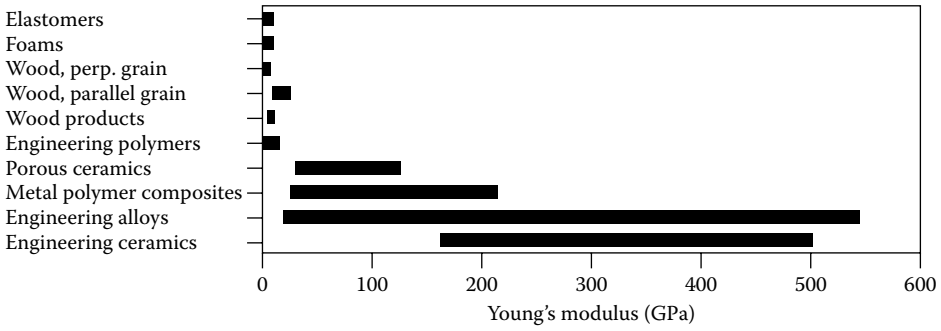


FIGURE 2.6
Elastic modulus for classes of materials plotted on linear scales. (Adapted from Dewhurst, P. and Reynolds, C.R. *Journal of Materials Engineering and Performance*, 6(3), 53–62, 1997.)

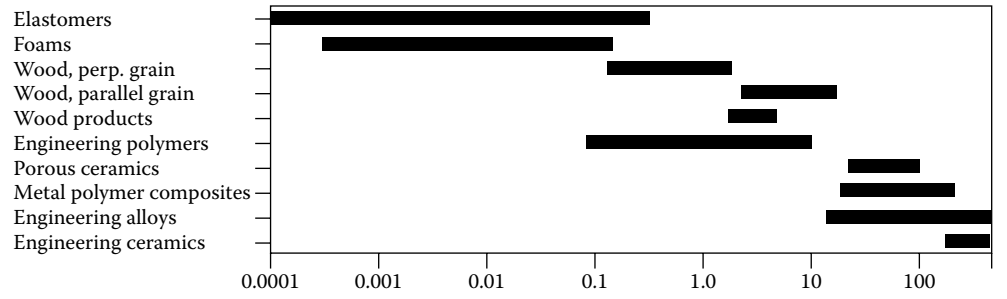


FIGURE 2.7
Elastic modulus for classes of materials plotted on logarithmic scales. (Adapted from Dewhurst, P. and Reynolds, C.R. *Journal of Materials Engineering and Performance*, 6(3), 53–62, 1997.)

automatically if a new material is introduced with a higher or lower property value than any of the existing materials. However, these extreme materials are in most cases unlikely to be exceeded.

Consider property P and let P_{max}, P_{min} be the highest and least values in the database. Thus, from Equation 2.13, taking values 0 and 100 for N gives

$$\alpha = P_{min} \tag{2.14}$$

$$\beta = \log \frac{(P_{max}/P_{min})}{100} \tag{2.15}$$

Substituting Equations 2.14 and 2.15 into 2.13 gives

$$N = 100 \frac{\log(P/P_{min})}{\log(P_{max}/P_{min})} \tag{2.16}$$

For example, for Young's modulus, E, the largest value in the database is likely to be the value for diamond, which gives

$$E_{max} = 1.03 \times 10^6 \text{ MN/m}^2$$

while the least value may be the value for natural rubber which gives

$$E_{min} = 4.59 \text{ MN/m}^2$$

With these values, the "100-scale" for Young's modulus is given from Equation 2.16 as

$$N = 18.68 \log(0.218E) \tag{2.17}$$

where E has units of MN/m^2.

Table 2.3 gives N values for Young's modulus for a small range of commonly used materials. It can be seen that the values appear to represent an engineer's perception of material stiffness. In particular, values greater than 50 apply to materials that are found in structural applications.

Largest and least values for a range of principal fundamental material properties are given in Table 2.4. A small material database is given in Table 2.5 that includes representative

TABLE 2.3

"100 Scale" Values for Young's Modulus

Material Name	N
Diamond	100
Tungsten carbide	95
Steel	87
Magnesium	75
Polycarbonate (33% glass)	64
Pine (parallel to grain)	61
Particle board	51
High-density polyethylene	42
Urethane foam	26
Cork	12
Natural rubber	0

materials from metal alloys, polymers, rubbers, foams, ceramics, and natural materials. The last column in the table gives "100-scale" values for the derived property in the adjacent column. These are discussed below.

A number of derived parameters of importance in mechanical design are given in Table 2.6. It can be seen that they are represented by the general form

$$D = P_1^{m_1} P_2^{m_2} P_3^{m_3} \ldots \tag{2.18}$$

For example, if $P_1 = Y_t$, $P_2 = E$, $P_3 = \rho$, $m_1 = 2$, $m_2 = -1$, and $m_3 = -1$, then D is the derived parameter for best spring performance per weight as given in Table 2.6.

Let the log-linear relationships for $P_1, P_2, P_3, \ldots$, be

$$\begin{aligned} P_1 &= \alpha_1 10^{\beta_1 N_1} \\ P_2 &= \alpha_2 10^{\beta_2 N_2} \\ P_3 &= \alpha_3 10^{\beta_3 N_3} \end{aligned} \tag{2.19}$$

TABLE 2.4

Largest and Least Material Property Values

Property	Material Name	Largest Value	Least Value	Units
Tensile yield strength	Alloy steel	1375	—	MN/m^2
	Cork	—	1.0	
Compressive strength	Tungsten carbide	4950	—	MN/m^2
	Cork	—	1.0	
Young's modulus	Diamond	1.0×10^6	—	MN/m^2
	Rubber	—	4.6	
Density	Tungsten carbide	13,300	—	MN/m^2
	Cork	—	140	
Cost	Industrial diamond	725	—	$/kg
	Concrete	—	0.13	

TABLE 2.5

Material Database and Derived Parameter Ranking

Generic Material	Cost, $/kg	Tensile Yield Strength, MN/m²	Elastic Modulus, MN/m²	Compressive Yield Strength, MN/m²	Density, kg/m³	Derived Parameter	N
Gary cast iron	2.86E–01	2.93E+02	1.34E+05	2.93E+02	7.21E+03	7.08E–03	41
Ductile iron	3.52E–01	4.48E+02	1.65E+05	3.10E+02	7.13E+03	7.67E–03	43
Malleable iron	4.18E–01	3.45E+02	1.60E+05	3.45E+02	7.38E+03	7.33E–03	42
Mild steel (c.q. annealed)	9.90E–01	2.62E+02	2.07E+05	2.62E+02	7.77E+03	7.58E–03	43
Alloy steel (high-strength)	6.16E+00	1.38E+03	2.07E+05	1.38E+03	7.85E+03	7.50E–03	42
Stainless steel	2.75E+00	2.48E+02	1.93E+05	2.48E+02	8.04E+03	7.16E–03	41
Aluminum alloy (high-strength)	5.28E+00	1.93E+02	7.10E+04	1.93E+02	2.75E+03	1.50E–02	62
Beryllium copper	3.85E+01	1.10E+03	1.28E+05	1.10E+03	8.27E+03	6.07E–03	36
Copper, hard	2.86E+00	3.10E+02	1.17E+05	3.10E+02	8.96E+03	5.44E–03	33
Magnesium	7.70E+00	2.34E+02	4.48E+04	2.34E+02	1.80E+03	1.96E–02	70
Titanium	2.68E+01	9.45E+02	1.13E+05	9.45E+02	4.74E+03	1.02E–02	51
Lead	2.86E+00	2.00E+01	1.52E+04	2.00E+01	1.14E+04	2.17E–03	7
Epoxy (glass-reinforced)	5.28E+00	6.55E+01	3.10E+03	2.48E+02	1.91E+03	7.60E–03	43
Polyethylene (high-density)	7.48E–01	2.48E+01	8.27E+02	2.48E+01	9.71E+02	9.65E–03	50
Polycarbonate (glass-reinforced)	3.52E+00	1.59E+02	1.16E+04	1.45E+02	1.53E+03	1.48E–02	62
Rubber (isoprene)	3.48E+00	2.76E+01	4.59E+00	2.76E+01	9.71E+02	1.71E–03	0
Polyurethane foam	1.76E+00	1.52E+01	1.08E+02	1.72E+01	4.99E+02	9.51E–03	49
Particle board (medium density)	3.52E–01	1.55E+01	2.93E+03	1.45E+01	6.10E+02	2.34E–02	75
Pine	2.05E+00	7.93E+01	8.27E+03	3.31E+01	3.61E+02	5.59E–02	100
Diamond	7.26E+02	2.69E+02	1.03E+06	4.00E+03	3.52E+03	2.86E–02	81
Silicon carbide (sintered)	6.60E+01	6.90E+01	3.31E+05	1.03E+03	2.97E+03	2.32E–02	75
Tungsten carbide	2.64E+02	8.96E+02	5.39E+05	4.95E+03	1.33E+04	6.09E–03	36
Glass (soda lime, general purpose)	3.30E–01	9.17E+01	7.31E+04	1.38E+03	2.47E+03	1.69E–02	66
Pottery	6.60E–01	3.31E+01	7.03E+04	5.00E+02	2.22E+03	1.85E–02	68
Concrete	1.32E–01	1.65E+00	3.00E+04	2.48E+01	2.50E+03	1.24E–02	57
Cork	1.50E+00	1.00E+00	2.00E+01	1.00E+00	1.39E+02	1.96E–02	70
Index values	0.000	0.000	0.333	0.000	–1.000		

TABLE 2.6

Derived Parameter D for Best Performance

To Obtain:	Maximum Performance	Minimum Weight	Minimum Cost
Strongest tension member	Y_t	Y_t/ρ	$Y_t/\rho C_m$
Strongest compression member	Y_c	Y_c/ρ	$Y_c/\rho C_m$
Strongest beam or plate	Y_t	$Y_t^{0.5}/\rho$	$Y_t^{0.5}/\rho C_m$
Stiffest structural member	E	$E^{1/3}/\rho$	$E^{1/3}/\rho C_m$
Best coil or tension spring	Y_t^2/E	$Y_t^2/(E\rho)$	$Y_t^2/(E\rho C_m)$
Best diaphragm spring	$Y_t^{1.5}/E$	$Y_t^{1.5}/(E\rho)$	$Y_t^{1.5}/(E\rho C_m)$

Y_t = tensile yield stress, Y_c = compressive yield stress, E = Young's modulus, ρ = density, C_m = material cost/weight.

The general form of a derived parameter then becomes

$$D = \left(\alpha_1^{m_1}\alpha_2^{m_2}\alpha_3^{m_3}\ldots\right)10^{\left(m_1\beta_1N_1+m_2\beta_3N_3+\cdots\right)} \tag{2.20}$$

and we require that D be represented by

$$D = \alpha 10^{\beta N} \quad \text{where } 0 \le N \le 100 \tag{2.21}$$

Thus, from Equation 2.16, the "100-scale" value for the derived parameter is given by

$$N = 100\frac{\log(D/D_{\min})}{\log(D_{\max}/D_{\min})} \tag{2.22}$$

Equation 2.22 can be simplified further by recognizing that the factor $\left(\alpha_1^{m_1}\alpha_2^{m_2},\ldots\right)$ cancels in the argument of both logarithmic expressions. Thus, we define parameter W as

$$W = m_1\beta_1N_1 + m_2\beta_2N_2 + \cdots \tag{2.23}$$

Substituting W into Equation 2.22 gives

$$N = 100\frac{\log(10^{W-W_{\min}})}{\log(10^{W_{\max}-W_{\min}})} \tag{2.24}$$

$$= 100\frac{(W-W_{\min})}{(W_{\max}-W_{\min})} \tag{2.25}$$

This transformation from "100-scale" values for individual parameters to the "100-scale" value for any derived parameter is easily accomplished on a spreadsheet using Equations 2.23 and 2.25. Table 2.5 is the printout of such a spreadsheet written with Microsoft Excel. The bottom row of the spreadsheet contains values for m, the index values of the derived parameter. The last two columns contain the values for W and the "100-scale" N values for the derived parameter, respectively.

Note that the index values entered into the last row are those for the beam stiffness for minimum weight. It can be seen that for this application (and no other design constraints), pine is the best choice ($N = 100$) and rubber is the worst choice ($N = 0$). The 100 score for pine indicates why straight grain wood is still a material of choice for small aerobatic aircraft structures. Note that manufacturing feasibility is not a part of this selection process. Thus,

while diamond scores a credible 81, its use would obviously be restricted to very small and very expensive devices. If we change the index for cost from 0 to –1 in Figure 2.5, then the derived parameter changes to represent the beam stiffness for minimum cost. The best choice then changes to concrete. Particle board is a close second with a score of 96, diamond becomes 6, and tungsten carbide is 0 because of its combination of high cost and high density. The high scores for concrete and particle board explains their use for low-cost beams and floor structures, respectively. The main purpose of the "100-scale" method is for such easy visualization of the relative merits of materials for different applications. The method can be extended to include combinations of two or more derived parameters. For example, the primary requirement for an automobile panel may be bending stiffness for least cost. However, diaphragm spring quality is a valuable additional material property since this makes the material more dent resistant. The 100-scale method can be expanded to cover such situations by using a weighted geometric mean of the two derived parameters [16].

Sometimes the choice of a material is based on the inverse of one of the fundamental properties. Examples would include specific volume representing lightness instead of density representing heaviness, flexibility instead of stiffness, softness instead of compressive strength, and so on. Assuming that we are interested in inverse property $(1/P)$, where P is represented by Equation 2.13 let

$$\frac{1}{P} = \alpha 10^{\beta M} \tag{2.26}$$

From Equations 2.14 and 2.15, the values of α and β for the inverse property are given by

$$\alpha = \frac{1}{P_{\max}} \tag{2.27}$$

$$\beta = \frac{\log\left[(1/P_{\min})/(1/P_{\max})\right]}{100} \tag{2.28}$$

$$= \frac{\log(P_{\max}/P_{\min})}{100} \tag{2.29}$$

and so the value for M becomes (refer to Equation 2.16),

$$\begin{aligned} M &= 100\frac{\log\left[(1/P)(1/P_{\max})\right]}{\log(P_{\max}/P_{\min})} \\ &= 100\frac{\left\{\left[\log(P_{\max}/P_{\min}) - \log(P/P_{\min})\right]\right\}}{\log(P_{\max}/P_{\min})} \\ &= 100 - N \end{aligned} \tag{2.30}$$

This result simply stems from the "100-scale" span from minimum to maximum values, which exchange places when the inverse property is considered. However, the fact that not just "100" and "0" change places, but that "95" becomes "5," "90" becomes "10," and so on, is intuitively satisfying.

2.6 Primary Process/Material Selection

Systematic procedures can be developed for the selection of primary process/material combinations. Such procedures operate by eliminating processes and materials as a more detailed specification of the required part's attributes occurs. The elements of such a selection procedure can be illustrated by considering, as an example, the part shown in Figure 2.8, which is to be used as an oven bracket. The example has been used previously by Wilson et al. [17,18] and is used again here as an illustrative example. In terms of the shape-producing capabilities listed in Table 2.2, this part is specified as follows.

Shape Attributes

1. Depressions	Yes
2. Uniform wall	Yes
3. Uniform cross-section	Yes
4. Axis of rotation	No
5. Regular cross-section	No
6. Captured cavity	No
7. Enclosed cavity	No
8. No draft	Yes

Material Requirements

1. Maximum temperature of 500°C
2. Excellent corrosion resistance to weak acids and alkalis

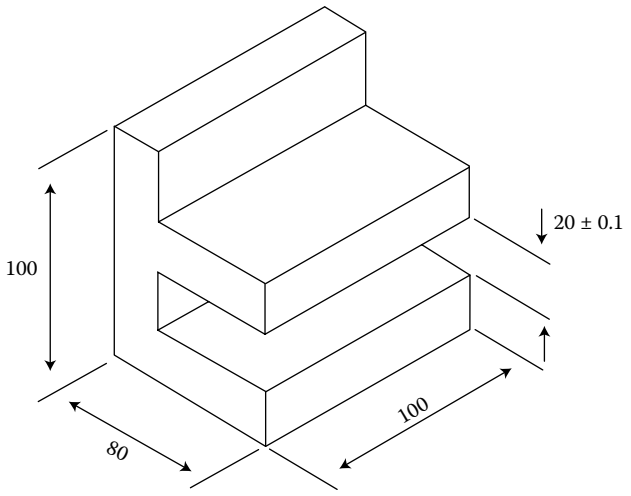


FIGURE 2.8
Oven bracket part.

In this list, the shape attributes with a "Yes" eliminate those processes that are not capable of producing these features. Those features with a "No" eliminate those processes that are only capable to producing parts with these features present. Applying these requirements progressively to the basic process/material compatibility matrix shown in Figure 2.3 produces the results shown in Figures 2.9 through 2.11. Figure 2.9 shows the processes eliminated by the first four shape attributes listed above and Figure 2.10 shows the processes eliminated by the other four shape attributes. Combining these together results in

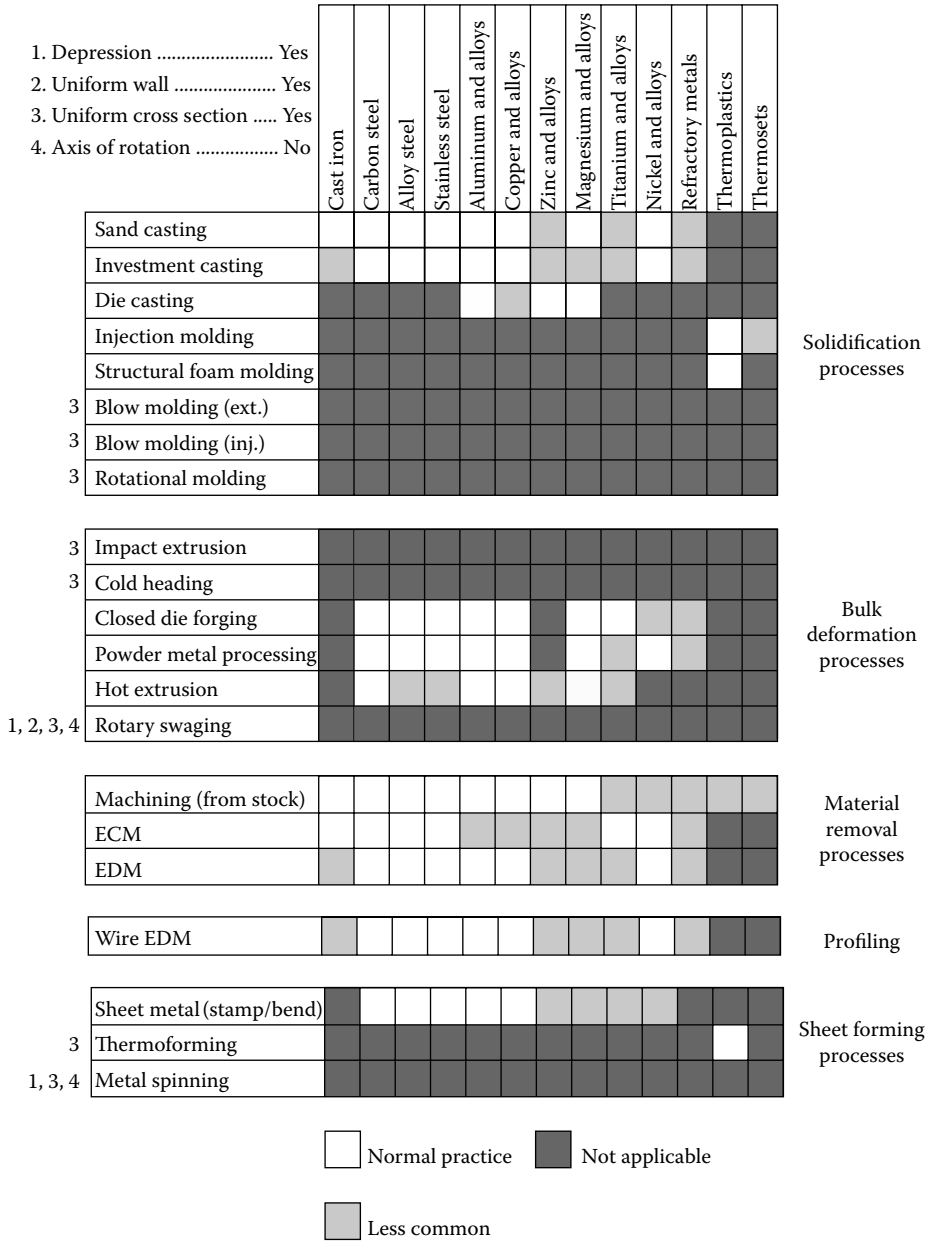


FIGURE 2.9
Process elimination based on four geometric attributes of the part in Figure 2.8.

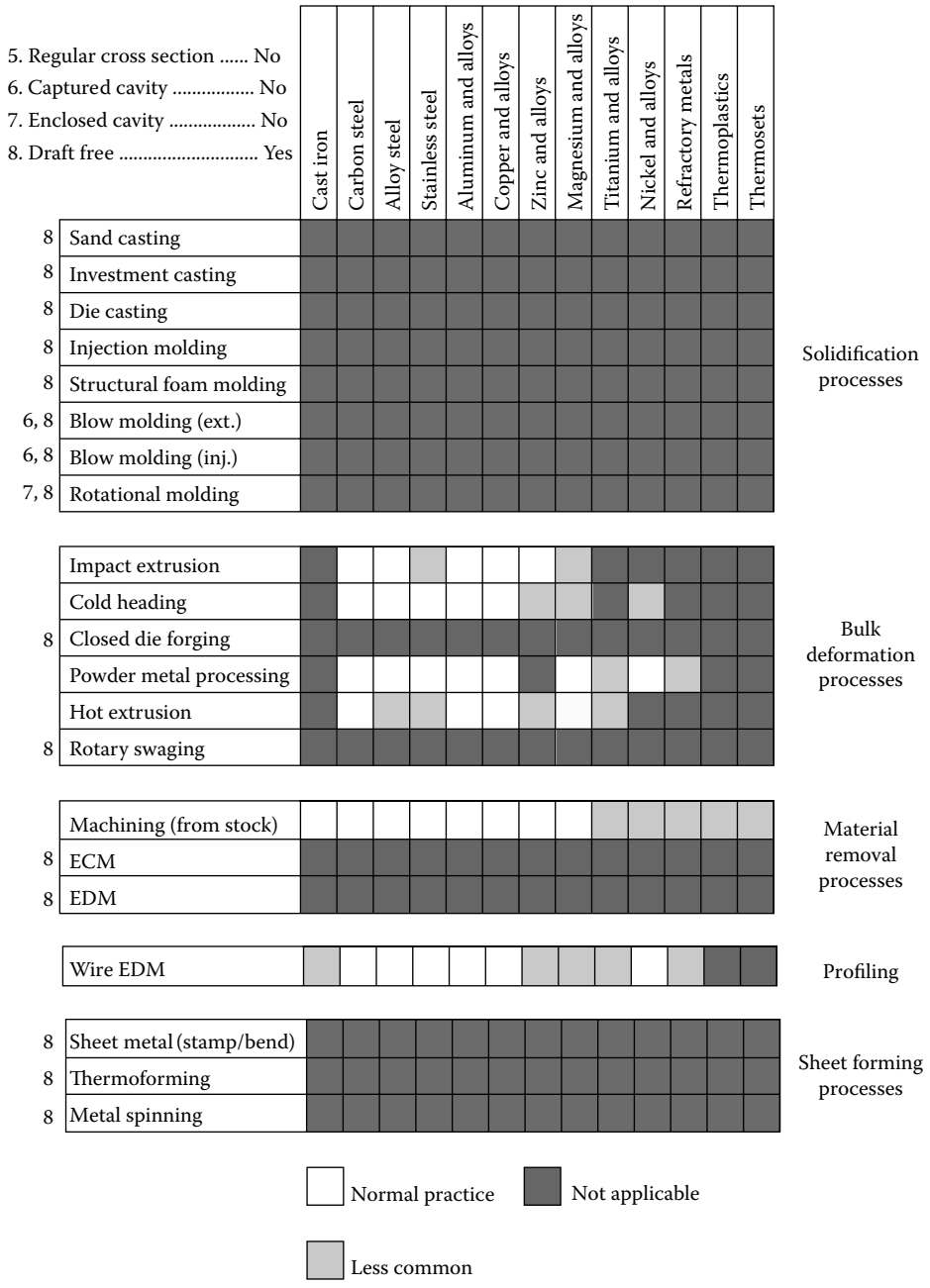


FIGURE 2.10
Process elimination based on further four attributes of the part in Figure 2.8.

four selected processes (Figure 2.11): powder metal parts, hot extrusion, machining from stock, and wire electric discharge machining (EDM). Finally, imposing the material requirements results in the final selection of processes and materials shown in Figure 2.12. These selected combinations can then be ranked by other criteria, such as estimates of manufacturing costs.

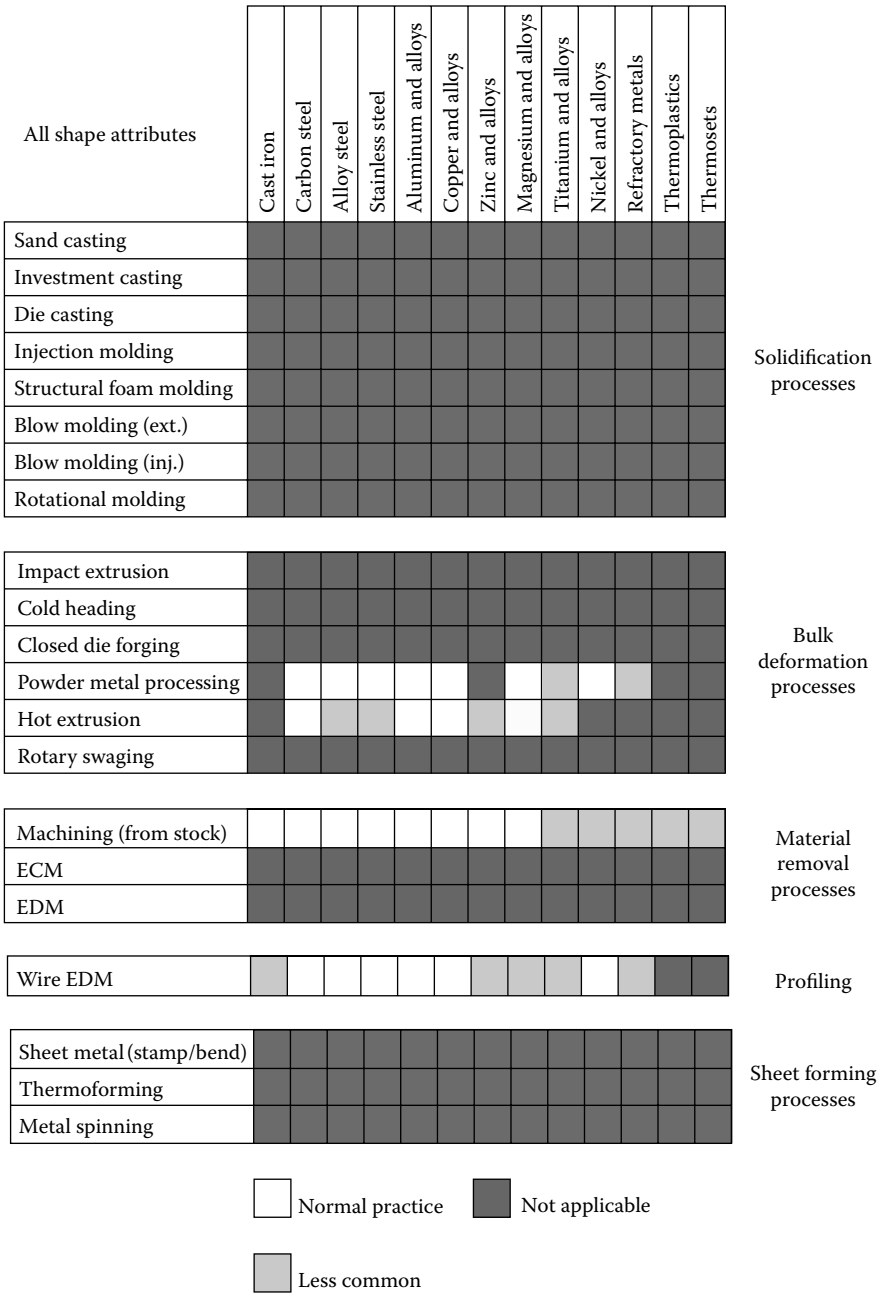


FIGURE 2.11
Final process selection based on geometric attributes of the part in Figure 2.8.

In this example, wire EDM would clearly not be an economic choice. The wire electrode spark erosion process involves very long cycle times and is used principally in tool and die making as described in Table 2.1. It is only used in part production for small batches of wafer thin parts, which can be cut in multiples from stacks of blanks, or for very small batches of complex uniform cross-section parts. This leaves only three processes available

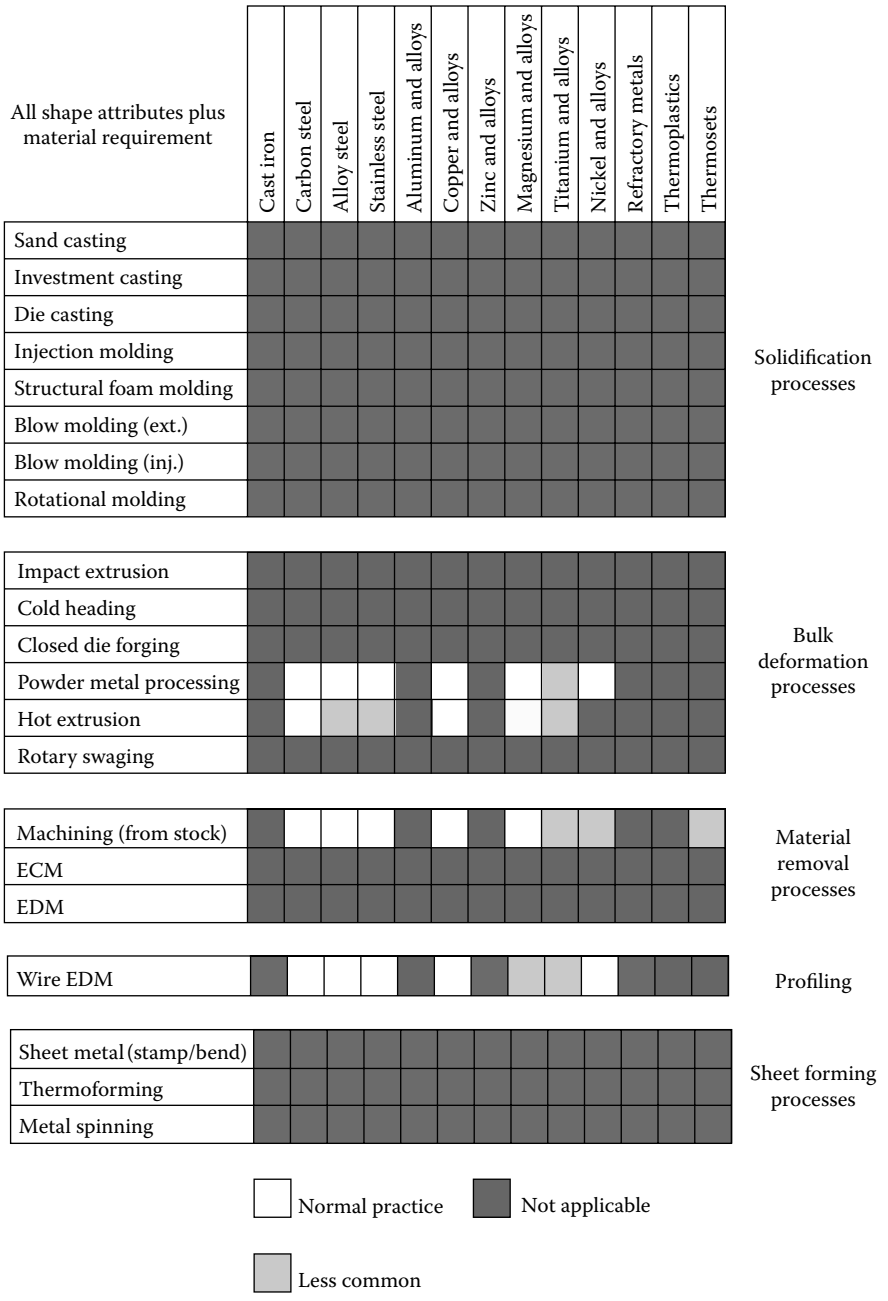


FIGURE 2.12
Final selection based on process/material combinations of the part shown in Figure 2.8.

to carry out the primary processing. If these processes were deemed not to be acceptable choices, then the alternatives would be to make changes to some of the shape attributes, or allocate one or more of the attributes to secondary processes. If, for example, we allow slight tapered upper and lower surfaces in the 20 mm wide depression of the oven bracket, we would enable both sand casting and investment casting as potential processes.

2.7 Systematic Selection of Processes and Materials

The development of computer-based procedures for process/material selection from general part attributes could have a significant impact on early product design decision-making. Several approaches to this problem were made in the past, but this remains an important area of design still not fully supported by computer-aided engineering.

2.7.1 Computer-Based Primary Process/Material Selection

An initial research program was carried out in the area of combined material/process selection by Wilson and coworkers [17,18], resulting in the development of a Fortran-based computer program, for material and process selection, given the acronym MAPS. This work was followed by the development of a primary material/process selector using a commercial relational database system. In this computer-aided material and process selector (CAMPS) [19], inputs were made under the headings of part shape, size, and production parameters to search a comprehensive process database and identify processing possibilities. In addition, required performance parameters were specified by making selections under the general categories of mechanical properties, thermal properties, electrical properties, and physical properties. As many selections as required could be made, and at each stage the candidate processes were presented to the system user. Processes could be eliminated directly because of shape or size, or when performance selections eliminated all the materials associated with a particular process, in a similar manner to the charts shown in Figures 2.9 through 2.12.

The CAMPS system also classified all possible selections into ranges labeled A through F. This was intended to ensure ease of use in the early stages of design when precise numerical values for many of the parameters would not be known. For example, for a structural part, yield strength is clearly an important requirement. However, the minimum allowable yield stress value depends on the part wall thickness, which in turn depends on the process/material combination to be used.

This early approach to process and material selection has been incorporated into a robust cost-estimating software tool for use at the early stages of product design [20]. This program contains definable process limits, such as maximum dimensions, minimum wall thickness, and so on. The selection procedure indicates that any combinations of process and material that are not suitable or for which the part geometry may be outside normal processing limits. Figure 2.13 shows an initial part description where the general part type and overall dimensions, including wall thickness, are defined. Following this, a process must be selected as indicated in Figure 2.14, and then the compatible materials are indicated (red for incompatible, green for compatible, and yellow for compatible but exceeding a normal processing limit). In the case of Figure 2.14, cold chamber die casting has been selected and the indicated compatible materials are copper, magnesium, aluminum, and zinc alloys.

2.7.2 Expert Processing Sequence Selector

While the type of approach described above may generally result in the selection of appropriate combinations of materials and primary processes, in some cases matching of the material and primary process alone to the finished part attributes, without considering viable sequences of operations, may lead to the omission of some appropriate combinations of primary processes and materials. Previous work by one of the writers and his

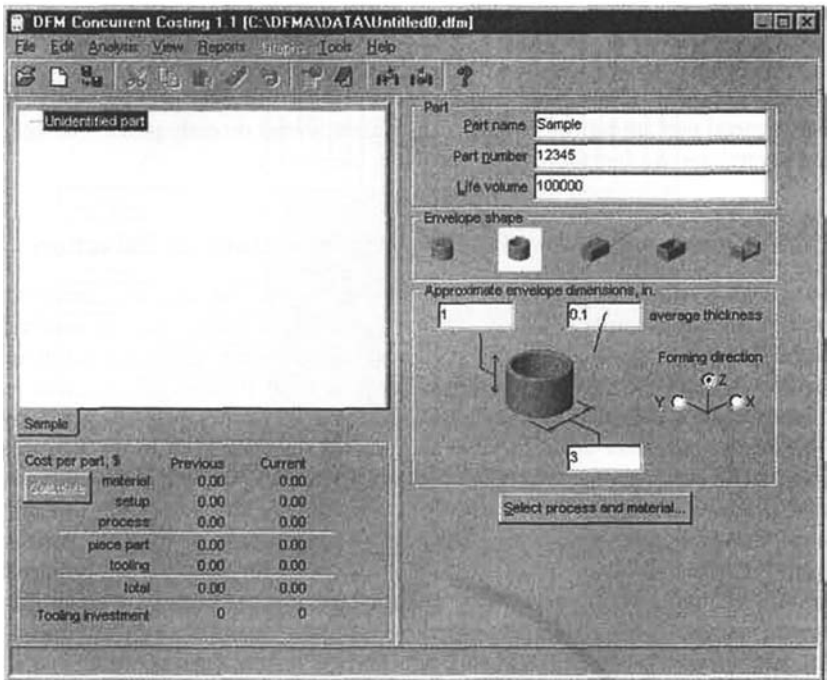


FIGURE 2.13
General description of proposed part.

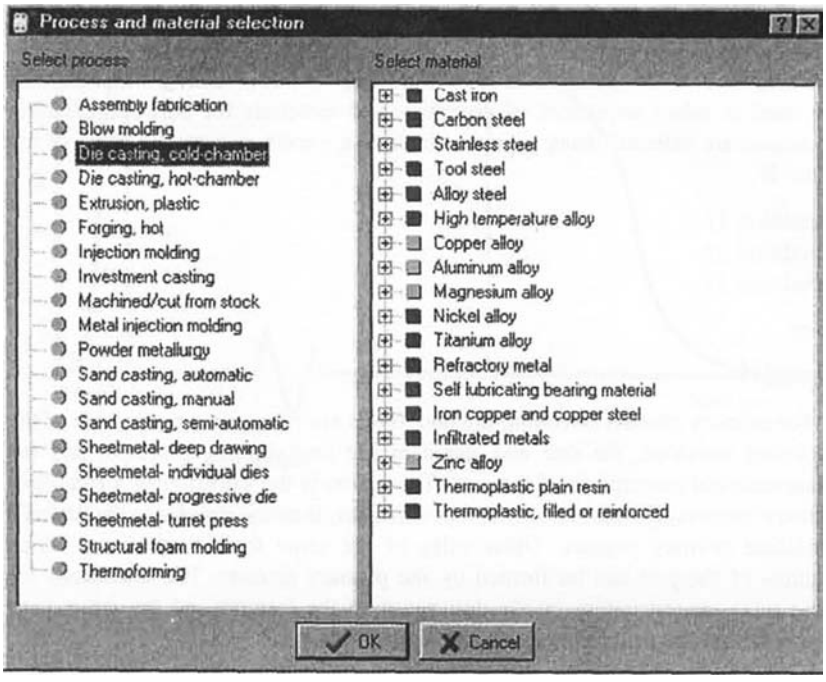


FIGURE 2.14
Material classes compatible with cold-chamber die casting.

research assistant, included an expert processing sequence generator to enhance this aspect of material and process selection [21,22].

With this procedure the user classified the geometry and specified the material constraints for the part. The result was a list of viable sequences of processes and compatible materials. The procedure was divided into four steps: geometry input, process selection, material selection, and system update. The geometry of the part was first classified according to its size, shape, cross-section, and features. Using pattern-matching rules, processes were then selected that would form the geometry of the part. Material selection uses fuzzy set theory materials, as described earlier.

The geometrical classification of a part is concerned with the following characteristics:

1. The overall size
2. The basic shape
3. The accuracy and surface finish
4. The cross-section
5. Functional features—projections, depressions, and so on

As described earlier, processes are classified as either primary, primary/secondary, or tertiary to take advantage of the natural order of processes in a sequence. Rules, formulated from the knowledge about processes and materials, are used to select sequences of processes and materials for part manufacture. Processes are selected using a pattern-matching expert system and rules of the form. If …

```
(condition 1)
(condition 2)
(condition 3)
then...
(action 1)
```

For primary process selection, the conditions are restrictions on the size of the enclosing envelope, the fundamental part shape, and the cross-sectional description of the part. The action is the selection of a candidate primary process. If a part satisfies the restrictions, then the process is chosen as a candidate primary process. Other rules of the same form then assess which features of the part can be formed by the primary process. The conditions for these rules are restrictions on the descriptors of the features and the action is to conclude that the primary process can form the feature.

The boundaries of process capabilities, for inclusion in the selection rules, are not well defined. Parts with requirements that are near the boundaries of the capabilities of a process are more difficult to produce than parts that fall well within these boundaries. Therefore, the process selection rules are better formulated with fuzzy logic membership functions to model the progressive transition from “easy” to “difficult or impossible” to manufacture by the selected process. For example, Figure 2.15 shows a typical membership function for primary process selection for the attribute part size for, say, die casting. Similar fuzzy selection rules can be applied to other part attributes. This process also enables a preliminary ranking of selections to be made based on the values of the membership functions obtained.

Next, the material database is searched for the primary process selected and uses the fuzzy logic approach described earlier to choose candidate materials. Since the properties of a material are related to how the material is processed, each process has its own material

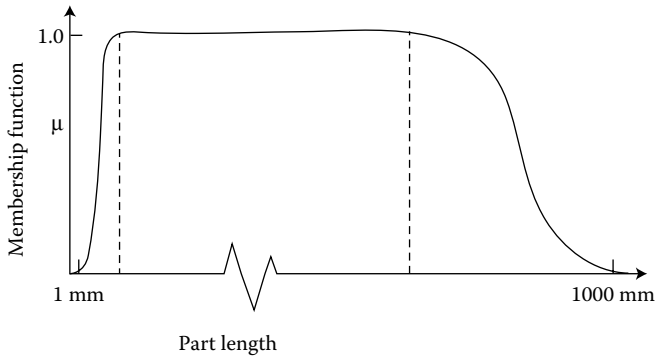


FIGURE 2.15
Example of membership function for process selection rules.

database. Materials are selected by mapping the user's input onto the material properties. Material properties that can be affected by tertiary manufacturing processes are not used to exclude materials from consideration, at this stage. For example, corrosion resistance could be achieved by plating an otherwise unacceptable material.

Primary/secondary processes are selected in a similar manner to form any features of the part that cannot be formed by the primary process. Similarly, tertiary processes are selected to fulfil material requirements that the candidate material could not fulfil. A viable sequence of processes is found when all of the geometrical and material goals specified by the user are satisfied. Figure 2.16 shows this process graphically. Here circles represent the goals and processes. Satisfied goals are indicated by filled-in circles with arrows pointing to the material or process that satisfied the goal.

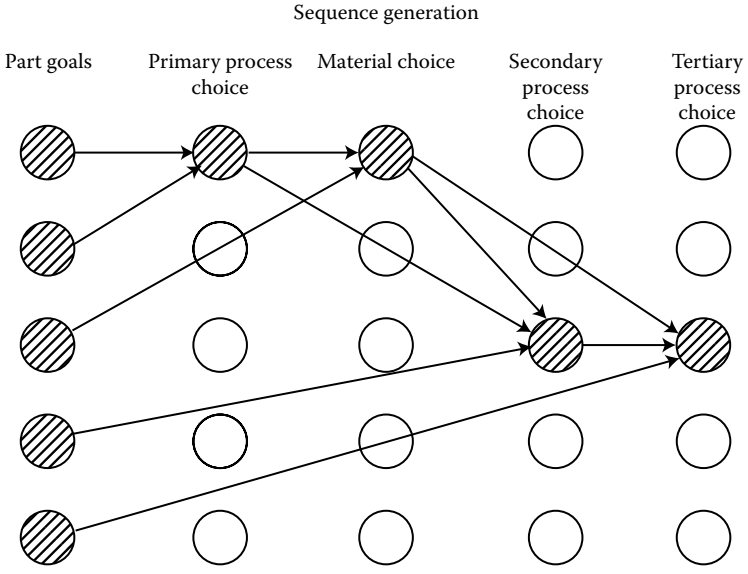


FIGURE 2.16
Procedure for processing sequence selection.

If a suitable process or material cannot be found to form required features or satisfy material requirements, then the procedure backtracks to solve the impasse. For instance, if a suitable material cannot be found, then the procedure backtracks to choose another primary process. Similarly, if a tertiary process cannot be found to satisfy a material requirement, then the procedure backtracks to choose an alternative material.

A characteristic of this approach to material and process selection is that as the list of part attributes to be fulfilled grows, the number of possible sequences may also increase. This differs from the procedure for selecting primary process/material combinations in which the list of possible combinations generally decreases, as the specification of the part becomes more precise. For example, the addition of a surface finish tolerance to the attribute list introduces secondary processes into sequences that could produce this requirement. For this reason, it is important that consideration be given to the economic ranking of the processing sequences generated.

2.7.3 Economic Ranking of Processes

Viable material/process combinations determined by selection procedures as described above require evaluation as to which is the most suitable; usually by estimating which is the most economic. This requires the availability of procedures for realistically evaluating manufacturing costs early in the design process. Several of the later chapters deal with cost-estimating procedures for various processes. It should be noted, however, that even at the very early design stages, methods for cost assessment can be used for the ranking of alternative material/process combinations.

As an example of how early cost estimates can be made for a particular process, machining is considered. Further details on cost estimating for design for machining are contained in Chapter 7. From a detailed analysis of cost estimating for machined parts [23,24], it can be concluded that, in general, the time to remove a given volume of material in rough machining is mainly determined by the specific cutting energy (or unit power) of the material and the power available for machining. For finish-machining a given surface area, the recommended speeds and feeds for minimum machining cost could be used. Also, it is possible to make appropriate allowances for tool replacement costs.

Further research [25] has shown that a large amount of statistical data is available on the shapes and sizes of machined components and the amount of machining carried out on them. Statistical data are also available on the sizes of the machine tools relative to the sizes of the workpieces machined. Combining this data with information gathered on machine costs and power availability, it can be shown that estimates of machined component costs can be made based on the minimum design information, such as might be readily available early in the design process [26,27].

The information required can be divided into three areas:

1. Workpiece and production data
2. Factors affecting nonproductive costs
3. Factors affecting machining time and costs

The first item under the heading of workpiece and production data describes the shape category of the workpiece. It was found in previous studies [28] that common workpieces can be classified into seven basic categories, as illustrated in Figure 2.17. Other items under this first heading include: the material, the form of the material (standard stock or near-net shape), dimensions of the workpiece, cost per unit weight, average machine and operator

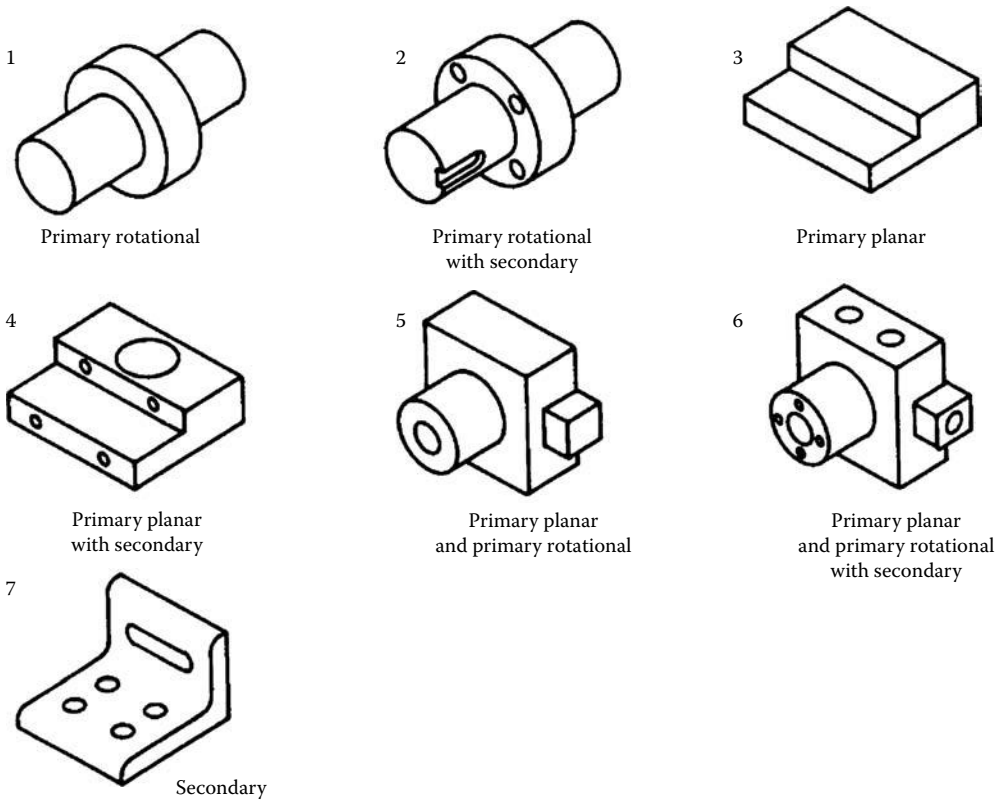
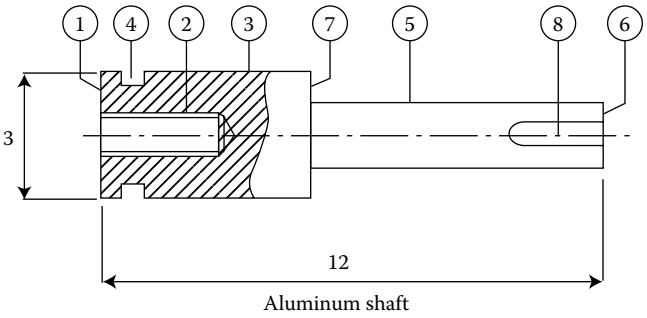


FIGURE 2.17
Seven basic categories of machines' component parts. (Adapted from PERA, *Survey of Machining Requirements in Industry*, PERA, Melton Mowbray, UK.)

rate, and batch size per setup. A knowledge of the workpiece and production data not only allows the cost of the workpiece to be estimated, but also allows predictions to be made of the probable magnitudes of the remaining items necessary for the estimates of nonproductive costs and machining costs.

For example, for the workpiece shown in Figure 2.18, the total cost of the finished component was estimated to be $24.32—a figure obtained from knowledge of the work material, its general shape category and size, and its cost per unit volume. A cost estimate for this component based on its actual machined features and using the approximate equations developed in [25] gives a total cost of $22.83. A more detailed estimate obtained using more traditional cost-estimating methods gives a total cost of $22.95.

A comparison of these three estimates together with comparisons for several other workpieces are presented in Figure 2.19, where it can be seen that the approximate method using actual data gives figures surprisingly close to the accurate estimate. Also, the initial crude estimate based on typical workpieces is quite accurate and probably sufficient for the purposes of early cost estimating when various material and process combinations are considered and before the component has been designed. However, these considerations should preferably occur after the proposed product has been simplified as much as possible, through a design for assembly analysis, as will be described in more detail in the next chapter.



Machine	Feature	Operations
Horizontal band saw	–	Cut off workpiece
CNC lathe	1	Finish face
	2	Center drill, drill, tap
	3	Finish tum
	4	Groove
	–	Reclamp
	5	Rough and finish tum
	6	Finish face
	7	Finish face
Vertical miller	8	End mill keyway

FIGURE 2.18
Category 2 part—rotational with secondary features.

This example for machining illustrates that it is possible to obtain reliable cost estimates based on some initial general design information and that such cost estimates can be refined as more detailed design information becomes available. The cost models for the common primary shape-generating processes detailed in the later chapters have been combined into a software tool [20] that enables a cost comparison to be obtained for a proposed part using different manufacturing processes and materials. The estimation procedures are structured in such a way that an initial cost estimate is determined from the general shape, size, and material selected for the part, using appropriate default values for various parameters. These initial cost estimates are then refined as more details of the part geometry and other factors are entered. The geometric features such as part volume, perimeter, and projected area can be obtained from an in-built geometry calculator or from a computer-aided design (CAD) model of the part.

As an illustration of the use of such a tool to compare material and process selections consider the following example. Figure 2.20 shows a small connecting-rod shape that is considered for manufacture. This is a symmetrical part with a flat parting plane that divides the shape into two mirror images. It is assumed that this part is to be made from brass. The type of process selection procedures described earlier, as illustrated in Figures 2.13 and 2.14, show that the following compatible processes are suitable for manufacture of the part:

- Die casting
- Hot forging

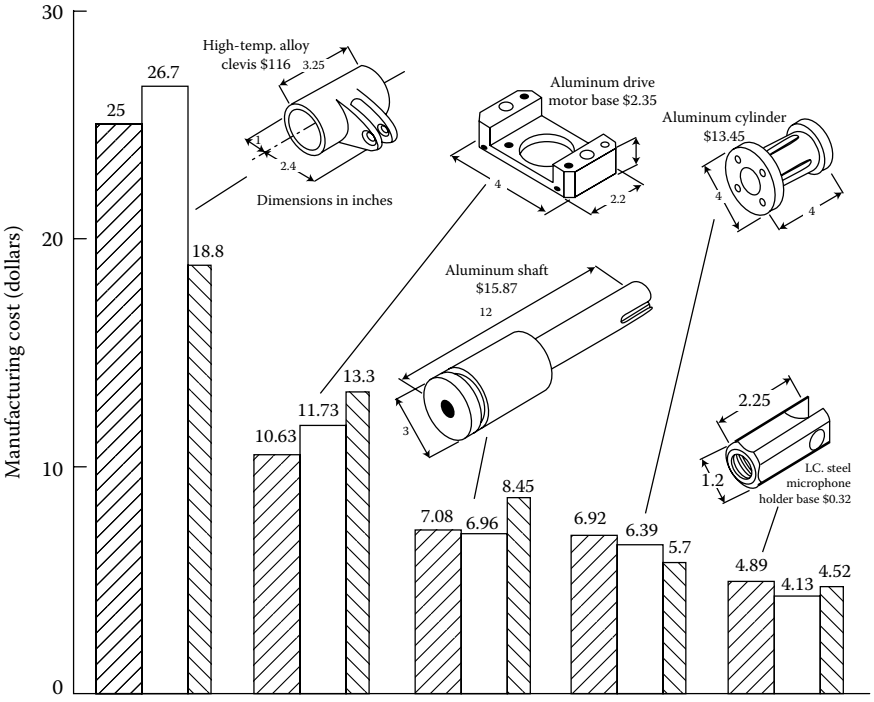


FIGURE 2.19
Comparison of machining cost estimates. The cost indicated next to each part drawing is the material cost for the part, ▨, detailed analysis; □, estimate; ▧, initial estimate.

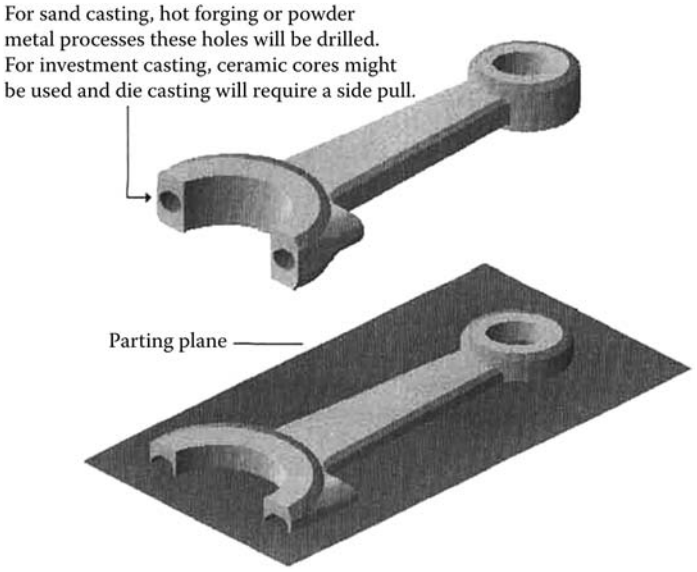


FIGURE 2.20
Connecting rod.

- Investment casting
- Automatic sand casting
- Powder metal processing

Some of the features, in particular the horizontal holes, need to be produced by secondary machining for some of the processes, as illustrated in the figure.

Figure 2.21 compares the estimated cost for the selected processes for different production volumes. These cost estimates include the costs of tooling and any secondary operations required. These curves show that powder metallurgy would be the least expensive process for life volumes greater than about 20,000 and that hot forging would be more economical for smaller life volumes. However, it should be realized that for very small quantities machining from the solid would undoubtedly be the most economical procedure, but this has not been considered here.

Figure 2.22 shows a more detailed breakdown of the cost contributions for a production volume of 100,000 parts for each process. The material costs for investment casting and hot forging are higher than the costs for other processes. In investment casting the pattern costs and ceramic molding costs are added to the metal costs and in hot forging where four forgings per cycle are assumed there is a large amount of scrap generated in the form of flash. The high cost of setup for automatic sand casting would be expected. The lowest process cost is for die casting, which again would be expected, since this is a highly efficient operation once the tooling has been manufactured. However, the high cost of tooling for this process is evident in the bar chart and is partly due to the short cavity life with the selected material. Powder metal processing is clearly the preferred process for this life volume of 100,000 (Figure 2.23).

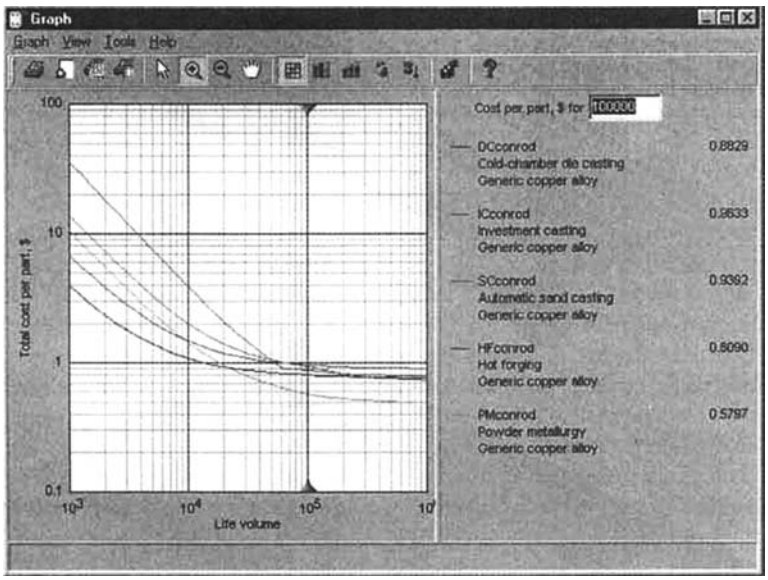


FIGURE 2.21
Connecting rod costs for different processes and production volumes.

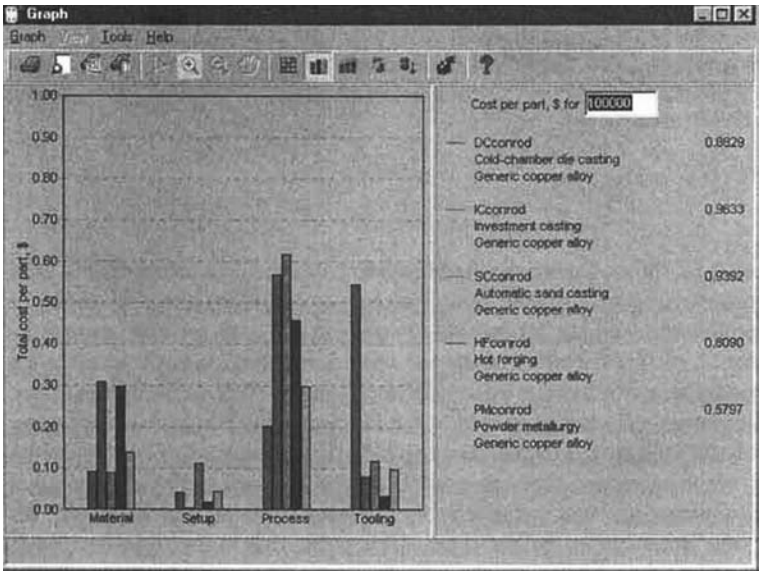


FIGURE 2.22
Cost breakdown for production volume of 100,000.

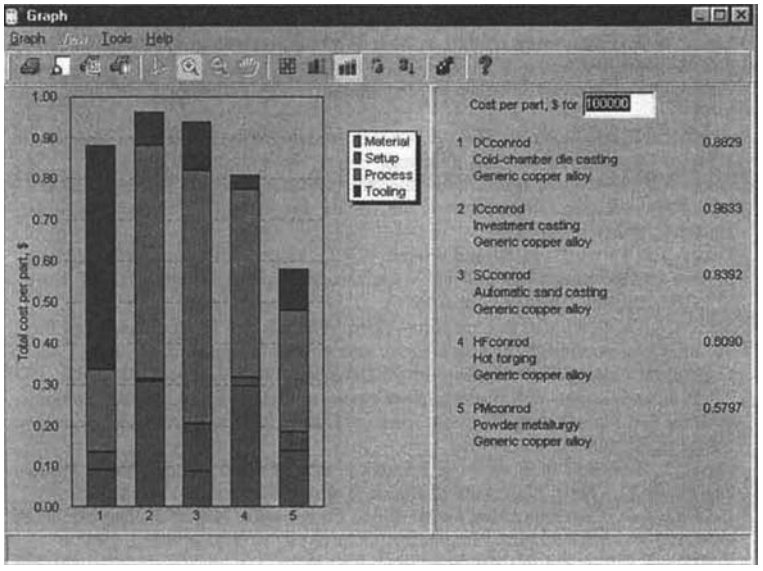


FIGURE 2.23
Cost comparisons for production volume of 100,000.

PROBLEMS

1. Figure 2.24 shows the side view of a modern hollow golf driver head. The preferred weight of a driver head is 200 g and the volume is 460 cc; the latter value is the maximum allowable by the U.S. Golf Association. To achieve these two design specifications, modern driver heads are constructed as hollow shells. Most

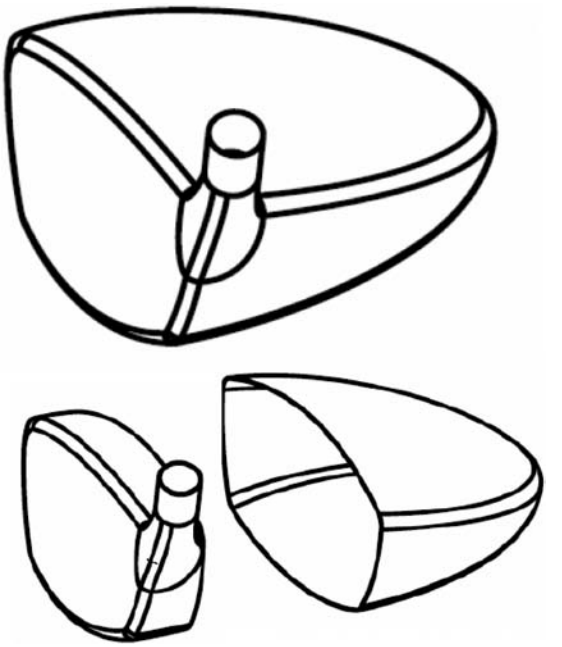


FIGURE 2.24
Hollow metal golf driver head construction.

commonly the face is manufactured separately, as shown in the section on the right of the figure, and either welded or bonded to the hollow shell body. For the highest ball speed off the face after impact, the face of a modern driver is designed to act as a stiff diaphragm spring. Use the material data in Table 2.5 and the diaphragm spring maximum performance parameter in Table 2.6 to determine candidate metal alloys for the face, which also possess high strength needed for the golf ball impact. Since it is difficult to make modern large driver heads within the 200 g target weight, repeat the calculations using the derived parameter for best diaphragm spring property per weight. Do your selections agree with the manufacturers' material of choice for driver heads?

2. Figure 2.25 shows a support platform for a precision electrical instrument. The platform is 100 mm high, and the platform base and top have outer dimensions 75×75 mm. The square cutout in the top plate has dimensions 50×50 mm. The platform is to be made from an electrically conductive metal.

   Use the procedures in Sections 2.3 and 2.4 to identify all candidate primary processes from the list in Figure 2.3. The top and bottom surface of the platform must be flat and parallel. Any other surface on the part may have slight taper or draft, if required, for particular primary process choices. Some of the features on the finished part may be assigned to secondary machining processes to increase the list of candidate primary processes. For these cases, add an ordered list of the required secondary processes to the primary one, to create a simple production plan. When considering machining from stock as a possible option, also consider if a primary process could be used to eliminate the need for machining some of the required main features.
3. A version of the support platform in Figure 2.25 is required for aerospace use, for which its electrical conductivity should be as high as possible combined with minimum weight. Assume that all the section thicknesses should have the same value, h, so that the part volume can be expressed approximately in the form

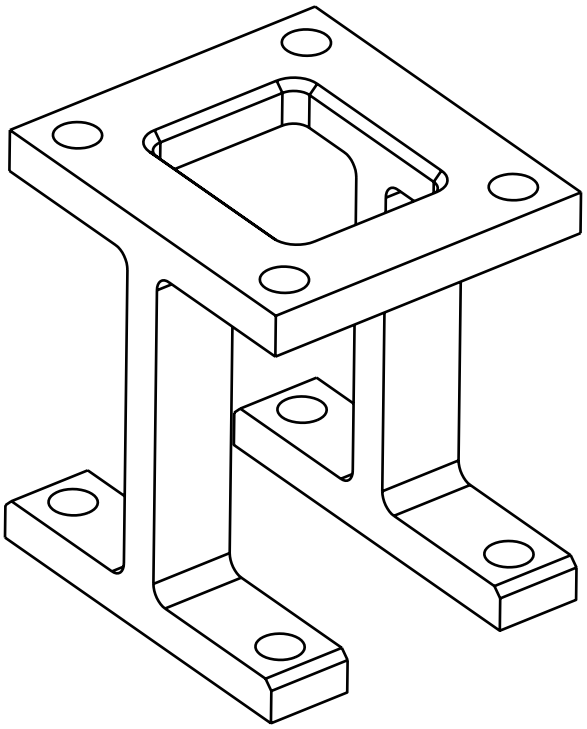


FIGURE 2.25
Electrical instrument support platform.

$V = C_0h$, where C_0 is a constant. Using electrical resistivity, γ (Ω – cm), and density, ρ(g/cm^3), determine the derived parameter which represents electrical current flow/weight. Use this parameter to compare different possible materials. Refer to materials handbooks for resistivity and density data, or use web material databases such as www.matweb.com. Since alloying elements can have a significant effect on electrical resistivity, compare only pure metals in this exercise as a starting point for the investigation of candidate alloys.

(*Hint: Assume an applied voltage, v, and conductive paths up through the legs of width, w, and length, L are fixed by the design. Also assume that the leg thickness h changes with the change of material to obtain the required level of conductivity. Write an expression for current flow, I, in terms of these parameters and the variable thickness, h. Use this with an approximate expression of part weight to obtain the required result.*)

4. Figure 2.26 illustrates the outer housing of a rotor assembly, of which a production volume of 100,000 is required. The assembly is designed to spin at a high speed during which the housing is subjected to high tensile stresses. Preliminary designs calculations suggest that the housing could be made of aluminum alloy with a wall thickness in the range of 2.0–3.0 mm depending on the selected alloy. The wall thickness may be different for other candidate materials but low strength materials requiring an excessively thick wall should be avoided. A good surface finish of approximately 50 μin. is required.

   The part is 13 cm high. The large diameter is 20 cm which steps down to 17.5 cm at the midpoint. The bottom of the housing is open and the top has large hole of 12.5 cm diameter in the center surrounded by 12 1.5-cm diameter holes.

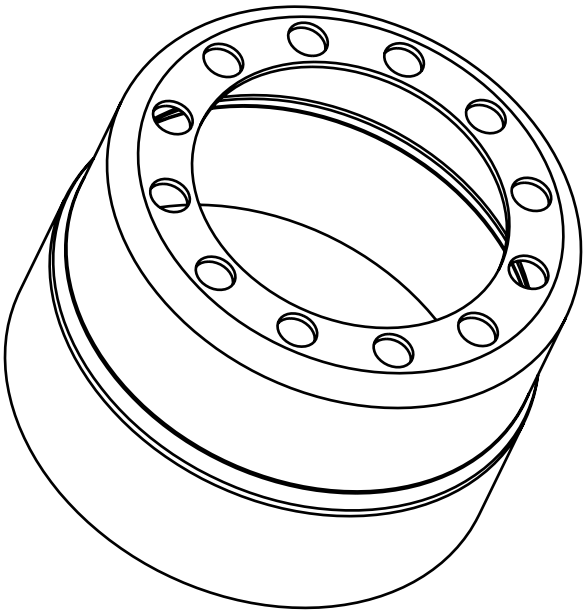


FIGURE 2.26
Rotor housing.

Use the procedures in Sections 2.3 and 2.4 to identify all candidate primary processes, for manufacture of the housing, from the list in Figure 2.3. The inner and outer main surfaces may have a slight taper or draft, if required, for particular primary process choices. Some of the features on the finished part may be assigned to secondary processes. For these cases add an ordered list of the required secondary processes to the primary one, to create a simple production plan.

(Hint: First eliminate processes from Table 2.2 on the basis of shape attributes. This leaves a relatively large set of candidate processes. Next review these candidates in Table 2.1 to check the requirements of part size, surface finish, process limitations, and associated materials against the design requirements.)

5. Saturn Automobile Corporations is one of the very few car manufacturers to have replaced some of the commercial quality steel body panels with injection-molded ones. The material they chose to use is glass-reinforced polycarbonate, blended with ABS for improved mold flow characteristics. The elastic modulus of this blended reinforced thermoplastic is $E = 5$ GN/m^2, and the yield stress is $Y_t = 80$ MN/m^2. The steel panels had a nominal thickness of 1 mm and corresponding material properties of $E = 200$ GN/m^2, and $Y_t = 300$ MN/m^2.

   Use an appropriate derived parameter to investigate Saturn's marketing claim that the thermoplastic panels are more "ding" resistant. Determine the wall thicknesses Saturn would have needed to use to obtain the same panel stiffness as the sheet steel ones being replaced.

   (Hint: 'Ding resistance' is determined by the diaphragm spring quality of the panels, so use the appropriate derived parameter for comparison. Refer to Section 2.5.3 for help with the last part of this problem.)

6. Review the equations relating the maximum center load which can supported by a simply supported beam with length L, width w, thickness h, and yield strength

in tension Y_t. If length and width are fixed by the design, show that two beams A and B (or equivalently two plates) have the same load-carrying capability if

$$h_B^2 Y_{tB} = h_A^2 Y_{tA} \quad \text{or equivalently} \quad h_B = h_A \left(\frac{Y_{tA}}{Y_{tB}} \right)^{1/2}$$

Use this relationship as an approximate test of the requirement for equal or improved bending strength of the Saturn panels, described in Problem 5, compared to the sheet steel ones.

7. Suggested class project: Study Table 2.1, which covers the more common manufacturing processes in consumer–product production. Identify a product manufacturing process not included in Table 2.1. Complete an entry for your process in Tables 2.1 and 2.2. Provide references for your process information.
8. Construct the Excel spreadsheet illustrated in Table 2.5. Use this to explore the best material choices for each of the 18 criteria given in Table 2.6.

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3

Product Design for Manual Assembly

3.1 Introduction

Design for assembly (DFA) should be considered at all stages of the design process, but especially during the early stages. As the design team conceptualizes alternative solutions, it should give serious consideration to the ease of assembly of the product or subassembly. The team requires a DFA tool to effectively analyze the ease of assembly of the products or subassemblies it designs. The design tool should provide quick results and be simple and easy to use. It should ensure consistency and completeness in its evaluation of product assemblability. It should also eliminate subjective judgment from design assessment, allow free association of ideas, enable easy comparison of alternative designs, ensure that solutions are evaluated logically, identify assembly problem areas, and suggest alternative approaches for simplifying the product structure—thereby reducing manufacturing and assembly costs.

By applying a DFA tool, the communication between manufacturing and design engineering is improved, and ideas, reasoning, and decisions made during the design process become well-documented for future reference.

The *Product Design for Assembly* handbook [1] originally developed as a result of extensive university research, and, more recently, expanded versions in software form provide systematic procedures for evaluating and improving product design for ease of assembly. This goal is achieved by providing assembly information at the conceptualization stage of the design process in a logical and organized fashion. This approach also offers a clearly defined procedure for evaluating a design with respect to its ease of assembly. In this manner, a feedback loop is provided to aid designers in measuring improvements resulting from specific design changes. This procedure also functions as a tool for motivating designers; through this approach, they can evaluate their own designs and, if possible, improve them. In both cases, the design can be studied and improved at the conceptual stage when it can be simply and inexpensively changed. The DFA method accomplishes these objectives by:

1. Providing a tool for the designer or design team which assures that considerations of product complexity and assembly take place at the earliest design stage. This eliminates the danger of focusing exclusively during early design on product function with inadequate regard for product cost and competitiveness.
2. Guiding the designer or design team to simplify the product so that savings in both assembly costs and piece part costs can be realized.
3. Gathering information normally possessed by the experienced design engineer and arranging it conveniently for use by less-experienced designers.
4. Establishing a database that consists of assembly times and cost factors for various design situations and production conditions.

The analysis of a product design for ease of assembly depends to a large extent on whether the product is to be assembled manually, with special-purpose automation, with general-purpose automation (robots), or a combination of these. For example, the criteria for the ease of automatic feeding and orienting are much more stringent than those for manual handling of parts. In this chapter, we introduce design for manual assembly, since it is always necessary to use manual assembly costs as a basis for comparison. In addition, even when automation is seriously considered, some operations may have to be carried out manually, and it is necessary to include the cost of these in the analysis.

3.2 General Design Guidelines for Manual Assembly

As a result of experience in applying DFA, it has been possible to develop general design guidelines that attempt to consolidate manufacturing knowledge and present them to the designer in the form of simple rules to be followed when creating a design. The process of manual assembly can be divided naturally into two separate areas, handling (acquiring, orienting, and moving the parts), and insertion and fastening (mating a part to another part or group of parts). The following design for manual assembly guidelines specifically address each of these areas.

3.2.1 Design Guidelines for Part Handling

In general, for ease of part handling, a designer should attempt to:

1. Design parts that have an end-to-end symmetry and rotational symmetry about the axis of insertion. If this cannot be achieved, try to design parts having the maximum possible symmetry (see Figure 3.1a).
2. Design parts that, in those instances where the part cannot be made symmetric, are obviously asymmetric (see Figure 3.1b).
3. Provide features that prevent jamming of parts that tend to nest or stack when stored in bulk (see Figure 3.1c).
4. Avoid features that allow tangling of parts when stored in bulk (see Figure 3.1d).
5. Avoid parts that stick together or are slippery, delicate, flexible, very small or very large, or that are hazardous to the handler (i.e., parts that are sharp, splinter easily, etc.) (see Figure 3.2).

3.2.2 Design Guidelines for Insertion and Fastening

For ease of insertion, a designer should attempt to:

1. Design so that there is little or no resistance to insertion and provide chamfers to guide the insertion of two mating parts. Generous clearance should be provided, but care must be taken to avoid clearances that result in a tendency for parts to jam or hang-up during insertion (see Figures 3.3 through 3.6).
2. Standardize by using common parts, processes, and methods across all models and even across product lines to permit the use of higher volume processes that normally result in lower product cost (see Figure 3.7).

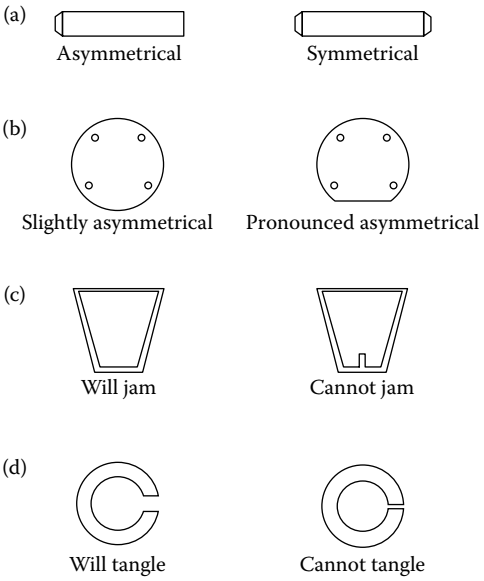


FIGURE 3.1
Geometrical features affecting part handling.

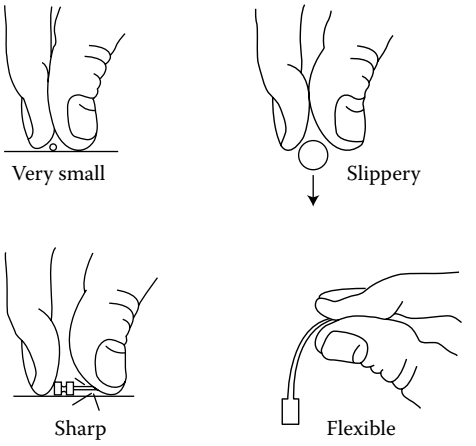


FIGURE 3.2
Some other features affecting part handling.

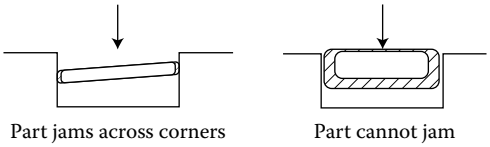


FIGURE 3.3
Incorrect geometry can allow a part to jam during insertion.

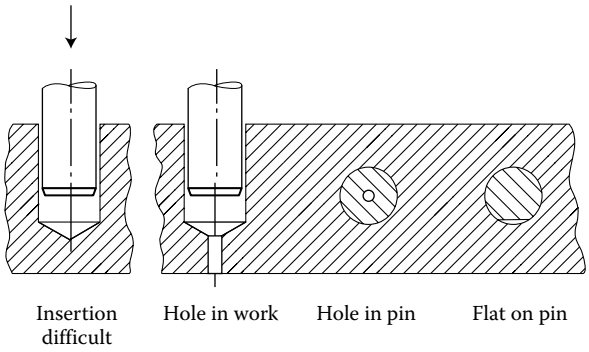


FIGURE 3.4
Provision of air-relief passages to improve insertion into blind holes.

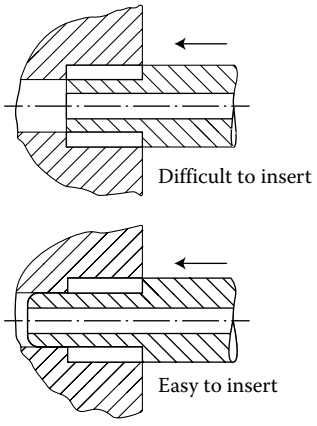


FIGURE 3.5
Design for ease of insertion—assembly of long-stepped bushing into counterbored hole.

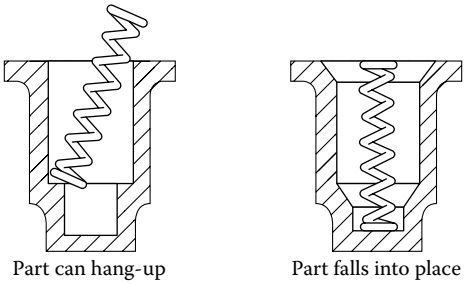


FIGURE 3.6
Provision of chamfers to allow easy insertion.

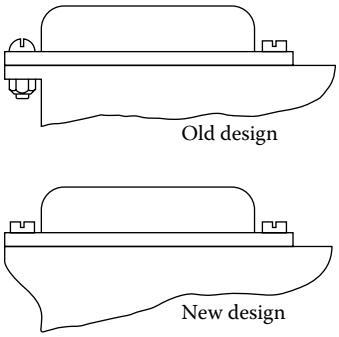


FIGURE 3.7
Standardize parts.

3. Use pyramid assembly—provide for progressive assembly about one axis of reference. In general, it is best to assemble from above (see Figure 3.8).
4. Avoid, where possible, the necessity for holding parts down to maintain their orientation during manipulation of the subassembly or during the placement of another part (see Figure 3.9). If holding down is required, then try to design so that the part is secured as soon as possible after it has been inserted.

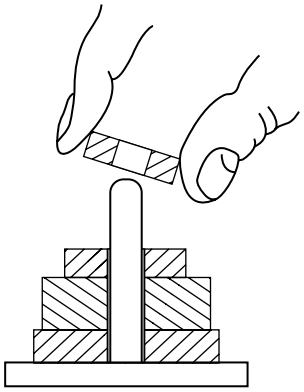


FIGURE 3.8
Single-axis pyramid assembly.

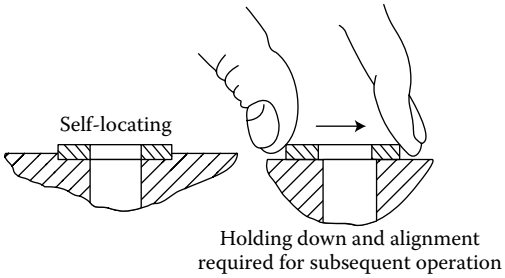


FIGURE 3.9
Provision of self-locating features to avoid holding down and alignment.

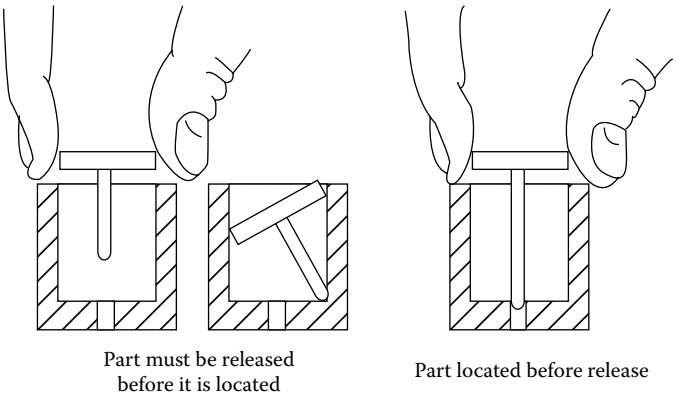


FIGURE 3.10
Design to aid insertion.

5. Design so that a part is located before it is released. A potential source of problems arises from a part being placed where, due to design constraints, it must be released before it is positively located in the assembly. Under these circumstances, reliance is placed on the trajectory of the part being sufficiently repeatable to locate it consistently (see Figure 3.10).
6. When common mechanical fasteners are used, the following sequence indicates the relative cost of different fastening processes, listed in the order of increasing manual assembly cost (Figure 3.11).
   a. Snap fitting
   b. Plastic bending
   c. Riveting
   d. Screw fastening
7. Avoid the need to reposition the partially completed assembly in the fixture (see Figure 3.12).

General rules are useful to follow when DFA is carried out. However, guidelines are insufficient in themselves for a number of reasons. First, guidelines provide no means by which to evaluate a design quantitatively for its ease of assembly. Second, there is no relative ranking of all the guidelines that can be used by the designer to indicate which guidelines result in the greatest improvements in handling, insertion, and fastening; there is no way to estimate the improvement due to the elimination of a part, or due to the redesign of a part for handling, and so on. It is, then, impossible for the designer to know which guidelines to emphasize during the design of a product.

Finally, these guidelines are simply a set of rules that, when viewed as a whole, provide the designer with suitable background information to be used to develop a design that would be more easily assembled than a design developed without such a background. An approach must be used that provides the designer with an organized method that encourages the design of a product that is easy to assemble. The method must also provide an estimate of how much easier it is to assemble one design, with certain features, than to assemble another design with different features. The following discussion describes the DFA methodology, which provides the means of quantifying assembly difficulty.

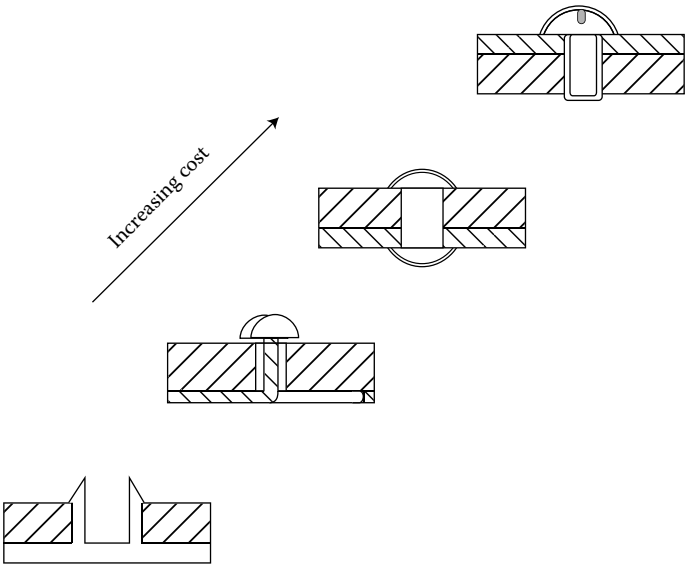


FIGURE 3.11
Common fastening methods.

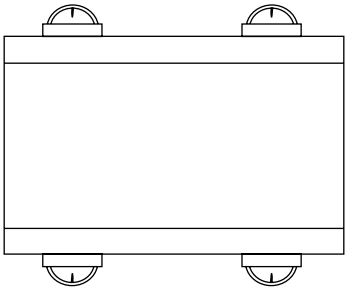


FIGURE 3.12
Insertion from opposite direction requires repositioning of the assembly.

3.3 Development of the Systematic Design for Assembly Methodology

Starting in 1977, analytical methods were developed [2] for determining the most economical assembly process for a product and for analyzing ease of manual, automatic, and robot assembly. Experimental studies were performed [3–5] to measure the effects of symmetry, size, weight, thickness, and flexibility on manual handling time. Additional experiments were conducted [6] to quantify the effect of part thickness on the grasping and manipulation of a part using tweezers, the effect of spring geometry on the handling time of helical compression springs, and the effect of weight on handling time for parts requiring two hands for grasping and manipulation.

Regarding the design of parts for the ease of manual insertion and fastening, experimental and theoretical analyses were performed [7–11] on the effect of chamfer design on

manual insertion time, the design of parts to avoid jamming during assembly, the effect of part geometry on insertion time, and the effects of obstructed access and restricted vision on assembly operations.

A classification and coding system for manual handling, insertion, and fastening processes, based on the results of these studies, was presented in the form of a time standard system for designers to use in estimating manual assembly times [12,13]. To evaluate the effectiveness of this DFA method, the ease of assembly of a two-speed reciprocating power saw and an impact wrench were analyzed and the products were then redesigned for easier assembly [14]. The initial design of the power saw (Figure 3.13) had 41 parts and an estimated assembly time of 6.37 min. The redesign (Figure 3.14) had 29 parts for a 29% reduction in part count, and an estimated assembly time of 2.58 min for a 59% reduction in assembly time. The outcome of further analyses [14] was a more than 50% savings in

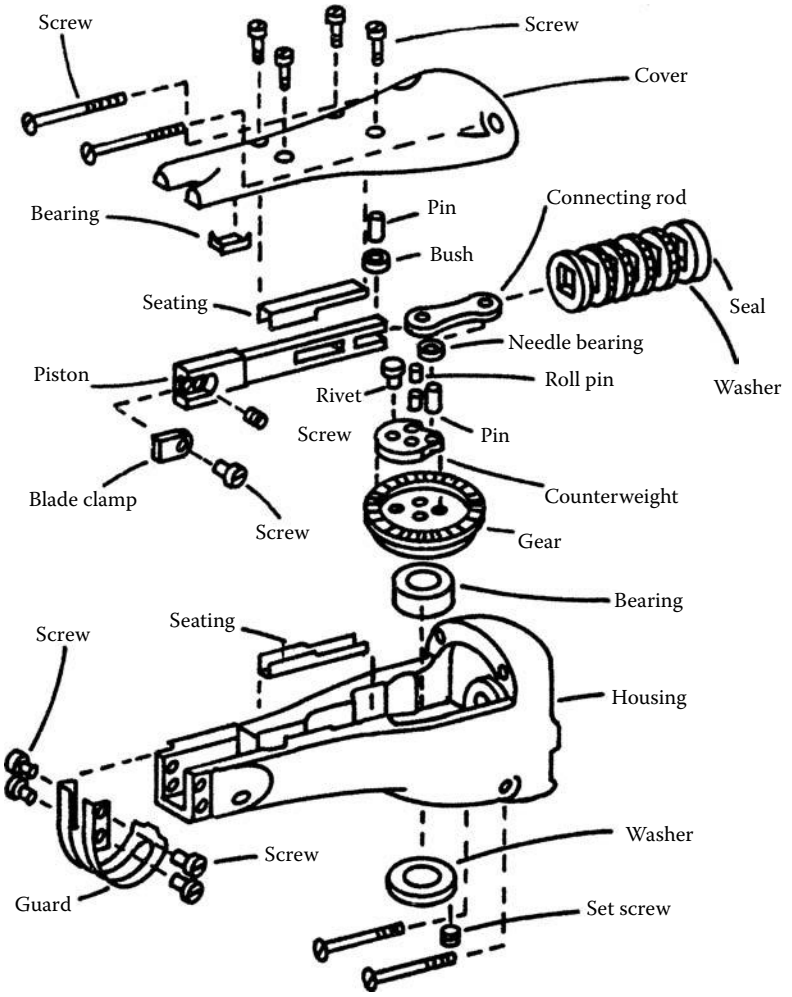


FIGURE 3.13
Power saw (initial design—41 parts, 6.37 min assembly time). (After Ellison, B. and Boothroyd, G. *Applying Design for Assembly Handbook to Reciprocating Power Saw and Impact Wrench, Report No. 10*, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, August 1980.)

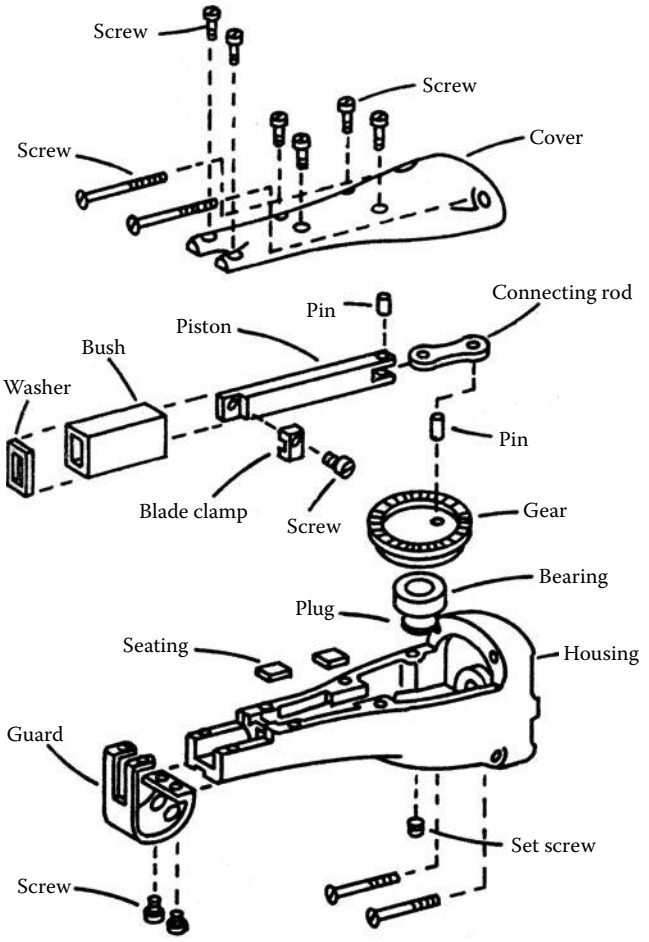


FIGURE 3.14
Power saw (new design—29 parts, 2.58 min assembly time). (After Ellison, B. and Boothroyd, G. *Applying Design for Assembly Handbook to Reciprocating Power Saw and Impact Wrench, Report No. 10*, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, August 1980.)

assembly time, a significant reduction in parts count, and an anticipated improvement in product performance.

3.4 Assembly Efficiency

An essential ingredient of the DFA method is the use of a measure of the DFA index or "assembly efficiency" of a proposed design. In general, the two main factors that influence the assembly cost of a product or subassembly are:

- The number of parts in a product
- The ease of handling, insertion, and fastening of the parts

The DFA index is a figure obtained by dividing the theoretical minimum assembly time by the actual assembly time. The equation for calculating the DFA index E_{ma} is

$$E_{ma} = \frac{N_{min} t_a}{t_{ma}} \tag{3.1}$$

where N_{min} is the theoretical minimum number of parts, t_a is the basic assembly time for one part, and t_{ma} is the estimated time to complete the assembly of the product. The basic assembly time is the average time for a part that presents no handling, insertion, or fastening difficulties (about 3 s).

The figure for the theoretical minimum number of parts represents an ideal situation where separate parts are combined into a single part unless, as each part is added to the assembly, one of the following criteria is met:

1. During the normal operating mode of the product, the part moves relative to all other parts already assembled. (Small motions do not qualify when they can be obtained through the use of elastic hinges.)
2. The part must be of a different material, or be isolated from all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
3. The part must be separate from all other assembled parts; otherwise, the assembly of parts meeting one of the preceding criteria would be prevented.

It should be pointed out that these criteria are to be applied without taking into account the general design or service requirements. For example, separate fasteners do not generally meet any of the preceding criteria and should always be considered for elimination. To be more specific, the designer considering the design of an automobile engine may feel that the bolts holding the cylinder head onto the engine block are necessary separate parts. However, they could be eliminated by combining the cylinder head with the block—an approach that has proved practical in certain circumstances.

If applied properly, these criteria require the designer to consider means whereby the product can be simplified, and it is through this process that enormous improvements in assemblability and manufacturing costs are often achieved. However, it is also necessary to be able to quantify the effects of changes in design schemes. For this purpose, the DFA method incorporates a system for estimating the assembly cost which, together with estimates of parts cost, gives the designer the information needed to take appropriate trade-off decisions.

3.5 Classification Systems

The classification system for assembly processes is a systematic arrangement of part features that affect the acquisition, movement, orientation, insertion, and fastening of the part together with some operations that are not associated with specific parts such as turning the assembly over.

The complete classification system, its associated definitions, and the corresponding time standards is presented in tables in Figures 3.15 and 3.16. It can be seen that the classification

MANUAL HANDLING-ESTIMATED TIMES (s)

Key: One hand

			Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
			Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
			Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand without the aid of grasping tools	(α+β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	360° ≤ (α+β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	540° ≤ (α+β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	(α+β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

One hand with grasping aids

			Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
			Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
			Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
			Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
			0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	α ≤ 180°	0 ≤ β ≤ 180°	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		β = 360°	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	α = 360°	α ≤ β ≤ 180°	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		β = 360°	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

Two hands for manipulation

			Parts present no additional handling difficulties					Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
			α ≤ 180°			α = 360°		α ≤ 180°			α = 360°	
			Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)		8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

Two hands or assistance required for large size

			Parts can be handled by one person without mechanical assistance									
			Parts do not severely nest or tangle and are not flexible								Parts severely nest or tangle or are flexible (2)	Two persons or mechanical assistance required for parts manipulation
			Part weight < 10 lb				Parts are heavy (>10 lb)					
			Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)			
			α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°		
			0	1	2	3	4	5	6	7	8	9
Two hands, two persons or mechanical assistance required for grasping and transporting parts		9	2	3	2	3	3	4	4	5	7	9

Notes:

1. Parts can present handling difficulties if they nest or tangle, sick together because of magnetic force or grease coating, and so on, are slippery, or require careful handling. Parts that nest or tangle are those that interlock when in bulk but can be separated by one simple manipulation of a single part; for example, taper cups, closed-end helical springs, circlips, and so on. Parts that are slippery are those that easily slip from fingers or standard grasping tool because of their shape and/or surface condition. Parts that require careful handling are those that are fragile or delicate, have sharp corners or edges, or present other hazards to the operator.
2. Parts that nest or tangle severely are those parts that interlock when in bulk and both hands are needed to apply a separation force or achieve specific orientation of inter-locking parts to achieve separation. Flexible parts are those that substantially deform during manipulation and necessitate the use of two hands. Examples of such parts are large paper or felt gaskets, rubber bands or belts, and so on.

FIGURE 3.15
Original classification system for part features affecting manual handling time. (Copyright 1999 Boothroyd Dewhurst, Inc. With permission.)

MANUAL INSERTION-ESTIMATED TIMES (s)

Key:

Part added but not secured

Part secured immediately

Separate operation

			Alter assembly no holding down required to maintain orientation and location (3)				Holding down required during subsequent processes to maintain orientation at location (3)			
			Easy to align and position during assembly (4)		Not easy to align or position during assembly		Easy to align and position during assembly (4)		Not easy to align or position during assembly	
			No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)
			0	1	2	3	6	7	8	9
Addition of any part (1) where neither the part itself nor any other part is finally secured immediately	Part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
		1	4	5	5	6	8	9	9	10
	Part and associated tool (including hands) cannot easily reach the desired location	Due to obstructed access or restricted vision (2)	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5
		Due to obstructed access and restricted vision (2)								

			No screwing operation or plastic deformation immediately after insertion (snap/press fits,circlips,spire nuts,etc.)		Plastic deformation immediately after insertion						Screw tightening immediately after insertion	
					Plastic bending or torsion			Riveting or similar operation				
					Easy to align and position during assembly (4)	Not easy to align or position during assembly		Easy to align and position during assembly (4)	Not easy to align or position during assembly			
			Easy to align and position with no resistance to insertion (4)	Not easy to align or position during assembly and/or resistance to insertion (5)		No resistance to insertion	Resistance to insertion (5)		No resistance to insertion	Resistance to insertion (5)	Easy to align and position with no torsional resistance (4)	Not easy to align or position and/or torsional resistance (5)
			0	1	2	3	4	5	6	7	8	9
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately	Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
	Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily	Due to obstructed accessor restricted vision (2)	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
		Due to obstructed access and restricted vision (2)	6	9	8	9	10	11	12	13	10	12

			Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-fastening processes	
			None or localized plastic deformation			Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	Metallurgical processes			Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of part(s), etc.)	Other processes (e.g. liquid insertion, etc.)
			Bending or similar process	Riveting or similar processes	Screw tightening or other processes		No additional material required (e.g. resistance, friction welding, etc.)	Additional material required				
								Soldering processes	Weld/braze processes			
			0	1	2	3	4	5	6	7	8	8
Assembly processes where all solid parts are in place		9	4	7	5	12	7	8	12	12	9	12

Notes:

1. A part is the solid of nonsolid element of an assembly during an assembly process. A subassembly is considered a part if it is added during assembly. However, adhesives, fluxes, fillers, and so on, used for joining parts are not considered to be parts.
2. Obstructed access means that the space available for the assembly operation causes a significant increase in the assembly time. Restricted vision means that the operator has to rely mainly on tactile sensing during the assembly process.
3. Holding down required means that the part is unstable after placement or insertion or during subsequent operations and will require griping, realignment, or holding down before it is finally secured. Holding down refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to, or during the next assembly operation. A part is located if it will not require holding down or realignment for subsequent operations and is only partially secured.
4. A part is easy to align and position if the position of the part is established by locating features on the part or on its mating part and insertion is facilitated by well designed chamfers or similar features.
5. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For example, a press fit is an interference fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

FIGURE 3.16

Original classification system for part features affecting insertion and fastening. (Copyright 1999 Boothroyd Dewhurst, Inc. With permission.)

numbers consist of two digits; the first digit identifies the row and the second digit identifies the column in the table.

The portion of the classification system for manual insertion and fastening processes is concerned with the interaction between mating parts as they are assembled. Manual insertion and fastening consists of a finite variety of basic assembly tasks (peg-in-hole, screw, weld, rivet, press-fit, etc.) that are common to most manufactured products.

It can be seen that for each two-digit code number, an average time is given. Thus, we have a set of time standards that can be used to estimate manual assembly times. These time standards were obtained from numerous experiments, some of which will now be described.

Definitions

For Figure 3.15:

Alpha is the rotational symmetry of a part about an axis perpendicular to its axis of insertion. For parts with one axis of insertion, end-to-end orientation is necessary when alpha equals 360°, otherwise alpha equals 180°.

Beta is the rotational symmetry of a part about its axis of insertion. The magnitude of rotational symmetry is the smallest angle through which the part can be rotated and repeat its orientation. For a cylinder inserted into a circular hole, beta equals zero.

Thickness is the length of the shortest side of the smallest rectangular prism that encloses the part. However, if the part is cylindrical, or has a regular polygonal cross-section with five or more sides, and the diameter is less than the length, then thickness is defined as the radius of the smallest cylinder which can enclose the part.

Size is the length of the longest side of the smallest rectangular prism that can enclose the part.

For Figure 3.16:

Holding down required means that the part will require gripping, realignment, or holding down before it is finally secured.

Easy to align and position means that insertion is facilitated by well-designed chamfers or similar features.

Obstructed access means that the space available for the assembly operation causes a significant increase in the assembly time.

Restricted vision means that the operator has to rely mainly on tactile sensing during the assembly process.

3.6 Effect of Part Symmetry on Handling Time

One of the principal geometrical design features that affects the time required to grasp and orient a part is its symmetry. Assembly operations always involve at least two component parts: the part to be inserted and the part or assembly (receptacle) into which the part is inserted [15]. Orientation involves a proper alignment of the part to be inserted relative to the corresponding receptacle and can always be divided into two distinct operations: (1)

alignment of the axis of the part that corresponds to the axis of insertion, and (2) rotation of the part about this axis.

It is therefore convenient to define two kinds of symmetry for a part:

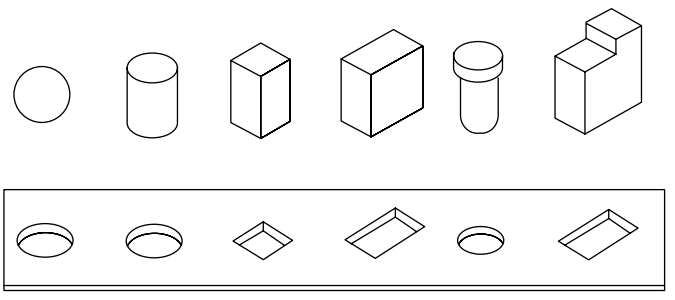
1. *Alpha Symmetry*: Depends on the angle through which a part must be rotated about an axis perpendicular to the axis of insertion to repeat its orientation.
2. *Beta Symmetry*: Depends on the angle through which a part must be rotated about the axis of insertion to repeat its orientation.

For example, a plain square prism that is to be inserted into a square hole would first have to be rotated about an axis perpendicular to the insertion axis. Since, with such a rotation, the prism repeats its orientation every 180°, it can be termed 180° alpha symmetry. The square prism would then have to be rotated about the axis of insertion, and since the orientation of the prism about this axis would repeat every 90°, this implies a 90° beta symmetry. However, if the square prism were to be inserted in a circular hole, it would have 180° alpha symmetry and 0° beta symmetry. Figure 3.17 gives examples of the symmetry of simple-shaped parts.

A variety of predetermined time standard systems are presently used to establish assembly times in the industry. In the development of these systems, several different approaches have been employed to determine relationships between the amount of rotation required to orient a part and the time required to perform that rotation. Two of the most commonly used systems are the methods time measurement (MTM) and work factor (WF) systems.

In the MTM system, the "maximum possible orientation" is employed, which is one-half the beta rotational symmetry of a part mentioned above [16]. The effect of alpha symmetry is not considered in this system. For practical purposes, the MTM system classifies the maximum possible orientation into three groups, namely, (1) symmetric, (2) semisymmetric, and (3) nonsymmetric [3]; again, these terms refer only to the beta symmetry of a part.

In the WF system, the symmetry of a part is classified by the ratio of the number of ways the part can be inserted to the number of ways the part can be grasped preparatory to insertion [17]. In the example of a square prism to be inserted into a square hole, one par-



α	0	180	180	90	360	360
β	0	0	90	180	0	360

FIGURE 3.17
Alpha and beta rotational symmetries for various parts.

ticular end first, it can be inserted in four ways out of the eight ways it could be suitably grasped. Hence, on the average, one-half of the parts grasped would require orientation, and this is defined in the WF system as a situation requiring 50% orientation [17]. Thus, in this system, account is taken of alpha symmetry, and some account is taken of beta symmetry. Unfortunately, these effects are combined in such a way that the classification can only be applied to a limited range of part shapes.

Numerous attempts were made to find a single parameter that would give a satisfactory relation between the symmetry of a part and the time required for orientation. It was found that the simplest and most useful parameter was the sum of the alpha and beta symmetries [5]. This parameter, which would be termed the total angle of symmetry, is therefore given by

$$\text{Total angle of symmetry} = \text{alpha} + \text{beta}. \tag{3.2}$$

The effect of the total angle of symmetry on the time required to handle (grasp, move, orient, and place) a part is shown in Figure 3.18. In addition, the shaded areas indicate the values of the total angle of symmetry that cannot exist. It is evident from these results that the symmetry of a part can be conveniently classified into five groups. However, the first group, which represents a sphere, is not generally of practical interest; therefore, four groups are suggested that are employed in the coding system for part handling (Figure 3.15). A comparison of these experimental results with the MTM and WF orientation parameters show that these parameters do not account properly for the symmetry of a part [5].

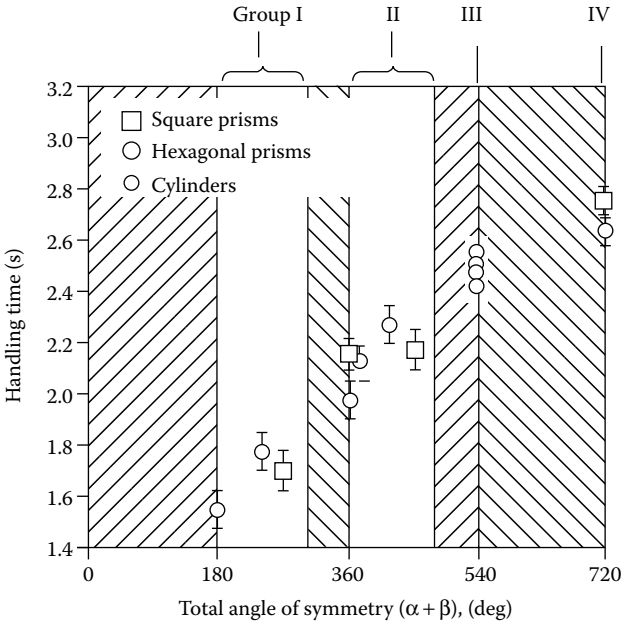


FIGURE 3.18
Effect of symmetry on the time required for part handling. Times are average for two individuals and shaded areas represent nonexistent values of the total angle of symmetry.

3.7 Effect of Part Thickness and Size on Handling Time

Two other major factors that affect the time required for handling during manual assembly are the thickness and size of the part. The thickness and size of a part are defined in a convenient way in the WF system, and these definitions have been adopted for the DFA method. The thickness of a "cylindrical" part is defined as its radius, whereas for noncylindrical parts the thickness is defined as the maximum height of the part with its smallest dimension extending from a flat surface (Figure 3.19). Cylindrical parts are defined as parts having cylindrical or other regular cross-sections with five or more sides. When the diameter of such a part is greater than or equal to its length, the part is treated as noncylindrical. The reason for this distinction between cylindrical and noncylindrical parts when defining thickness is illustrated by the experimental curves shown in Figure 3.19. It can be seen that parts with a "thickness" greater than 2 mm present no grasping or handling problems. However, for long cylindrical parts, this critical value would have occurred at a value of 4 mm had a diameter been used for the "thickness." Intuitively, we see that grasping a long cylinder 4 mm in diameter is equivalent to grasping a rectangular part of 2 mm thickness if each is placed on a flat surface.

The size (also called the major dimension) of a part is defined as the largest nondiagonal dimension of the part's outline when projected on a flat surface. It is normally the length of the part. The effects of part size on handling time are shown in Figure 3.20. Parts can be divided into four size categories as illustrated. Large parts involve little or no variation in handling time with changes in their size; the handling time for medium and small parts displays progressively greater sensitivity with respect to part size. Since the time penalty involved in handling very small parts is large and very sensitive to decreasing part size, tweezers are usually required to manipulate such parts. In general, tweezers can be assumed to be necessary when the size is less than 2 mm.

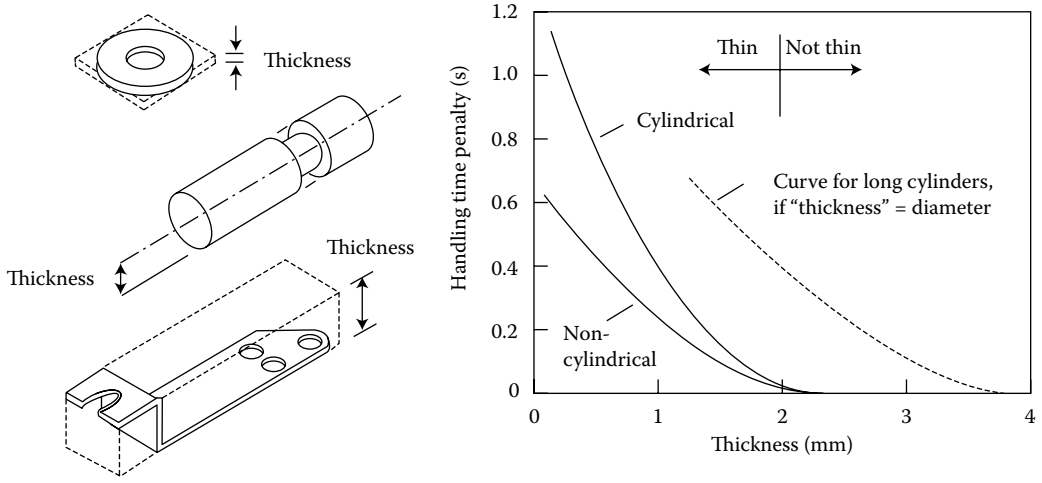


FIGURE 3.19
Effect of part thickness on handling time.

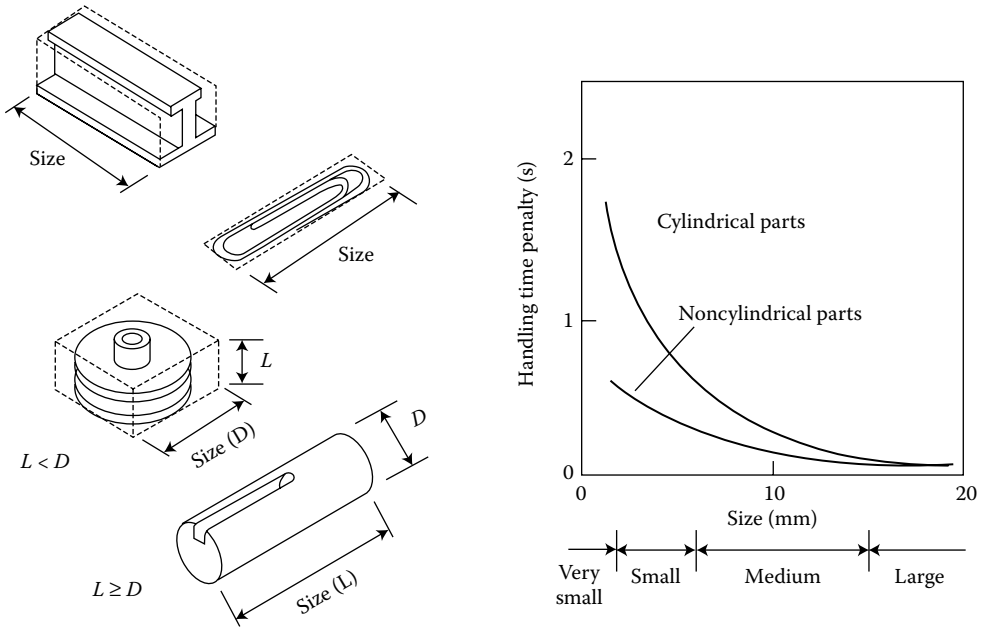


FIGURE 3.20
Effect of part size on handling time.

3.8 Effect of Weight on Handling Time

Work has been carried out [18] on the effects of weight on the grasping, controlling, and moving of parts. The effect of increasing weight on grasping and controlling is found to be an additive time penalty and the effect on moving is found to be a proportional increase of the basic time. For the effect of weight on a part handled using one hand, the total adjustment t_{pw} to handling time can be represented by the following equation [3]:

$$t_{pw} = 0.0125W + 0.011Wt_h \tag{3.3}$$

where W (lb) is the weight of the part and t_h (s) is the basic time for handling a "light" part when no orientation is needed and when it is to be moved by a short distance. An average value for t_h is 1.13, and therefore the total time penalty due to weight would be approximately $0.025W$.

If we assume that the maximum weight of a part to be handled using one hand is around 10–20 lb, the maximum penalty for weight is 0.25–0.5 s and is a fairly small correction. It should be noted, however, that Equation 3.3 does not take into account the fact that larger parts are usually moved greater distances, resulting in more significant time penalties. These factors are discussed later.

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3.9 Parts Requiring Two Hands for Manipulation

A part may require two hands for manipulation when:

- The part is heavy.
- Very precise or careful handling is required.
- The part is large or flexible.
- The part does not possess holding features, thus making one-hand grasp difficult.

Under these circumstances, a penalty is applied, because the second hand could be engaged in another operation—perhaps grasping another part. Experience shows that a penalty factor of 1.5 should be applied in these cases.

3.10 Effects of Combinations of Factors

In the previous sections, various factors that affect manual handling times have been considered. However, it is important to realize that the penalties associated with each individual factor are not necessarily additive. For example, if a part requires additional time to move it from A to B, it can probably be oriented during the move. Therefore, it may be wrong to add the extra time for part size and an extra time for orientation to the basic handling time. The following gives some examples of results obtained when multiple factors are present.

3.11 Effect of Symmetry for Parts That Severely Nest or Tangle and May Require Tweezers for Grasping and Manipulation

A part may require tweezers when (Figure 3.21):

- Its thickness is so small that finger-grasp is difficult.
- Vision is obscured and prepositioning is difficult because of its small size.
- Touching it is undesirable, for example, because of high temperature.
- Fingers cannot access the desired location.

A part is considered to nest or tangle severely when an additional handling time of 1.5 s or greater is required due to these factors. In general, two hands will be required to separate severely nested or tangled parts. Helical springs with open ends and widely spaced coils are examples of parts that severely nest or tangle. Figure 3.22 shows how the time required for orientation is affected by the alpha and beta angles of symmetry for parts that nest or tangle severely and may require tweezers for handling.

In general, orientation using hands results in a smaller time penalty than orientation using tweezers, therefore factors necessitating the use of tweezers should be avoided if possible.

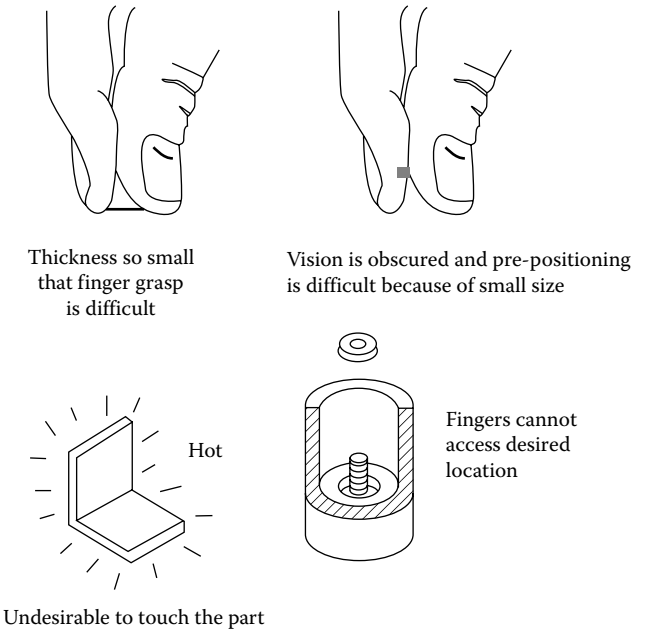

FIGURE 3.21
Examples of parts that may require tweezers for handling.

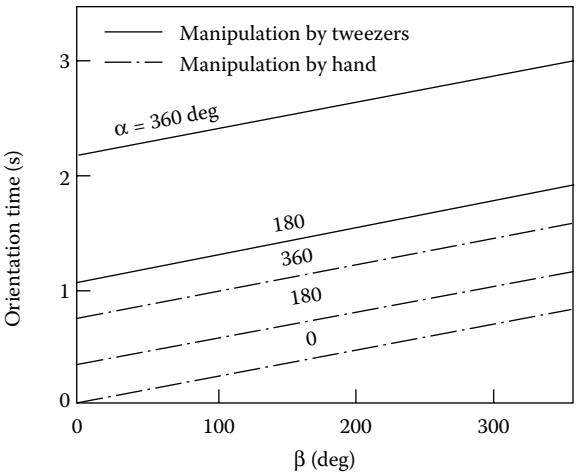

FIGURE 3.22
Effect of symmetry on handling time when parts nest or tangle severely. (Disentangling time is not included.)

3.12 Effect of Chamfer Design on Insertion Operations

Two common assembly operations are the insertion of a peg (or shaft) into a hole and the placement of a part with a hole onto a peg. The geometries of traditional conical chamfer designs are shown in Figure 3.23. In Figure 3.23a, which shows the design of a chamfered

peg, d is the diameter of the peg, w_1 is the width of the chamfer, and θ_1, is the semiconical angle of the chamfer. In Figure 3.23b, which shows the design of a chamfered hole, D is the diameter of the hole, w_2 is the width of the chamfer, and θ_2 is the semiconical angle of the chamfer. The dimensionless diametral clearance c between the peg and the hole is given by

$$\frac{(D-d)}{D}. \tag{3.4}$$

A typical set of results [9] showing the effects of various chamfer designs on the time taken to insert a peg in a hole are presented in Figure 3.24. From these and other results, the following conclusions are drawn:

1. For a given clearance, the difference in the insertion time for two different chamfer designs is always a constant.
2. A chamfer on the peg is more effective in reducing the insertion time than the same chamfer on the hole.
3. The maximum width of the chamfer that is effective in reducing the insertion time for both the peg and the hole is approximately $0.1D$.
4. For conical chamfers, the most effective design provides chamfers on both the peg and the hole, with $w_1 = w_2 = 0.1D$ and $\theta_1 = \theta_2 < 45$.
5. The manual insertion time is not sensitive to variations in the angle of the chamfer for the range $10 < \theta < 50$.
6. A radiused or curved chamfer can have advantages over a conical chamfer for small clearances.

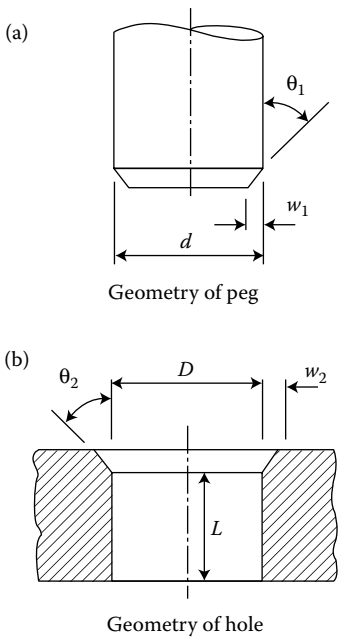

FIGURE 3.23
Geometries of peg and hole.

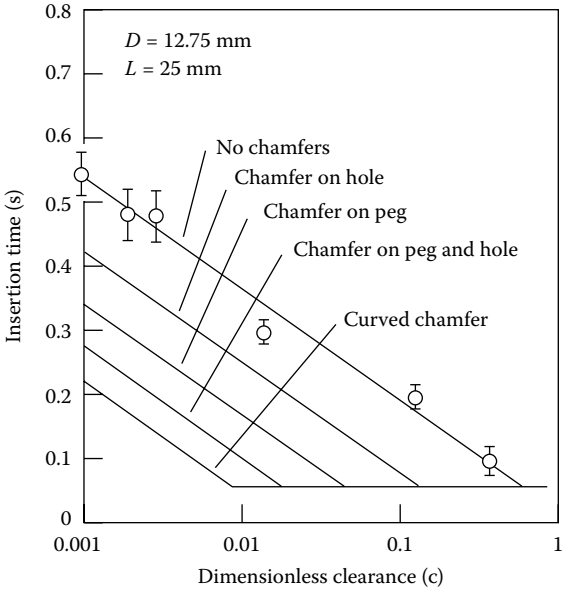

FIGURE 3.24
Effect of clearance on insertion time. (After Ho, C. and Boothroyd, G. *Design of chamfers for ease of assembly*, *Proceedings of the 7th North American Metalworking Conference*, May 1979, p. 345.) (For clarity, experimental results are shown for only one case.)

It was learned from the peg insertion experiments [9] that the long manual insertion time for the peg and hole with a small clearance is probably due to the type of engagement occurring between the peg and the hole during the initial stages of insertion. Figure 3.25 shows two possible situations that cause difficulties. In Figure 3.25a, the two points of contact

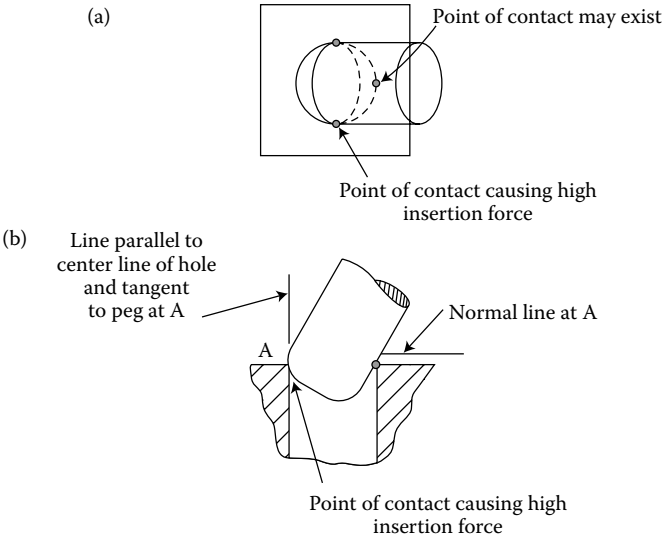

FIGURE 3.25
Points of contact on chamfer and hole.

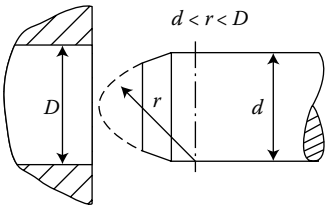

FIGURE 3.26
Chamfer of constant width.

arising on the same circular cross-section of the peg give rise to forces resisting the insertion. In Figure 3.25b, the peg is jammed at the entrance of the hole. An analysis was carried out to find a geometry that would avoid these unwanted situations. It showed that a chamfer conforming to a body of constant width (Figure 3.26) is one of the designs having the desired properties. It was found that for such a chamfer, the insertion time is independent of the dimensionless clearance c in the range $c > 0.001$. Therefore, the curved chamfer is the optimum design for peg-in-hole insertion operations (Figure 3.24). However, since the manufacturing costs for curved chamfers would normally be greater than for conical chamfers, the modified chamfer would only be worthy of consideration for very small values of clearance when the significant reductions in insertion time might compensate for the higher cost. An interesting example of a curved chamfer is the geometry of a bullet. Its design not only has aerodynamic advantages, but is also ideal for the ease of insertion.

3.13 Estimation of Insertion Time

Empirical equations have been derived [9] to estimate the manual insertion time t_i for both conical chamfers and curved chamfers. For conical chamfers (Figure 3.23), where the width of 45° chamfers is $0.1d$, the manual insertion time for a plain cylindrical peg t_i is given by

$$t_i = -70 \ln c + f(\text{chamfers}) + 3.7L + 0.75d \text{ ms} \tag{3.5}$$

or

$$t_i = 1.4L + 15 \text{ ms} \tag{3.6}$$

whichever is larger, and where

$$\begin{aligned} f(\text{chamfers}) = &-100 \text{ (no chamfer)} \\ &- 220 \text{ (chamfer on hole)} \\ &- 250 \text{ (chamfer on peg)} \\ &- 370 \text{ (chamfer on peg and hole).} \end{aligned} \tag{3.7}$$

For modified curved chamfers (Figure 3.26) the insertion time is given by

$$t_i = 1.4L + 1.5. \tag{3.8}$$

EXAMPLE

$D = 20$ mm, $d = 19.5$ mm, and $L = 75$ mm. There are chamfers on both the peg and hole. From Equation 3.4:

$$c = \frac{(20 - 19.5)}{20} = 0.025$$

From Equation 3.5:

$$t_i = -70 \ln (0.025) - 370 + 3.7(75) + 0.75(19.5)$$
$$= 181 \text{ ms}$$

From Equation 3.6:

$$t_i = 120 \text{ ms}$$

3.14 Avoiding Jams during Assembly

Parts with holes that must be assembled onto a peg can easily get jammed if they are not dimensioned carefully. This problem is typical of assembling a washer on a bolt. In analyzing a part assembled on a peg [7], the hole diameter can be taken to be one unit; all other length dimensions are then measured relative to this unit and are dimensionless (Figure 3.27). The peg diameter is $1 - c$, where c is the dimensionless diametral clearance between the two mating parts. The resultant force applied to the part during the assembly operation is denoted by P. The line of action of P intercepts the x-axis at e, 0. If the following equation is satisfied, the part slides freely down the peg:

$$P \cos\theta > \mu(N_1 + N_2) \tag{3.9}$$

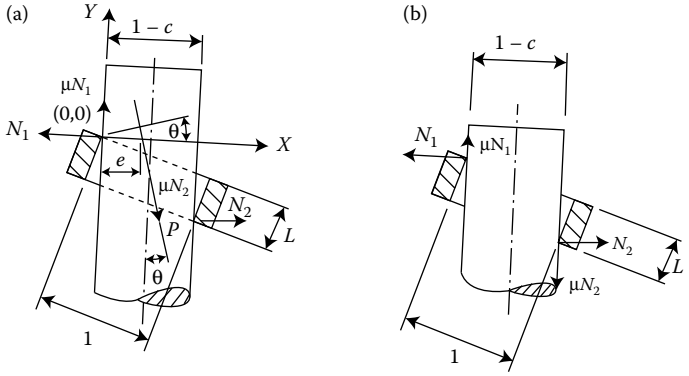

FIGURE 3.27
Geometry of part and peg.

By resolving forces horizontally

$$P\sin\theta + N_2 - N_1 = 0 \tag{3.10}$$

and by taking moments about (0, 0)

$$\{[1 + L^2 - (1-c)^2]^{1/2} + \mu(1-c)\}N_2 - eP\cos\theta = 0. \tag{3.11}$$

From Equations 3.9 through 3.11:

$$\left(\frac{2\mu e}{q-1}\right)\cos\theta + \theta\sin\theta < 0 \tag{3.12}$$

where

$$q = [1 + L^2 - (1-c)^2]^{1/2} + \mu(1-c)$$

Thus, when $e = 0$ and $\cos\theta > 0$, the condition

$$\tan\theta < \frac{1}{\mu} \tag{3.13}$$

ensures free sliding. If $e = 0$ and $\cos\theta < 0$, then the condition becomes

$$\tan\theta > \frac{1}{\mu}. \tag{3.14}$$

In the case when $\theta = 0$ (the assembly force is applied vertically), Equation 3.12 yields

$$2\mu e < q \tag{3.15}$$

or

$$e = \frac{m(1-c)}{2} \tag{3.16}$$

where m is a positive number. Substituting Equation 3.16 into Equation 3.15 gives

$$1 + L^2 > (1-c)^2[\mu^2(m-1)^2 + 1]. \tag{3.17}$$

When $m = 1$, the force is applied along the axis of the peg. Because $(1 + L^2)$ must always be larger than $(1 - c)^2$, the parts never jam under these circumstances.

Even if the part jams, a change in the line of action of the force applied frees the part. However, it is also necessary to consider whether the part can be rotated and wedged on the peg. If the net moment of the reaction forces at the contact points is in the direction that rotates the part from the wedged position, then the part frees itself. Thus, for the part to free itself when released

$$1 + L^2 > (1 - c)^2(\mu^2 + 1) \tag{3.18}$$

Comparing Equation 3.17 with Equation 3.18, shows that the condition for the part to wedge without freeing itself occurs when $m = 2$ in Equation 3.17.

3.15 Reducing Disc-Assembly Problems

When an assembly operation calls for the insertion of a disc-shaped part into a hole, jamming or hang-up is a common problem. Special handling equipment can prevent jams but a simpler, less-costly solution is to analyze all part dimensions carefully before production begins.

Again, the diameter of the hole is one unit; all other dimensions are measured relative to this unit and are dimensionless (Figure 3.28). The disc diameter is 1–c, where c is the dimensionless diametral clearance between the mating parts, P is the resultant force in the assembly operation, and μ is the coefficient of friction. When a disc with no chamfer is inserted into a hole, the condition for free sliding can be determined by

$$L^2 > \mu^2 + 2c - c^2 \tag{3.19}$$

If c is very small, then Equation 3.19 can be expressed as

$$L > \mu + \frac{c}{\mu} \tag{3.20}$$

If the disc is very thin, that is, if

$$(1 - c)^2 + L^2 < 1 \tag{3.21}$$

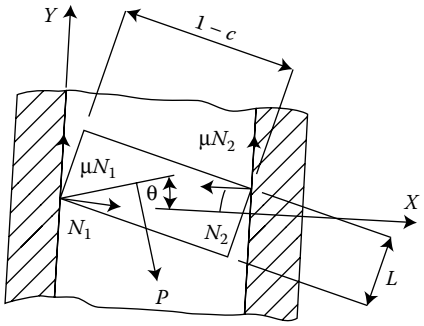

FIGURE 3.28
Geometry of disc and hole.

the disc can be inserted into the hole by keeping its circular cross-section parallel to the wall of the hole and reorienting it when it reaches the bottom of the hole.

3.16 Effects of Obstructed Access and Restricted Vision on Insertion of Threaded Fasteners of Various Designs

Considerable experimental work has been conducted on the time taken to insert threaded fasteners of different types under a variety of conditions. Considering first the time taken to insert a machine screw and engage the threads, Figure 3.29a shows the effects of the shape of the screw point and hole entrance, when the assembly worker cannot see the operation

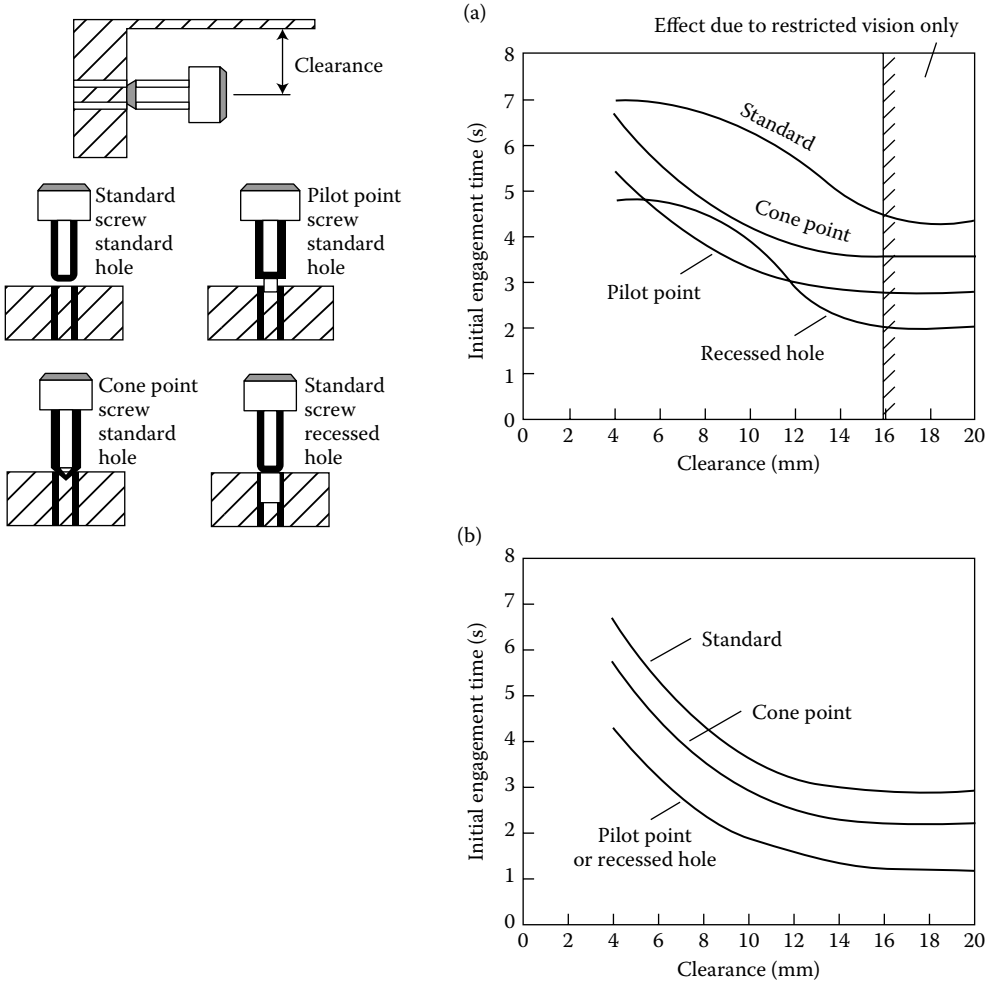

FIGURE 3.29
Effects of restricted access and restricted vision on the initial engagement of screws. (a) Restricted access and restricted vision; (b) restricted access only.

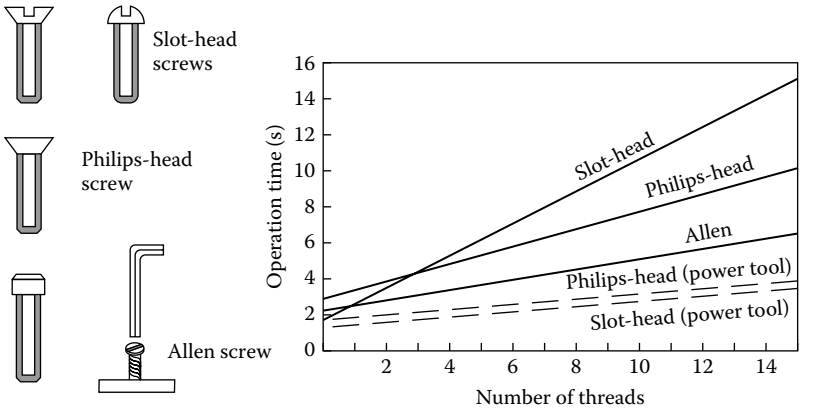

FIGURE 3.30
Effect of number of threads on time to pick up the tool, engage the screw, tighten the screw, and replace the tool.

and when various levels of obstruction are present. When the distance from the obstructing surface to the hole center is greater than 16 mm, the surface has no effect on the manipulations and the restriction of vision is the only factor. Under these circumstances, the standard screw inserted into a recessed hole gives the shortest time. For a standard screw with a standard hole, an additional 2.5 s is required. When the hole is closer to the wall, thereby inhibiting the manipulations, a further time of 2 or 3 s is necessary.

Figure 3.29b shows the results obtained under similar conditions but when vision was not restricted. A comparison with the previous results indicates that the restriction of vision had little effect when access was obstructed. This was because the proximity of the obstructing surface allows tactile sensing to take the place of sight. However, when the obstruction was removed, restricted vision accounts for up to 1.5 s additional time.

Once the screw threads are engaged, the assembly worker must grasp the necessary tool, engage it with the screw, and perform sufficient rotations to tighten the screw. Figure 3.30 shows the total time for these operations for a variety of screw head designs and for both hand-operated and power tools. There is no restriction on tool operation for any of these situations. Finally, Figure 3.31 shows the time to turn down a nut using a variety of hand-operated tools and where the operation of the tools is obstructed to various degrees. It can be seen that the penalties for a box-end wrench are as high as 4 s per revolution when obstructions are present. However, when considering the design of a new product, the designer will not normally consider the type of tool used and can reasonably expect that the best tool for the job would be selected. In the present case, this would be either the nut driver or the socket ratchet wrench.

3.17 Effects of Obstructed Access and Restricted Vision on Pop-Riveting Operations

Figure 3.32 summarizes the results of experiments [10] on the time taken to perform pop-riveting operations. In the experiments, the average time taken to pick up the tool, change the rivet, move the tool to the correct location, insert the rivet, and return the tool to its

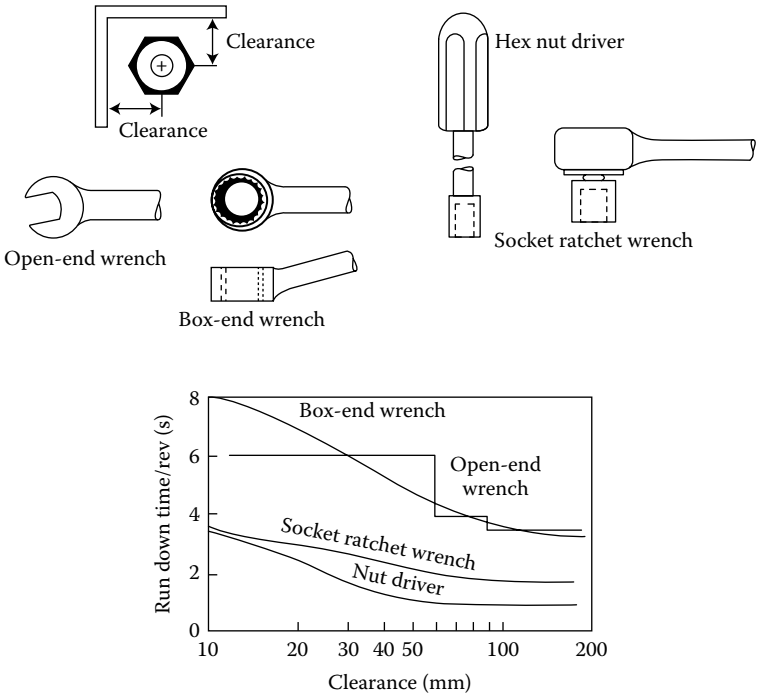

FIGURE 3.31
Effect of obstructed access on the time to tighten a nut.

original location is 7.3 s. In Figure 3.32a the combined effects of obstructed access and restricted vision are summarized, and Figure 3.32b shows the effects of obstructed access alone. In the latter case, time penalties of up to 1 s can be incurred although, unless the clearances are quite small, the penalties are negligible. With restricted vision present, much higher penalties, on the order of 2–3 s, are obtained.

3.18 Effects of Holding Down

Holding down is required when parts are unstable after insertion or during subsequent operations. It is defined as a process that, if necessary, maintains the position and orientation of parts already in place prior to or during subsequent operations. The time taken to insert a peg vertically through holes in two or more stacked parts can be expressed as the sum of a basic time t_b and a time penalty t_p. The basic time is the time to insert the peg when the parts are prealigned and self-locating, as shown in Figure 3.33a and can be expressed [11] as follows:

$$t_b = -0.07 \ln c - 0.1 + 3.7L + 0.75d_g \tag{3.22}$$

where

$c = (D - d)/D$ and is the dimensionless clearance ($0.1 \geq c \geq 0.0001$),

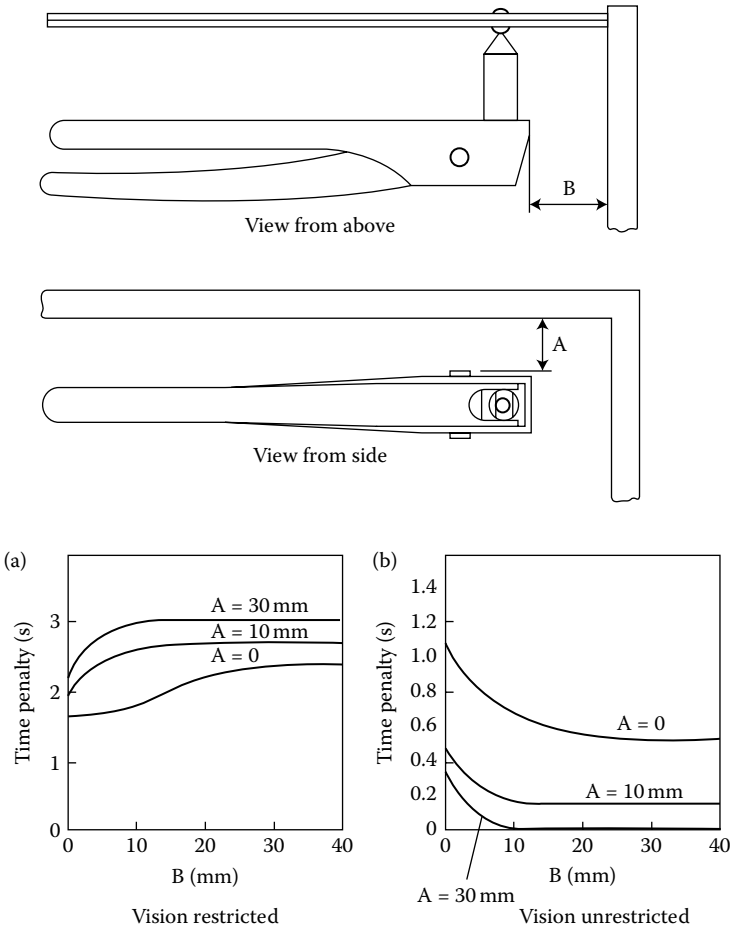

FIGURE 3.32
Effects of obstructed access and restricted vision on the time to insert a pop-rivet. (After Fujita, T., and Boothroyd, G. *Data Sheets and Case Study for Manual Assembly, Report No. 16*, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, April 1982.)

L = the insertion depth in meters,
d_g = the grip size in meters ($0.1\ \text{m} \geq d_g \geq 0.01\ \text{m}$).

EXAMPLE

$D = 20$ mm, $d = 19.6$ mm, $c = (D - \text{d})/D = (20 - 19.6)/20 = 0.02$, $L = 100$ mm $= 0.10$ m, $d_g = 40$ mm $= 0.04$ m, then

$$t_b = -0.07 \ln c - 0.1 + 3.7L + 0.75d_g$$
$$= -0.07 \ln 0.02 - 0.1 + 3.7 \times 0.10 + 0.75 \times 0.04$$
$$= 0.27 - 0.1 + 0.37 + 0.03$$
$$= 0.57 \text{ s}$$

The graphs presented in Figures 3.33 and 3.34 allow the time penalty t_p to be determined for three conditions:

- When easy-to-align parts are aligned and require holding down (Figure 3.33b)
- When difficult-to-align parts are aligned and require holding down (Figure 3.33c)
- When difficult-to-align parts require alignment and holding down (Figure 3.34)

For the example given above, where $t_b = 0.57$ s, the time penalty $t_p = 0.1$ s for the conditions of Figure 3.33b, the time penalty $t_p = 0.15$ s for the conditions of Figure 3.33c, and $t_p = 3$ s for the conditions of Figure 3.34.

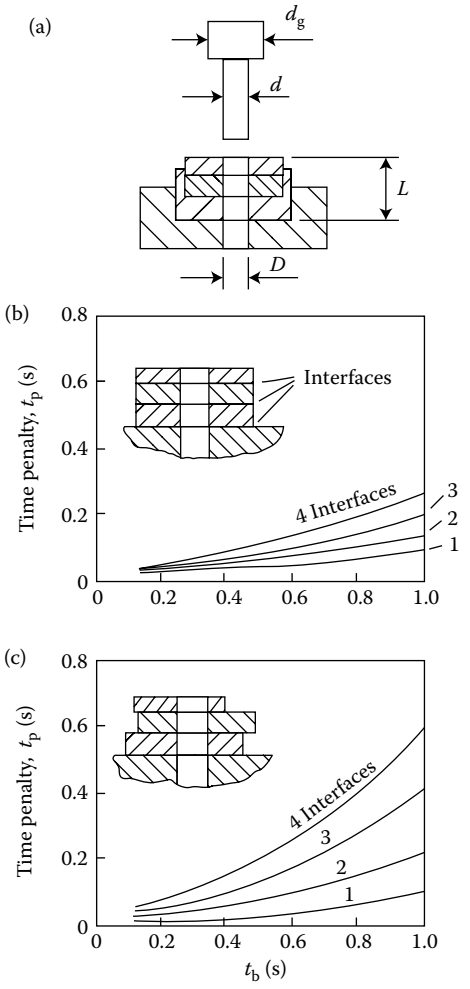

FIGURE 3.33
Effects of holding down on insertion time. (a) Parts self-locating and pre-aligned; (b) easy-to-align parts; and (c) not easy-to-align parts. (After Yang, S.C. and Boothroyd, G. *Data Sheets and Case Study for Manual Assembly, Report No. 15*, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, December 1981.)

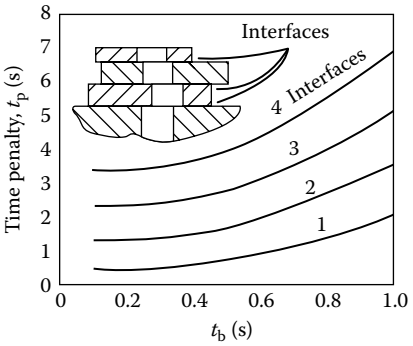

FIGURE 3.34
Effects of holding down and realignment on insertion time for difficult-to-align parts. (After Yang, S.C. and Boothroyd, G. *Data Sheets and Case Study for Manual Assembly, Report No. 15*, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, December 1981.)

3.19 Manual Assembly Database and Design Data Sheets

The preceding sections present a selection of the results of some of the analyses and experiments conducted during the development of the DFA method. For the development of the classification schemes and time standards presented earlier, it is necessary to obtain an estimate of the average time, in seconds, to complete the operation for all the parts falling within each classification or category. For example, the uppermost left-hand box in Figure 3.15 (code 00) gives 1.13 for the average time to grasp, orient, and move a part

- That can be grasped and manipulated with one hand
- Has a total symmetry angle of less than 360° (a plain cylinder, for example)
- Is larger than 15 mm
- Has a thickness greater than 2 mm
- Has no handling difficulties, such as flexibility, tendency to tangle or nest, and so on

Clearly, a wide range of parts fall within this category and their handling times somewhat vary. The figure presented is only an average time for the range of parts.

To illustrate the type of problem that can arise through the use of the group technology coding or classification scheme employed in the DFA method, we can consider the assembly of a part having a thickness of 1.9 mm. We shall assume that, except for its thickness of less than 2 mm, the part would be classified as code 00 (Figure 3.15). However, because of the part's thickness, the appropriate code would be 02 and the estimated handling time would be 1.69 s instead of 1.13 s, representing a time penalty of 0.56 s. Turning now to the results of experiments for the effect of thickness (Figure 3.19), it can be seen that for a cylindrical part the actual time penalty is of the order of only 0.01–0.02 s. We would therefore expect an error in our results of about 50%. Under normal circumstances, experience has shown that these errors tend to cancel—with some parts, the error results in an overestimation of time and with some results in underestimation. However, if an assembly contains a large number of identical parts, care must be taken to check whether the part

characteristics fall close to the limits of the classification; if they do, then the detailed results presented above can be consulted.

3.20 Application of the DFA Methodology

To illustrate how DFA is applied in practice, we shall consider the controller assembly shown in Figure 3.35. The assembly of this product first involves securing a series of assemblies to the metal frame using screws, connecting these assemblies together in various ways, and then securing the resulting assembly into the plastic cover, again using screws. An undesirable feature of the design of the plastic cover is that the small subassemblies must be fastened to the metal frame before the metal frame can be secured to the plastic cover.

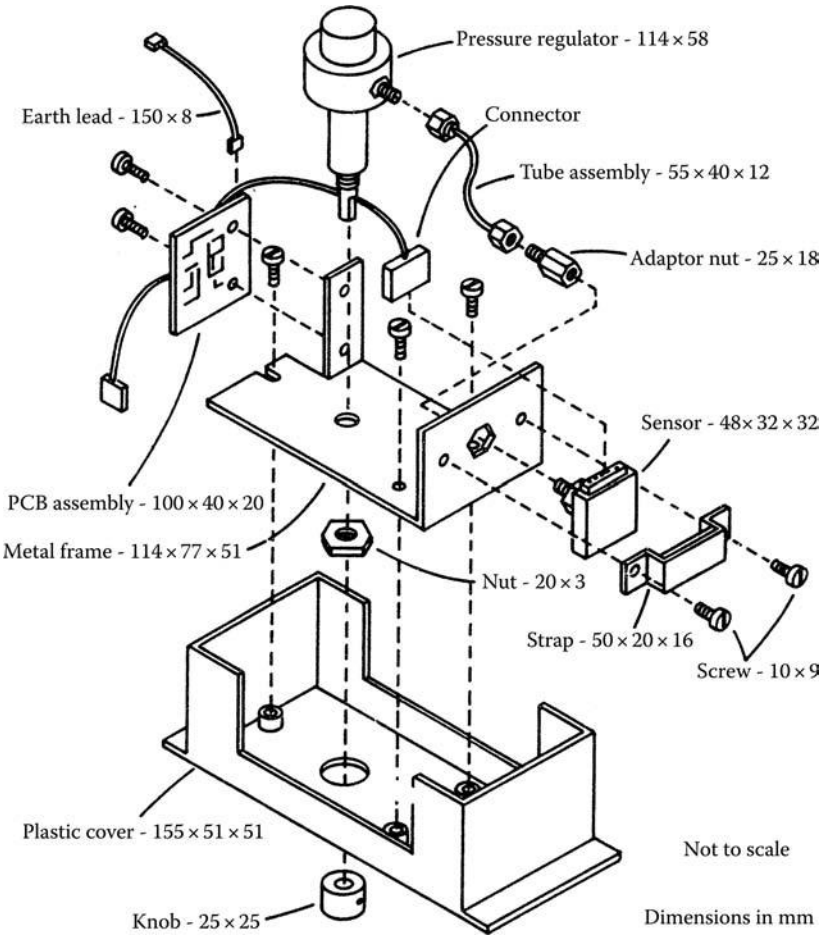

FIGURE 3.35
Controller assembly.

Figure 3.36 shows a completed worksheet analysis for the controller in the form of a tabulated list of operations and the corresponding assembly time and cost. Each assembly operation is divided into handling and insertion, and the corresponding time and two-digit code numbers for each process are given. The assembly starts by placing the pressure regulator (a purchased item) upside-down into a fixture. The metal frame is placed onto the projecting spindle of the pressure regulator and secured with the nut. The resulting assembly is then turned over in the fixture to allow the addition of other items to the metal frame.

Next, the sensor and the strap are placed and held in position while two screws are installed. Clearly, the holding of these two parts and the difficulty of the screw insertions impose time penalties on the assembly process.

After tape is applied to the thread on the sensor, the adaptor nut can be screwed into place. Then, one end of the tube assembly is screwed to the threaded extension on the pressure regulator and the other end to the adaptor nut. Clearly, both of these are difficult and time-consuming operations.

The printed circuit board (PCB) assembly is now positioned and held in place while two screws are installed, after which its connector is snapped into the sensor and the earth lead is snapped into place.

The whole assembly must be turned over once again to allow the positioning and holding of the knob assembly while the screw-fastening operation can be carried out. Finally, the plastic cover is placed in position and the entire assembly is turned over for the third time to allow the three screws to be inserted. It should be noted that access for the insertion of these screws is very restricted.

It is clear from this description of the assembly sequence that many aspects of the design could be improved. However, a step-by-step analysis of each operation is necessary before changes to simplify the product structure and reduce assembly difficulties can be identified and quantified. First, we shall look at how the handling and insertion times are established. The addition of the strap will be considered by way of an example. This operation is the sixth item on the worksheet and the line of information is completed as follows:

NUMBER OF ITEMS, RP

There is one strap.

HANDLING CODE

The insertion axis for the strap is horizontal in Figure 3.35 and the strap can only be inserted one way along this axis, and so the alpha angle of symmetry is 360°. If the strap is rotated about the axis of insertion, it repeats its orientation every 180°, which is, therefore, the beta angle of symmetry. Thus, the total angle of symmetry is 540°. Referring to the database for handling time (Figure 3.15), since the strap can be grasped and manipulated using one hand without the aid of tools and alpha plus beta is 540°, the first digit of the handling code is 2. The strap presents no handling difficulties (can be grasped and separated from bulk easily), its thickness is greater than 2 mm, and its size is greater than 15 mm; therefore, the second digit is 0 giving a handling code of 20.

HANDLING TIME PER ITEM, TH

A handling time of 1.8 s corresponds to a handling code of 20 (Figure 3.15).

Item name	Number of items	Manual handling code	Handling time per item, s	Manaual insertion code	Insertion time per item, s	Total operation time, s	Figures for min. parts	Description
1. Pressure regulator	1	30	1.95	00	1.50	3.45	1	Place in fixture
2. Metal frame	1	30	1.95	06	5.50	7.45	1	Add
3. Nut	1	00	1.13	36	8.00	9.13	0	Add and screw fasten
4. Reorientation	1			98	9.00	9.00		Reorient and adjust
5. Sensor	1	30	1.95	08	6.50	8.45	1	Add
6. Strap	1	20	1.80	08	6.50	8.30	0	Add and hold down
7. Screw	2	11	1.80	39	8.00	19.60	0	Add amd screw fasten
8. Apply tape	1			99	12.00	12.00		Operation
9. Adapter nut	1	10	1.50	49	10.50	12.00	0	Add and screw fasten
10. Tube assembly	1	91	3.00	10	4.00	7.00	0	Add and screw fasten
11. Screw fastening	1			92	5.00	5.00		Operation
12. PCB assembly	1	83	5.60	08	6.50	12.10	1	Add and hold down
13. Screw	2	11	1.80	39	8.00	19.60	0	Add and screw fasten
14. Connector	1	30	1.95	31	5.00	6.95	0	Add and snap fit
15. Earth lead	1	83	5.60	31	5.00	10.60	0	Add and snap fit
16. Reorientation	1			98	9.00	9.00		Reorient and adjust
17. Knob assembly	1	30	1.95	08	6.50	8.45	1	Add and screw fasten
18. Screw fastening	1			92	5.00	5.00		Operation
19. Plastic cover	1	30	1.95	08	6.50	8.45	0	Add and hold down
20. Reorientation	1			98	9.00	9.00		Reorient and adjust
21. Screw	3	11	1.80	49	10.50	36.90	0	Add and screw fasten
Totals	**25**					**227.43**	**5**	

FIGURE 3.36
Completed worksheet analysis for the controller assembly.

INSERTION CODE

The strap is not secured as part of the insertion process and since there is no restriction to access or vision, the first digit of the insertion code is 0 (Figure 3.16). Holding down is necessary while subsequent operations are carried out, and the strap is not easy to align because no features are provided to facilitate alignment of the screw holes. Therefore, the second digit is 3, giving an insertion code of 03.

INSERTION TIME PER ITEM, TI

An insertion time of 5.2 s corresponds to an insertion code of 03 (Figure 3.16).

TOTAL OPERATION TIME

This is the sum of the handling and insertion times multiplied by the number of items plus tool acquisition time (TA) if necessary, that is, TA + RP(TH + TI). For the strap, the total operation time is therefore 7.0 s.

FIGURES FOR MINIMUM PARTS

As explained earlier, the establishment of a theoretical minimum part count is a powerful way to identify possible simplifications in the product structure. For the strap, the three criteria for separate parts are applied after the pressure regulator, the metal frame, the nut, and the sensor have been assembled.

1. The strap does not move relative to these parts and so theoretically it can be combined with any of them.
2. The strap does not have to be of a different material—in fact it could be of the same plastic material as the body of the sensor and therefore take the form of two lugs with holes projecting from the body. At this point in the analysis, the designer would probably determine that since the sensor is a purchased stock item, its design could not be changed. However, it is important to ignore these economic considerations at this stage and consider only theoretical possibilities.
3. The strap clearly does not have to be separate from the sensor in order to allow the assembly of the sensor, and therefore none of the three criteria are met and the strap becomes a candidate for elimination. For the strap, a zero is placed in the column for minimum parts.

3.20.1 Results of the Analysis

Once the analysis is complete for all operations, the appropriate columns can be summed. Thus, for the controller, the total number of parts and subassemblies is 19 and there are six additional operations. The total assembly time is 206.43 s, and, for an assembly worker's rate of $30 per hr, the corresponding assembly cost is $1.72. The theoretical minimum number of parts is five.

A DFA index is now obtained using Equation 3.1. In this equation, t_a is the basic assembly (handling and insertion) time for one part and can be taken as 3 s on an average. Thus, the DFA index is

$$5 \times \frac{3}{206.43} = 0.07 \text{ or } 7\%$$

TABLE 3.1

Design Changes and Associated Savings

	Design Change	Items	Time Saving (s)
1.	Combine plastic cover with frame, eliminate three screws, and a reorientation	19, 20, 21	52.05
2.	Eliminate strap and two screws (provide snaps in plastic frame to hold sensor if necessary)	6, 7	24.1
3.	Eliminate screws holding PCB assembly (provide snaps in plastic frame)	13	17.1
4.	Eliminate two reorientations	4, 16	9.0
5.	Eliminate tube assembly and two screw fastening operations (screw adaptor nut and sensor direct to the pressure regulator)	10, 11	17.4
6.	Eliminate earth lead (not required with plastic frame)	15	8.7
7.	Eliminate connector (plug sensor into PCB)	14	5.25

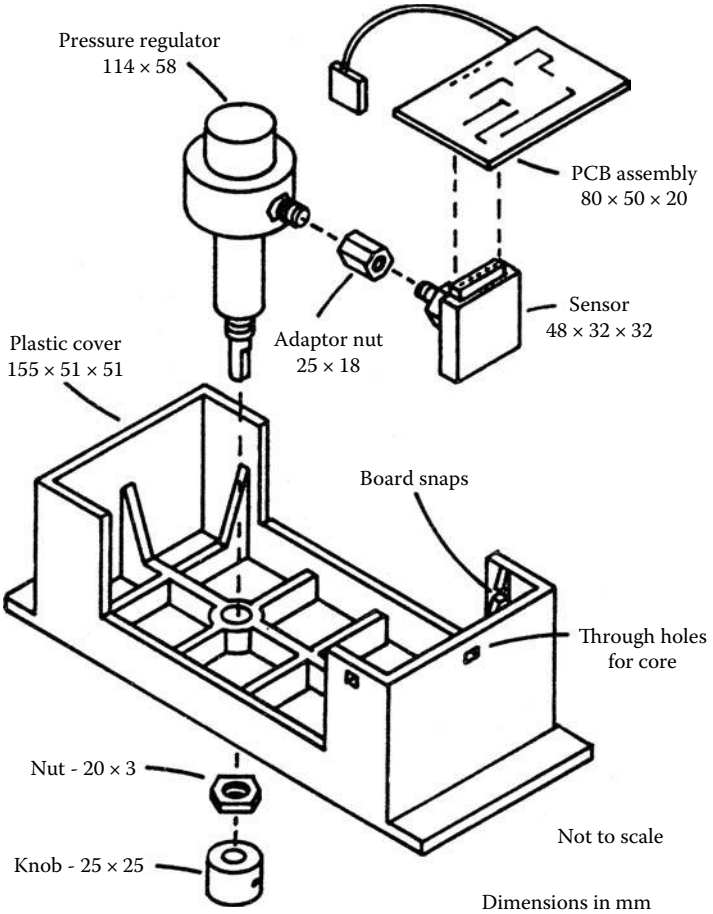

FIGURE 3.37
Conceptual redesign of the controller assembly.

Item name	Number of items	Manual handling code	Handling time per item, s	Manual insertion code	Insertion time per item, s	Total operation time, s	Figures for min. parts	Description
1. Pressure regulator	1	30	1.95	00	1.50	3.45	1	Place in fixture
2. Plastic cover	1	30	1.95	06	5.50	7.45	1	Add and hold down
3. Nut	1	00	1.13	39	8.00	9.13	0	Add and screw fasten
4. Knob assembly	1	30	1.95	08	6.50	8.45	1	Add and screw fasten
5. Screw fastening	1			92	5.00	5.00		Operation
6. Reorientation	1			98	9.00	9.00		Reorient
7. Apply tape	1			99	12.00	12.00		Operation
8. Adaptor nut	1	10	1.50	49	10.50	12.00	0	Add and screw fasten
9. Sensor sub.	1	30	1.95	39	8.00	9.90	1	Add and screw fasten
10. PCB assembly	1	83	5.60	30	2.00	7.60	1	Add and snap fit
Totals	**10**					**83.98**	**5**	

FIGURE 3.38
Completed analysis for the controller assembly redesign.

The high-cost processes should now be identified—especially those associated with the installation of parts that do not meet any of the criteria for separate parts. From the worksheet results (Figure 3.36), it can be seen that attention is clearly paid to combining the plastic cover with the metal frame. This would eliminate the assembly operation for the cover, the three screws, and the reorientation operation—representing a total time saving of 52.05 s—a figure that forms 25% of the total assembly time. Of course, the designer must check that the cost of the combined plastic cover and frame is less than the total cost of the individual items.

A summary of the items that can be identified for elimination or combination and the appropriate assembly time savings are presented in Table 3.1.

We have now identified design changes that could result in savings of 133.8 s of assembly time, which forms 65% of the total. In addition, several items of hardware would be eliminated, resulting in reduced part costs. Figure 3.37 shows a conceptual redesign of the controller in which all the proposed design changes are made, and Figure 3.38 presents the corresponding revised worksheet. The total assembly time is now 77.93 s and the assembly efficiency is increased to 19%—a fairly respectable figure for this type of assembly. Of course, the designer or design team must now consider the technical and economic consequences of the proposed designs.

First, there is the effect on the cost of the parts. However, experience shows, and this example would be no exception, that the savings from parts cost reduction would be greater than the savings in assembly costs, which in this case is $1.07. It should be realized that the documented savings in materials, manufacturing, and assembly represent direct costs. To obtain a true picture, overheads must be added and these can often amount to 200% or more. In addition, there are other savings more difficult to quantify. For example, when a part such as the metal frame is eliminated, all associated documentation—including part drawings—is also eliminated. Also, the part cannot be misassembled or fail in service—factors that lead to improved reliability, maintainability, and quality of the product. It is not surprising, therefore, that many U.S. companies have been able to report annual savings measured in millions of dollars as a result of the application of the DFA analysis method described here.

3.21 Further Design Guidelines

Some guidelines or design rules for the manual handling and insertion of parts were listed earlier. However, it is possible to identify a few more general guidelines that arise particularly from the application of the minimum parts criteria, many of which found application in the analysis of the controller.

1. *Avoid connections*: If the only purpose of a part or assembly is to connect A to B, then try to locate A and B at the same point. Figure 3.39 illustrates this guideline. Here the two connected assemblies are rearranged to provide increasing assembly and manufacturing efficiency. Also, two practical examples occurred during the analysis of the controller, when it was found that the entire tube assembly could be eliminated and that the wires from the PCB assembly to the connector were not necessary (Figure 3.35).

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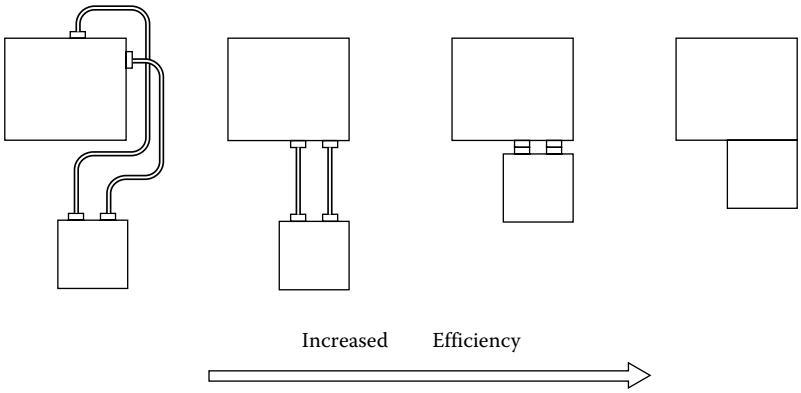

FIGURE 3.39
Rearrangement of connected items to improve assembly efficiency and reduce costs.

2. *Design so that access for assembly operations is not restricted*: Figure 3.40 shows two alternative design concepts for a small assembly. In the first concept, the installation of the screws would be very difficult because of the restricted access within the box-shaped base part. In the second concept, access is relatively unrestricted, because the assembly is built on the flat base part. An example of this type of problem occurs in the controller analysis when the screws securing the metal frame to the plastic cover are installed (item 21—Figure 3.36).
3. *Avoid adjustments*: Figure 3.41 shows two parts of different materials secured by two screws in such a way that an adjustment of the overall length of the assembly is necessary. If the assembly were replaced by one part manufactured from the more expensive material, difficult and costly operations would be avoided. The savings

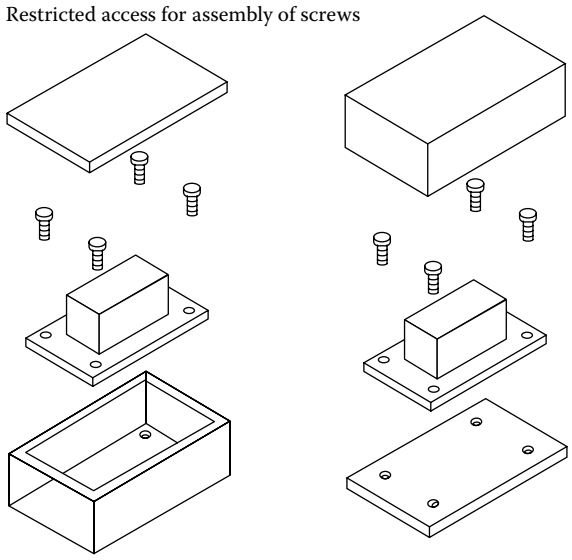

FIGURE 3.40
Design concept to provide easier access during assembly.

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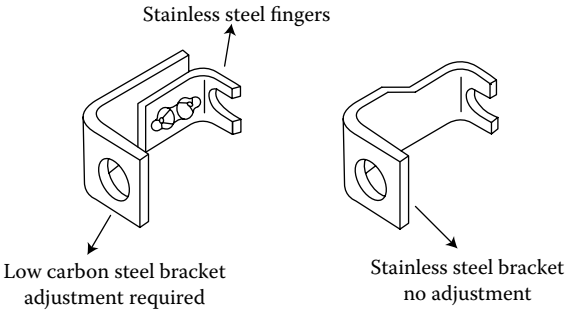

FIGURE 3.41
Design to avoid adjustment during assembly.

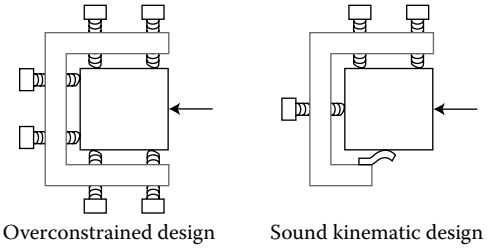

FIGURE 3.42
Showing how overconstraint leads to unnecessary complexity in product design.

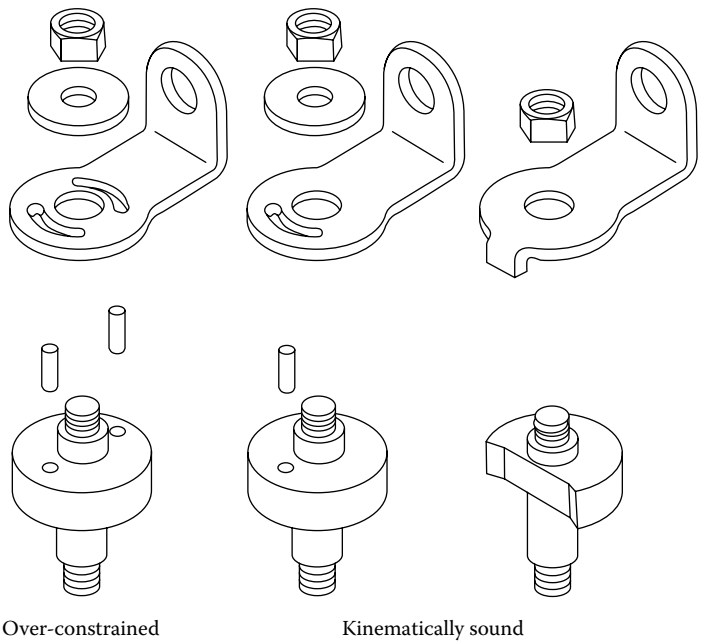

FIGURE 3.43
Showing how overconstraint leads to redundancy of parts.

from avoiding these operations would probably more than offset the increase in material costs.

4. *Use kinematic design principles*: There are many ways in which the application of kinematic design principles can reduce the manufacturing and assembly cost. Invariably, when located parts are overconstrained, it is necessary either to provide a means of adjustment of the constraining items or to employ more accurate machining operations. Figure 3.42 shows an example where to locate the square block in the plane of the page; six point constraints are used, each requiring adjustment. According to kinematic design principles, only three point constraints are needed together with closing forces. Clearly, the redesign shown in Figure 3.42 is simpler, requiring fewer parts, fewer assembly operations, and less adjustment. In many circumstances, designs where overconstraint is involved result in redundant parts. In the design involving overconstraint in Figure 3.43 one of the pins is redundant. However, application of the minimum parts criteria to the design with a single pin would suggest combining the pin with one of the major parts and combining the washer with the nut.

3.22 Large Assemblies

In the original DFA method, estimates of assembly time were based on a group technology approach in which design features of parts and products were classified into broad categories and, for each category, average handling and insertion times were established. Clearly, for any particular operation, these average times can be considerably higher or lower than the actual times. However, for assemblies containing a significant number of parts, the differences tend to cancel so that the total time is reasonably accurate. In fact, application of the DFA method in practice has shown that assembly time estimates are reasonably accurate for small assemblies in low-volume production where all the parts are within the easy arm reach of the assembly worker.

Clearly, with large assemblies, the acquisition of the individual parts from their storage locations in the assembly area involves significant additional time. Also, in mass production transfer-line situations, the data for low-volume production overestimates these times. Obviously, one database of assembly times cannot be accurate for all situations.

Let us take an example. From the DFA databases in Figures 3.15 and 3.16, the time for acquiring and inserting a standard screw, which is not easy to align, is 8.2 s. This time includes acquisition of the screw, placing it in the assembly manually with a couple of turns, acquiring the power tool, operating the tool, and then replacing it. However, in high-volume production situations, the screws are often automatically fed, and so the time is reduced to about 3.6 s per screw or, for well-designed screws, the time per screw can be less than 2 s.

The DFA method was extended to allow these possibilities, and more accurate estimates of assembly times are obtained. However, this can reduce the effectiveness of the method. In the preceding example, an analysis using the shorter time for screw insertion indicates that eliminating screws are not so advantageous in reducing the assembly time. However, it is known that simplifying the product by combining parts and eliminating separate fasteners has the greatest benefit through reductions in the parts' cost rather than through reductions in assembly cost; yet the suggestions for these improvements arise from analyses of the assembly of the product. Hence, separate fasteners should, perhaps, be

severely penalized even if they take little time to install. In fact, it can be argued that in the preceding example, where screws could be inserted quickly, special equipment was being used to solve problems arising from poor design. This is a good argument for suggesting that early DFA analyses should be carried out assuming that only standard equipment is available. Perhaps later, at the detailed-design stage, attempts can be made to improve the assembly time estimates. Clearly, accurate estimates cannot be made unless detailed descriptions of manufacturing and assembly procedures are available—a situation not present during the early stages of design when the possibilities for cost savings through improved product design are at their greatest. On the other hand, a database of assembly times suitable for small assemblies measuring only a few inches cannot be expected to give even approximate estimates for assemblies containing large parts measuring several feet. It is desirable, therefore, to have databases appropriate to those situations where the size of the product and the production conditions differ significantly. Again, it should be realized that great detail regarding the assembly work area is not generally available to the designer during the conceptual stages of design.

With these points in mind, the following sections describe an approach to the development of databases that are used to estimate the acquisition and insertion times for parts assembled into large products.

3.23 Types of Manual Assembly Methods

Part acquisition time is highly dependent on the nature of the layout of the assembly area and the method of assembly. For small parts placed within an easy reach of the assembly worker, the handling times given in Figure 3.15 are adequate if bench assembly (Figure 3.44) or multistation assembly (Figure 3.45) is employed. It is assumed in both cases that major body motions by the assembly worker are not required.

For volumes that do not justify transfer systems and if the assembly contains several parts that weigh more than about 5 lb or that are over 12 in. in size, it is not possible to place an adequate supply of parts within an easy arm's reach of the assembly worker. In this case, provided that the largest part is less than 35 in. in size and no part weighs more than 30 lb, the modular assembly center might be used (Figure 3.46). This is an arrangement of workbench and storage shelves where the parts are situated as conveniently as possible for the assembly worker. However, because turning, bending, or walking may be

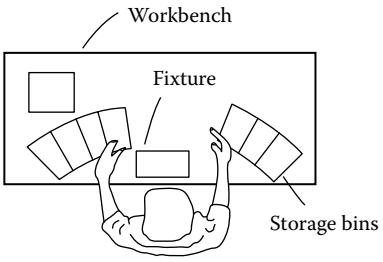

FIGURE 3.44
Bench assembly.

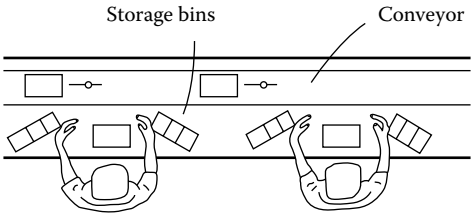

FIGURE 3.45
Multistation assembly.

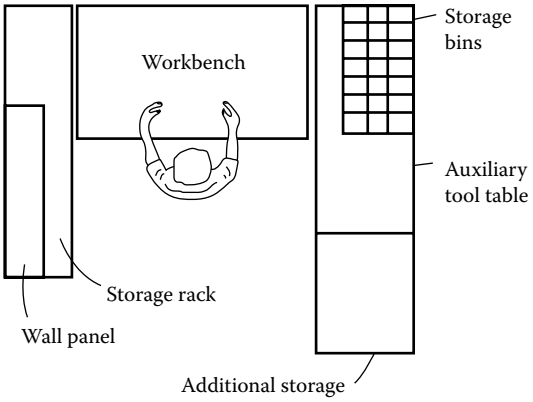

FIGURE 3.46
Modular assembly center.

necessary for the acquisition of some parts, the handling times are increased. It is convenient to identify three modular work centers to accommodate assemblies falling within three size categories where the largest part in the assembly is less than 15 in., from 15 to 25 in., and from 25 to 35 in., respectively.

For products with even larger parts, the custom assembly layout can be used. Here, the product is assembled on a worktable or on the floor and the various storage shelves and auxiliary equipment are arranged around the periphery of the assembly area (Figure 3.47). The total working area is larger than that of the modular assembly center and depends on the size category of the largest parts in the assembly. Three subcategories of the custom assembly layout are employed: for assemblies whose largest parts are from 35 to 50 in., from 50 to 65 in., and larger than 65 in.

Also, for large products a more flexible arrangement can be used; this is called the flexible assembly layout. The layout (Figure 3.48) would be similar in size to the custom assembly layout and the same three subcategories would be employed according to the size of the largest part. However, the use of mobile storage carts and tool carts make assembly more efficient.

In both the custom assembly layout and the flexible assembly layout, possibility arises that mechanical assistance in the form of cranes or hand trucks may be needed. In these cases, the working areas may need to be increased in order to accommodate the additional equipment.

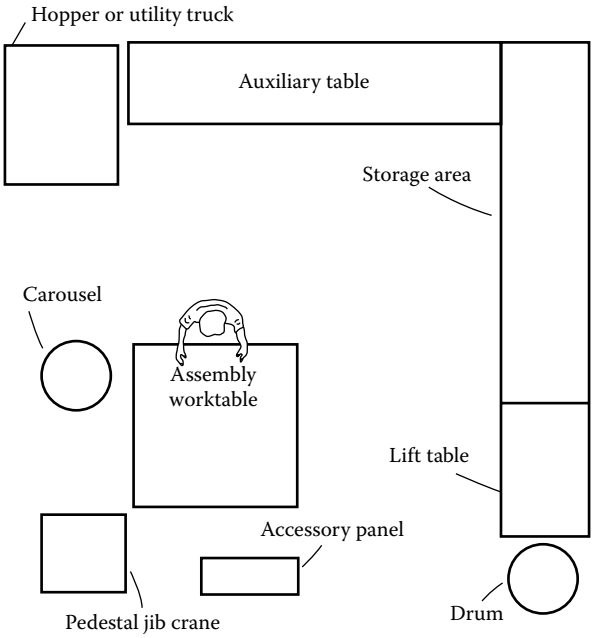

FIGURE 3.47
Custom assembly layout.

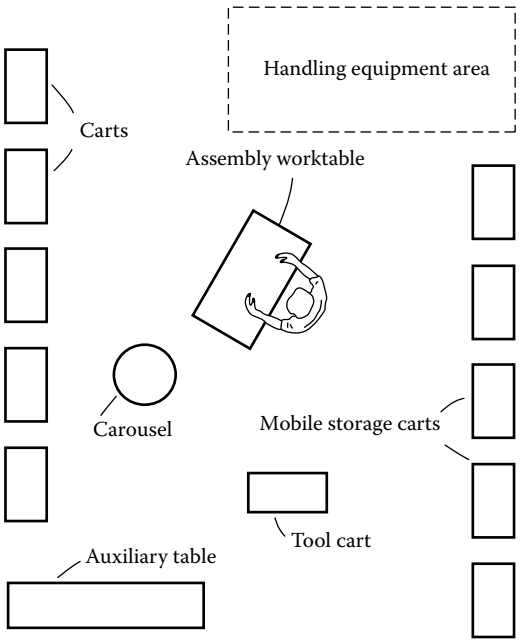

FIGURE 3.48
Flexible assembly layout.

For high-volume assembly of products containing large parts (such as in the automobile industry) transfer lines moving past manual assembly stations would be employed (Figure 3.49).

Two other manual assembly situations exist. The first is the assembly of small products with very low volumes—perhaps in a clean room. This would include the assembly of intricate and sensitive devices such as the fuel control valves for an aircraft where instructions must be read for each step and where the worker is near the beginning of the learning curve. The second is where the assembly of large products is mainly carried out on site. This type of assembly is usually termed as installation, and an example would be the assembly and installation of a passenger elevator in a multistoried building.

In any assembly situation, special equipment may be needed. For example, a positioning device is sometimes needed for positioning and aligning the part—especially prior to welding operations. In these cases, the device must be brought from storage within the assembly area, and then returned after the part is positioned and perhaps secured. Thus, the total handling time for the device is roughly twice the handling time for the part and must be taken into account if the volume to be produced is small.

Figure 3.50 summarizes the basic types of manual assembly methods described above. It can be seen that the first three methods assume only small parts are being assembled. In these cases, it can be assumed that the parts are all placed close to hand and are acquired one-at-a-time. Therefore if, say, six screws are to be inserted, there is no advantage in collecting the six screws simultaneously. However, with the assembly of products containing large parts, where small items such as fasteners may not be located within easy reach or where the assembly worker must move to various locations for the small items, there may be considerable advantage in acquiring multiple parts when needed.

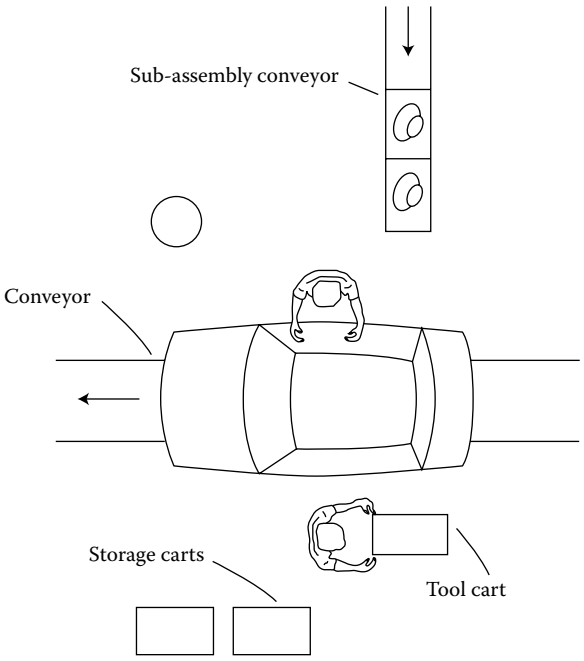

FIGURE 3.49
Multistation assembly of large products.

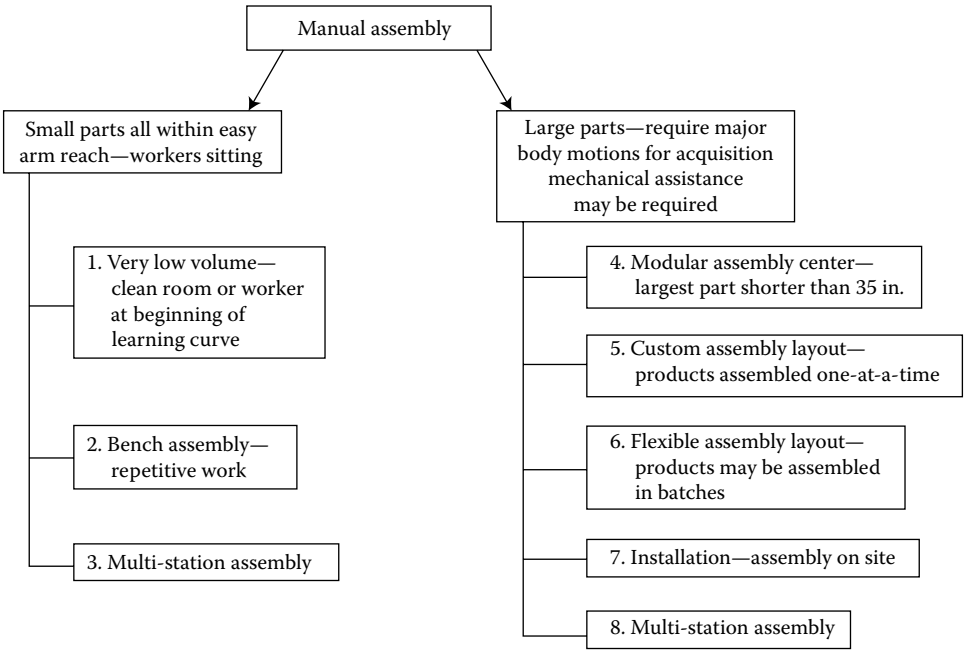

FIGURE 3.50
Manual assembly methods.

3.24 Effect of Assembly Layout on Acquisition Times

For assembly method categories, 4, 5, and 6, Figure 3.51 presents a summary of the results obtained from a thorough study of typical assembly layouts of various sizes. For each of the nine subcategories described above, a typical layout is designed using standard items such as worktables and storage racks. Then the various sizes and weights of parts are assumed to be stored at the most suitable locations. An example for the custom assembly layout is shown in Figure 3.52. Using MTM time standards [19], the times for the retrieval of parts within the various size and weight categories are then estimated [20]. Finally, the results are averaged to give the data in Figure 3.51. In addition, since it is found that the times for the custom assembly and flexible assembly layout are similar, these are combined and averaged. Thus, for example, the basic part retrieval or acquisition time for the mid-sized custom assembly layout or the mid-sized flexible assembly layout (largest part 50–65 in.) was determined to be 11.61 s.

For the effect of part weight, a correction factor can be applied, as described in an earlier section. However, the resulting correction is quite small and, therefore, it would seem feasible to divide parts into broad weight categories of, say, 0–30 lb and over 30 lb. The reason for the last category is that such parts would normally require two persons or lifting equipment for handling. Corrected values of handling time for the first weight category (0–30 lb) were obtained by assuming an average weight of 15 lb.

For the second weight category, the part requires two persons to handle. The figures for this category were obtained by estimating the time for two persons to acquire a part weighing

				one item (small or large) or multiple small parts				small part – jumbled can be grasped in multiples	
	average distance to location of parts (ft.)	size of largest part in assembly (in.)		weight < 30 lbs.		weight > 30 lbs.		additional time per part	
				easy to grasp	difficult to grasp (1)	two persons	manual crane	easy to grasp	difficult to grasp (1)
				0	**1**	**2**	**3**	**4**	**5**
Factory assembled large products (2)	<4	<15	**0**	2.54	4.54	8.82	18.42	0.84	1.11
	4 to 7	15 to 25	**1**	4.25	6.25	14.34	27.10	0.84	1.11
	7 to 10	25 to 35	**2**	5.54	7.54	18.54	31.22	0.84	1.11
	10 to 13	35 to 50	**3**	9.93	11.93	32.76	39.50	0.84	1.11
	13 to 16	50 to 65	**4**	11.61	13.61	36.75	44.93	0.84	1.11
	>16	>65	**5**	12.41	14.41	40.80	50.07	0.84	1.11

Notes: 1) For large items, no features to allow easy grasping (eg. no finger hold). For small items, those that are slippery, nested, tangled, or stuck together require careful handling are difficult to grasp.
2) Times are for acquisition only. Multiply by 2 If replacement time is to be included (eg. fixture).

FIGURE 3.51
Acquisition times (s) for items not stored within easy reach of the assembly worker. (Copyright Boothroyd Dewhurst, Inc. 1991.)

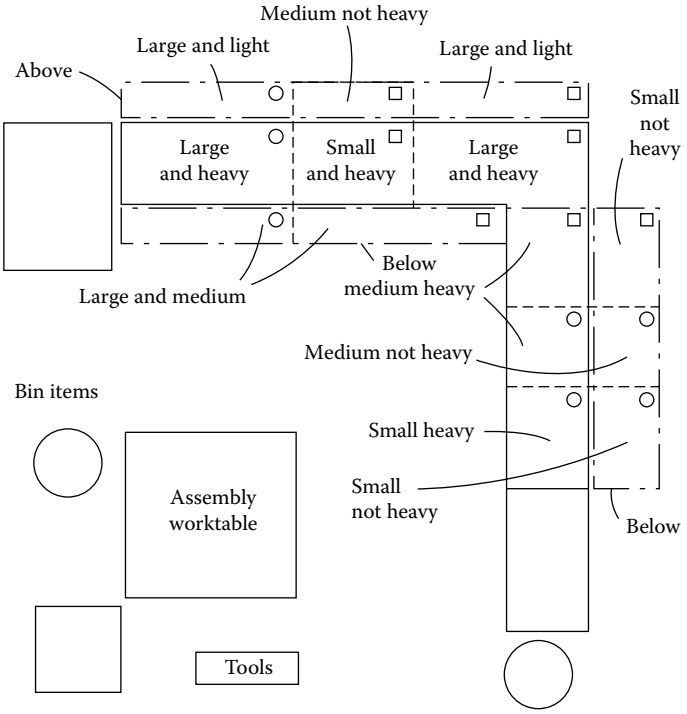

FIGURE 3.52
Assumed distribution of parts in custom assembly layout: □, low turnover; ○, high turnover.

45 lb, doubling this time, and multiplying the result by a factor of 1.5. This factor allows the fact that two persons working together typically only manage to work in coordination for 67% of their time.

For the third weight category, where lifting equipment is needed, allowance must be provided for the time taken for the worker to acquire the equipment, use it to acquire the part, move the part to the assembly, release the part, and finally return the lifting equipment to its original location. Figure 3.51 gives the estimated times for these operations, assuming that no increase in the size of the assembly area is required in order to accommodate the lifting equipment. These estimates were obtained using the MOST time standard system [21] and included the times required to acquire the equipment, move it to the part's location, hook the part, transport it to the assembly, unhook the part, and, finally, return the equipment to its original location.

For small parts, where several are required and can be grasped in one hand, it is usually advantageous to acquire all the needed parts in one trip to the storage location. Figure 3.53 presents the results of an experiment where the effect of the distance traveled by the assembly worker on the acquisition and handling time per part was studied. It can be seen that when the parts are stored out of easy arm reach, it is preferable to acquire all the parts needed in the one trip to the storage location. From results such as these, it is possible to estimate the acquisition times for the multiple acquisition of parts stored away from the assembly fixture. Figure 3.51 presents these times for each of the product size categories.

In the work [20] leading to the development of Figure 3.51, the size of the largest part in the product was assumed to determine the size and nature of the assembly area layout. However, to provide an alternative method of identifying the layout size, for each layout an average distance from the assembly to the storage location of the major parts was determined. These averages are listed in the second column in Figure 3.51 and provide an alternative method for the determination of the appropriate layout.

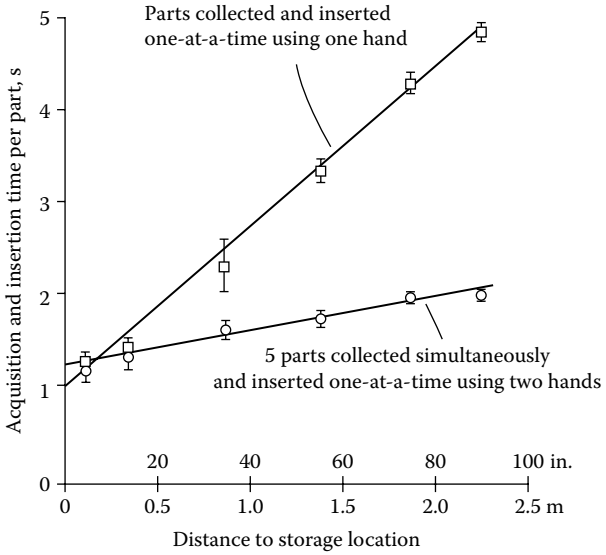

FIGURE 3.53
Effects of distance to storage location on the acquisition and assembly time for small parts.

3.25 Assembly Quality

The DFA procedures described in this chapter have been used by Motorola, Inc. since the mid-1980s. In 1991, Motorola reported the results of a DFA redesign of the motor vehicle adapter for their family of two-way professional hand-held radios [22]. Their benchmarking of competitors' electronic products indicated a best-in-class manual assembly efficiency (DFA index), as given by Equation 3.1, of 50%, and they evaluated many different concepts to reach that goal. The final design had 78% fewer parts than their previous vehicle adapter and an 87% reduction in assembly time. They also measured the assembly defect rates of the new design in production and compared the results to defect rates for the old design. The result was a 95.6% reduction in assembly defects per product. Encouraged by this result, the Motorola engineers surveyed a number of products that had been analyzed using DFA and produced a relationship between assembly defects per part and the DFA assembly efficiency values. This relationship is discussed in Chapter 1, and as illustrated in Figure 1.10 shows a strong relationship between assembly quality and the assembly efficiency value of a product.

These Motorola data were subsequently analyzed independently by other researchers [23] to produce an even more powerful relationship for use in early design evaluation. These researchers postulated that since DFA assembly time values are related to the difficulty of assembly operations, the probability of an assembly error may also be a function of the predicted assembly operation times. In the study, it was reported that 50 combinations of defect rates versus assembly characteristics were tested for meaningful correlation. Of these, the variation of average assembly defect rate per operation with average DFA time estimate per operation showed the strongest linear correlation, with correlation coefficient $r = 0.94$. The actual data are shown in Figure 3.54. The equation of the regression line is given by

$$D_i = 0.0001(t_i - 3.3) \tag{3.23}$$

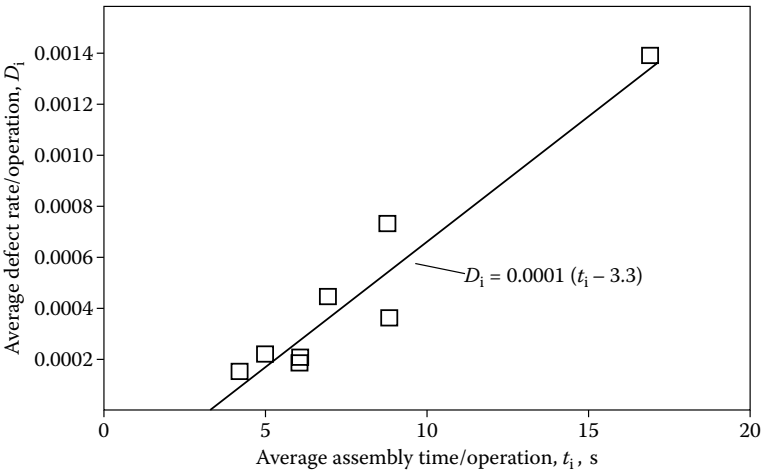

FIGURE 3.54
Relation between the assembly defect rate and average DFA assembly time. (Adapted from Barkan, P. and Hinckley, C.M. *Manufacturing Rev.*, 6(3), September 1993.)

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where
D_i = average probability of assembly defect per operation
t_i = average assembly time per operation.

As discussed earlier, the average assembly time predicted by the DFA time standard database, for parts which present no assembly difficulties, is approximately 3 s. Thus, Equation 3.23 can be interpreted as an estimated assembly defect rate of 0.0001, or 1 in 10,000, for every second of extra time associated with the difficulties of assembly. In fact, if the regression line in Figure 3.54 is constrained to pass through $t_i = 3$, then the correlation coefficient is still 0.94 to two decimal places. For this reason, we will use 3.0 instead of 3.3 in the expressions and calculations below.

For a product requiring n assembly operations, the probability of a defective product, containing one or more assembly errors, is therefore approximately

$$D_a = 1 - \left[1 - 0.0001(t_i - 3.0)\right]^n \tag{3.24}$$

Alternatively, the expected number of assembly errors in one of these products is given by

$$N_d = 0.00001(t_i - 3.0)n \tag{3.25}$$

These relationships can be applied very easily in the early stages of design to compare the likely assembly error rates of alternative design concepts for small products assembled in large quantities. This can provide powerful directional guidance for product quality improvements, since it is becoming widely accepted that faulty assembly steps, rather than defective components, are more often the reason for production quality problems [24].

For the controller assembly example discussed earlier, the existing design requires 25 operations for final assembly and has a total estimated assembly time, obtained from the DFA analysis, of 206.43 s; see Figure 3.36. The average time per operation is thus 206.43/25, equal to 8.26 s. Applying Equation 3.24 then gives

$$D_a = 1 - \left[1 - 0.0001(8.26 - 3.0)\right]^{25} = 0.0131 \tag{3.26}$$

Thus, the estimated probability of a defective assembly is 0.0131, or 1.31%.

For the redesigned controller assembly, the number of final assembly operations has been reduced to 10, and the estimated assembly time is 77.93 s; see Figure 3.38. The average time per operation is now 7.8 s, and the likely number of defective assemblies is given by

$$D_a = 1 - \left[1 - 0.0001(7.8 - 3.0)\right]^{10} = 0.0048 \tag{3.27}$$

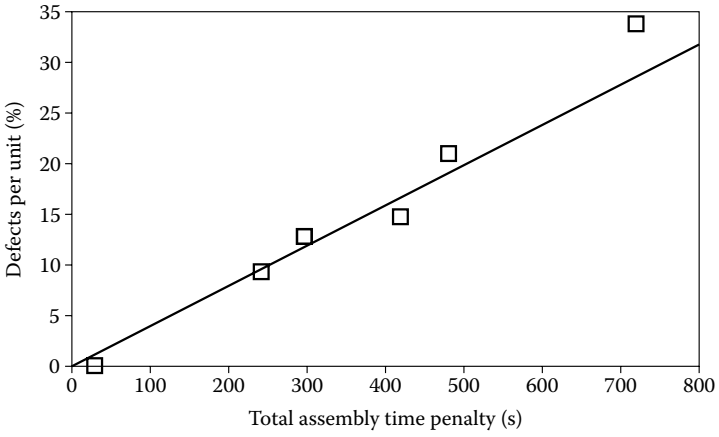

FIGURE 3.55
Relation between the total DFA assembly time penalty and assembly defect rates per unit. (Adapted from Wright, T.P. *Journal of Aeronautical Sciences*, 3, pp. 49–73, 1936.)

Thus, the predicted assembly defect rate is about one-third of that of the original design. This defect rate could be reduced further, by considering detail design improvements to further decrease the average operation time of 7.8 s.

The expression $(t_i - 3.0)n$ in Equation 3.25 can be interpreted as the total time penalty associated with the assembly of a product. For example, for the original design of the controller assembly, the 25 assembly operations would take only 75.0 s if there were no assembly difficulties. The total assembly time penalty is (8.25 – 3.0) 25, equal to 131.4 s. Equation 3.25 thus predicts that the assembly defects per unit would be proportional to the total assembly time penalty. This interpretation is supported by another set of industrial quality data illustrated in Figure 3.55. These data were obtained from a disk drive manufacturer [25], and it should be noted that one outlier with a defect rate of approximately 65% has been omitted from the figure. It should also be noted that the slope of the regression line in Figure 3.55 is approximately 0.0004. This suggests that the assembly workers make mistakes at four times the rate of those involved in building the Motorola products. This may be the result of the delicate nature of disk drive assemblies and the need to maintain very small clearances in these devices.

3.26 Applying Learning Curves to the DFA Times

The learning-curve theory applied to industrial production has its roots in early aerospace manufacturing. A now famous paper by Wright [26] resulted from the study of small aircraft construction in the 1920s and 1930s. Wright noted that as repetitive tasks are performed, improvement occurs at a diminishing rate. In particular, he noted that twice as many repetitions are required to achieve each successive constant incremental improvement. This constant improvement with doubling is embodied in a simple power law, referred to as the Wright model, which is expressed as

$$T_{1,x} = T_1 x^b \tag{3.28}$$

where
$T_{1,x}$ = average time of production for x units
T_1 = time of production for the first unit
x = number of identical units
b = the reduction exponent.

The reduction exponent can, in turn, take the general form

$$b = \frac{\log r}{\log f} \tag{3.29}$$

where
r = the average time for a factor increase in output divided by the time for the first output expressed as a percentage
f = the factor increase in output.

Normally a doubling of output is the basis for learning curve analyses, and the improvement is given as r percent. In this case, Equation 3.29 becomes

$$b = \frac{\log(r/100)}{\log 2} \tag{3.30}$$

For example, the often-quoted 90% learning curve represents the situation where the average time to produce $2x$ units is 90% of the average time taken to produce the first x of those units. From Equation 3.30 this gives

$$b = \frac{\log 0.9}{\log 2} = -0.152$$

Note that if b is known, then the learning curve percent value is given by the inverse of Equation 3.30

$$r = 2^b \ 100\% \tag{3.31}$$

Other forms of the learning curve have been proposed and used since the work of Wright; see Refs. [27,28]. In particular, in cases where the times for producing successive individual units are of primary interest, a more appropriate model may be represented by

$$T_x = T_1 x^c \tag{3.32}$$

where
T_x = time to produce the xth unit
x = number of identical units
c = "individual" reduction exponent.

This alternative model is attributed to Crawford [29], whose work was carried out for Lockheed Aircraft Corporation. For batch assembly work, the Wright model is more appropriate and will be used below to calculate learning-curve adjustments to predict assembly times.

The reduction exponent represents the improvements that would be expected as the worker "learns" to operate more efficiently through repetitive identical tasks. However, Equation 3.28 can be viewed in a much broader sense as a progress function that models progress accomplished through improved process techniques, tools, and training methods, as well as the learning associated with repetitions of the same task [30]. In these situations, a learning-curve percentage value of 85 is more appropriate than the 90% value typically used to model worker performance improvement only [27].

The learning-curve equations described above can be used to adjust DFA times for situations in which only a few assemblies are to be produced. To carry out this adjustment, the number of task repetitions, for which the DFA times apply, must first be established. Since the handling and insertion experiments used to obtain the DFA times were mainly based on 100 task repetitions, this number will be used as the basis for the example calculations below. In other words, it will be assumed that DFA times are equivalent to $T_{1,100}$ times on the appropriate learning curve. We can thus make learning-curve transformations, using the Wright model, as follows:

$$T_{1,100} = T_1 100^b \tag{3.33}$$

or

$$T_1 = \frac{T_{1,100}}{100^b} \tag{3.34}$$

Thus, for the first assembly of a small batch B of products, the average time is given by the Wright model as

$$T_{1,B} = T_1 B^h \tag{3.35}$$

Finally, substituting from Equation 3.34 for T_1 gives

$$T_{1,B} = T_{1,100}\left(\frac{B}{100}\right)^b \tag{3.36}$$

where

b = reduction exponent
$T_{1,B}$ = adjusted DFA time for batch size B
B = total batch to be assembled
$T_{1,100}$ = assumed basic DFA time value.

EXAMPLE

A set of only five measuring instruments is to be produced. A DFA analysis shows an estimated assembly time given by T_A. Using a 90% learning curve, provide an estimate for the average time to build the first two units. Use this value to determine the average time to assemble the next three units. Assume that the DFA time estimate would apply well for the average assembly time of 100 units.

a. Substituting T_A for $T_{1,100}$ in Equation 3.36 and using $b = -0.152$ for a 90% learning curve gives

$$T_{1,2} = (2/100)^{-0.152} T_A = 1.81 T_A \tag{3.37}$$

b. The predicted assembly time for all five units is given by

$$5 \times T_{1,2} = 5\left(5/100\right)^{-0.152} T_A = 7.88 T_A \tag{3.38}$$

Similarly, the total time for the first two units is

$$2 \times T_{1,2} = 2\left(2/100\right)^{-0.152} T_A = 3.62 T_A \tag{3.39}$$

Thus, the average time for units 3, 4, and 5 can be given by

$$T_{3,5} = \frac{(7.88 - 3.62)T_A}{3} = 1.42 T_A \tag{3.40}$$

PROBLEMS

1. Estimate the manual assembly time and design efficiency of the piston assembly shown in Figure 3.56. Suggest a redesign of this assembly to reduce the number of parts and increase the assembly efficiency. Estimate the manual assembly time and design efficiency of the redesigned assembly. The assembly sequence of the piston assembly is as follows:
   a. The base is placed in a fixture.
   b. The piston is inserted into the base. The piston must be carefully aligned, because the piston rod does not engage the hole in the bottom of the base before it must be released.
   c. The piston stop is inserted into the cylinder.
   d. The spring is inserted into the cylinder and tangles severely with others in bulk.
   e. The cover is placed onto the base and held in place to maintain alignment.
   f. The two screws are inserted and driven home to secure the cover.
2. Estimate the manual assembly time and design efficiency for the shaft assembly shown in Figure 3.57. The assembly procedure is as follows:
   a. The retainer bush is placed in the work fixture.
   b. The shaft is inserted into the bush.
   c. The securing screw is inserted into the bush and is difficult to align and position.
   d. The spring tangles severely and, when separated from others, is dropped onto the shaft.
   e. The washer is inserted onto the shaft and then held down while the snap fastener is positioned using a standard grasping tool.
3. Analyze the terminal block shown in Figure 3.58 for manual assembly. Give the estimated assembly time and the design efficiency.
4. Figure 3.59 shows an exploded view of a diaphragm assembly from a gas flow meter. Determine a suitable assembly sequence for this product and carry out an analysis for manual assembly. Estimate the assembly time, together with the design efficiency. Develop a redesign for this assembly with a reduced part count

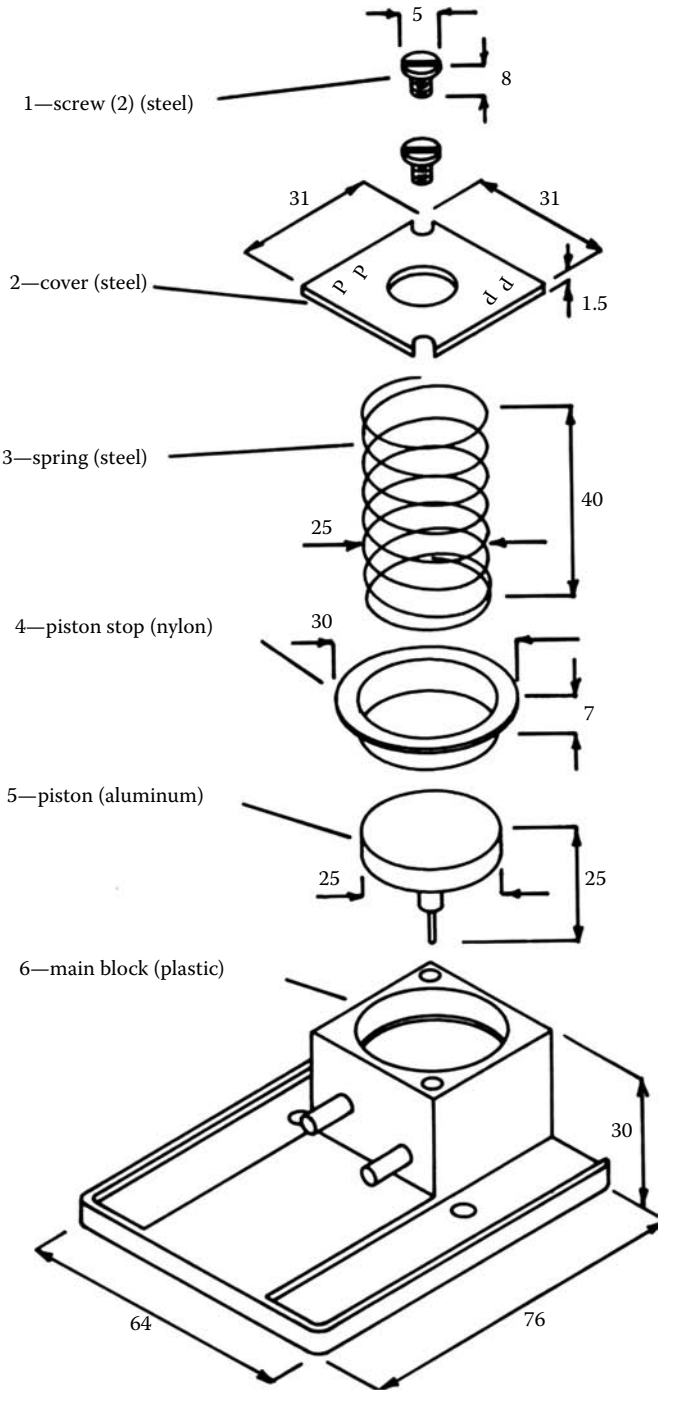

FIGURE 3.56
Piston assembly (dimensions in mm).

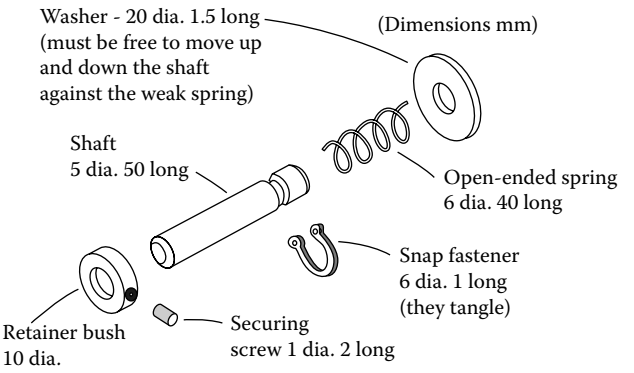

FIGURE 3.57
Shaft assembly.

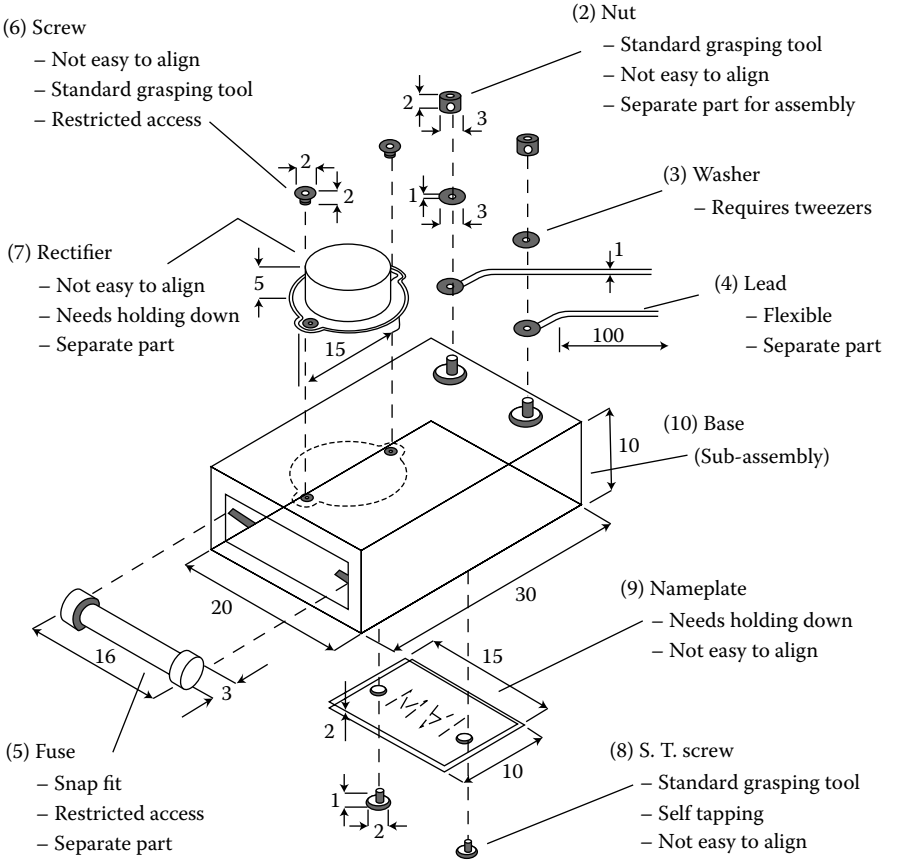

FIGURE 3.58
Terminal block.

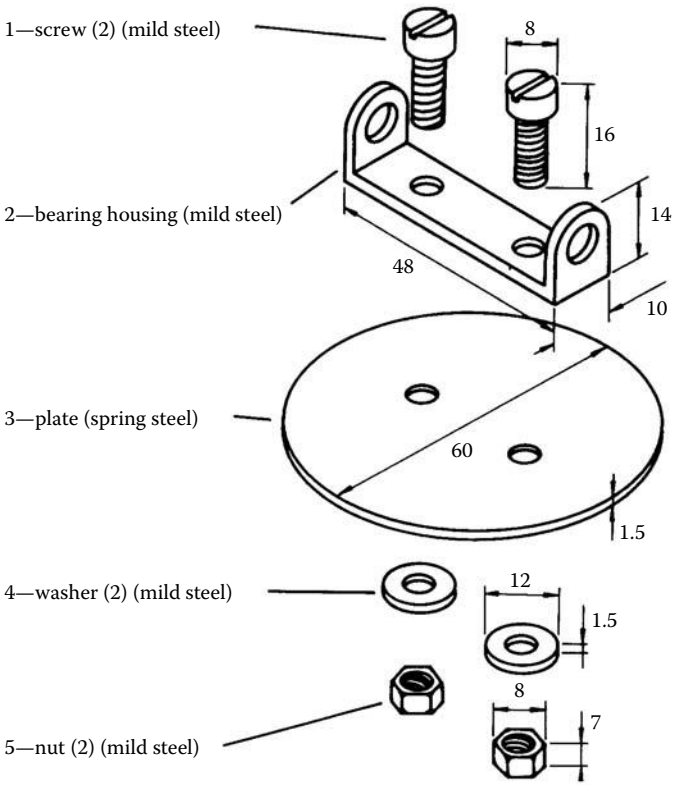

FIGURE 3.59
Gas meter diaphragm assembly (dimensions in mm).

and reduced assembly time. Estimate the assembly time and design efficiency for manual assembly of the redesigned assembly.

5. Analyze the gear-box assembly shown in Figure 3.60 for manual assembly. Obtain the estimated assembly time, assuming that none of the parts are easy to align and position. Also obtain the theoretical minimum number of parts, assuming that the springs and the earth lead must be different materials from the remaining parts. Suggest a redesign for the gear box, assuming that two screws only are needed to secure the upper cover, and estimate the assembly cost for the redesign. Assume a manual labor rate of $36 per hour.
6. A design concept consists of a cylindrical stepped base machined from nylon, a diaphragm disk, and a clamping ring as shown in Figure 3.61a. For the ease of assembly, and to reduce manufacturing costs, you propose to combine the diaphragm and clamping ring into a single aluminum alloy die casting as shown in Figure 3.61b. For the die cast diaphragm design, assume the coefficient of friction between the diaphragm and the nylon base during assembly is 0.15.
   a. Would you expect jamming problems during assembly with this value of friction and the given diameter and overall disk thickness dimension of 15 mm.
   b. If you determine that jamming would occur, to what value would you increase the overall thickness, from the initial value of 15 mm, to stop the jamming condition? Alternatively, if you determine that jamming would not occur, how much smaller could you make the overall thickness and still avoid jamming during assembly?

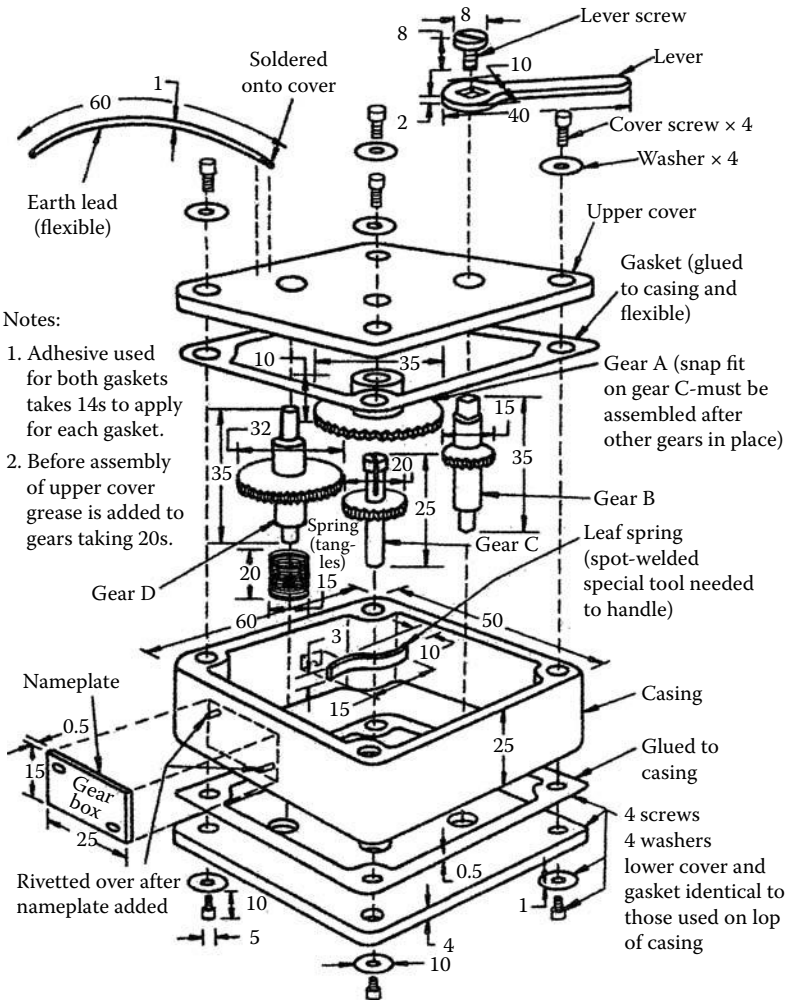

FIGURE 3.60
Gear box assembly.

7. The final assembly of a new high-performance aircraft engine turbocharger involves 182 assembly operations. The assembly time has been estimated, using the DFA standard data times, to take 1700 s.
   a. Using this information, determine the probability that any given one of the completed turbochargers contains an assembly error. Assume that with attention to quality being the central issue in aircraft manufacture, the assembly workers perform at 2× the quality level of the benchmark Motorola workers; that is, make assembly mistakes at only half the rate.
   b. You have an order for the new turbocharger from Piper Aircraft Company, to supply a batch of 24 immediately, and then a second batch of 24 in 3 months time. Assuming that the same assembly workers build both batches, estimate the total time for assembly of the first batch and then the total time for the second batch. Use an 85% learning curve as the basis for your calculations.
8. You company has just designed a new aircraft fuel pump with higher output than a previous model. You decide that the previous model is similar enough to the

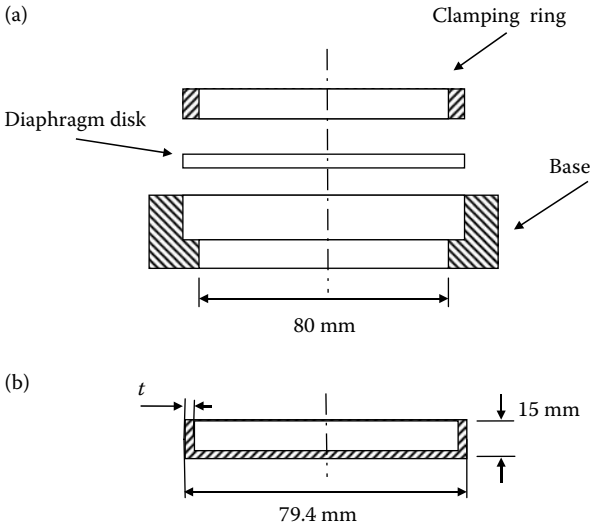

FIGURE 3.61
(a) Original diaphragm assembly, and (b) combined diaphragm and clamping ring.

new one to use previous assembly times for estimating purposes. You need to produce a quotation to Boeing for the delivery of a first test set of 24 pumps. As part of the quote, you need to estimate the average assembly time for the first 24 units. A group of technicians, not production workers, assemble the batch of 24 prototype units.

a. Assume that you have found from records that the total time to assemble the first six units of the previous model was 122 h. Use these data to calculate your estimate with an 85% learning curve.
b. Assume that times were never recorded for the first assemblies of the previous model. However, you know that currently after assembling 280 of the previous model the production assembly time per unit is 6.5 h. Use this information instead of that given in (a) to determine your assembly estimate with an 85% learning curve.
c. Assume both sets of data (a and b). Use both sets of data to estimate the exponent b of the learning curve and the percentage learning curve value (r%) which best fit the data. Use your calculated values of b and r% to determine an improved assembly time estimate.

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4

Electrical Connections and Wire Harness Assembly

4.1 Introduction

The design for manual assembly procedure described in Chapter 3 has been successfully applied to mechanical products. However, when products contain a significant number of electrical connections, the labor involved in their assembly often far outweighs the labor involved in the assembly of the mechanical parts and associated fasteners.

For example, Figure 4.1 shows the potential reduction in assembly time through the redesign of a control unit [1]. It can be seen that in the original design, where the total assembly time was 260 min (4.3 h), about half was devoted to the hand soldering of wires and a further 31% was devoted to the mechanical fastening of wires. A proposed redesign using no hand soldering and eliminating many of the connections would reduce the total assembly time to only 33 min (0.55 h).

A further example is that of a descrambler for satellite TV reception. This product, about the size of a VCR, contained 10 printed circuit boards and, as can be seen in Table 4.1, 51 connecting wires or cables and 31 circuit board jumper wires, making a total of 164 connections. Table 4.1 shows that these items involved an assembly time of 7236 s (2.01 h) which formed 68% of the total assembly time for the product of 10,613 s (2.95 h). Table 4.2

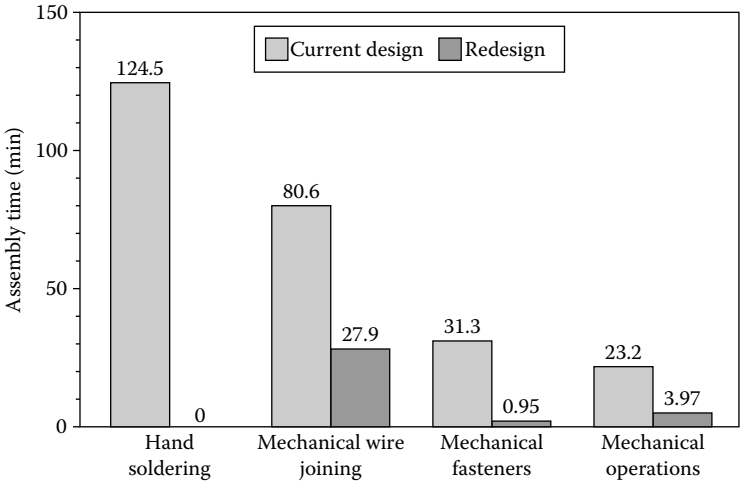

FIGURE 4.1
Possible assembly time savings due to the redesign of a commercial control unit.

TABLE 4.1

Labor Content of a Descrambler

Number	Item	Assembly Time (s)
51	Connecting wires or cables	5768
31	Circuit board jumper wires	1468
138	Mechanical fasteners	1143
80	Electronic components manually inserted	796
112	Mechanical operations	753
20	Hand solder of components	403
33	Other parts identified as candidates for elimination	282
	Totals	10,613

TABLE 4.2

Possible Savings through Descrambler Redesign

Design Change	Saving ($)	Percent
Eliminate cabling	48.06	40
Combine boards	15.00	11
Eliminate jumper wires	12.23	10
Eliminate mechanical fasteners	9.53	8
Total	84.82	69

presents a summary of the opportunities for savings through redesign. For example, if the 10 circuit boards could be combined into one board, thereby eliminating the interconnections and if the jumper wires could be avoided, we might be able to reduce assembly costs by 61%.

Figure 4.2 shows one of the first advertisements for the IBM PS2 computer. This amazing achievement in the ease of assembly was mainly brought about by the elimination of all internal cabling.

It is interesting to note that if the minimum parts criteria described in Chapter 3 are applied to connections of any kind, these connections can never be theoretically justified. In fact, if the sole purpose of an item is to connect A to B, then the item can be eliminated by arranging for A and B to be adjacent to one another, as was illustrated in Figure 3.40. Often, unfortunately, other constraints dictate that A and B must be positioned at different locations and that connections are necessary. This means that it is desirable in DFMA analysis to be able to estimate the penalties resulting from such constraints. In other words, we must quantify the cost of interconnections.

The personal System/2 Model 50 is the first computer to come with a built-in party game. The object of this game is to disassemble and reassemble the machine as quickly as possible. Screwdrivers are prohibited. Sounds impossible? With a little practice, you might be able to clock in at under a minute.

FIGURE 4.2
Advertisement in *PC Magazine*, May 26, 1987.

When several electrical interconnections are necessary, the cables or wires can be installed separately in the product and then tied together and secured as appropriate. Alternatively, they can be assembled and tied together prior to installation in the product. This latter assembly of wires or cables is called a wire or cable harness assembly.

4.2 Wire or Cable Harness Assembly

A completed harness assembly usually consists of a main trunk, where multiple wires or cables are bundled and tied together, with individual wires or smaller bundles of wires leaving the main trunk at various points known as breakouts. Figure 4.3 diagrammatically illustrates possible arrangements and terminology in the wire harness assembly. Figure 4.4 shows the principal operations involved—starting with wire preparation, followed by harness assembly, and ending with installation in the product. Harnesses are usually constructed by manually laying out the individual wires or cables on a board that has a full-size schematic drawing of the harness mounted on its surface to guide the assembly worker. Also, pegs or nails are positioned in such a way that the wires are constrained to run along the required paths. During construction, the ends of the wires must be held in position. If wires are to be terminated in a connector, then the connector may previously have been inserted into a receptacle mounted on the board in the correct position. The ends of the terminated wires are then inserted into the back of the connector. Sometimes, if the wires are sufficiently rigid, they are simply inserted into the connector, which does not need positive location on the board. Wire ends that are to be connected during installation

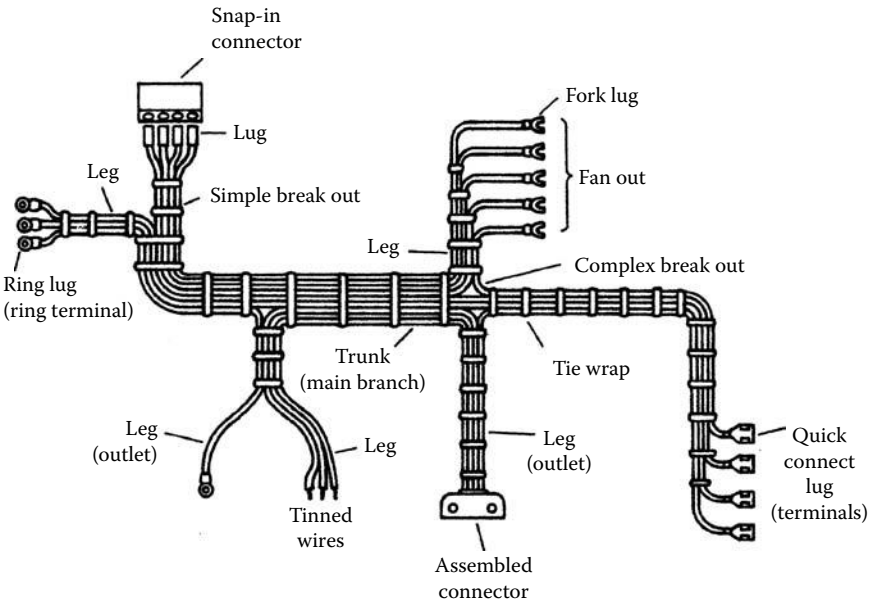

FIGURE 4.3
Terminology.

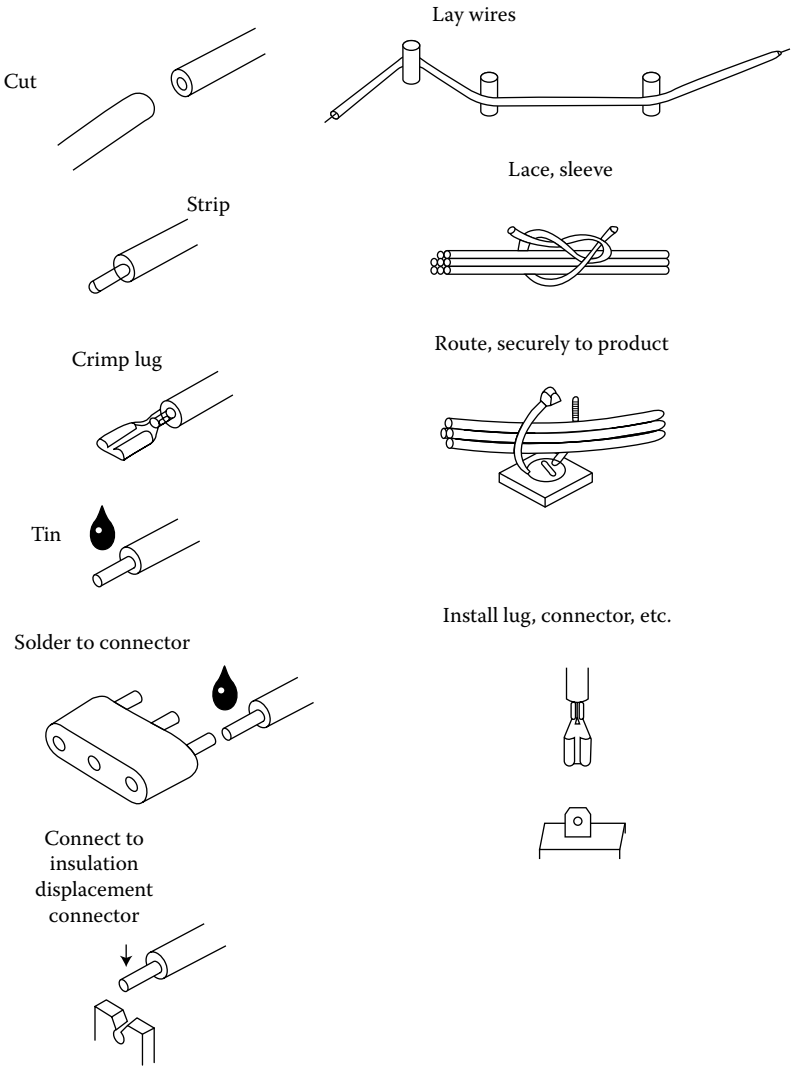

FIGURE 4.4
Principal operations.

in the product are retained temporarily on the board. This is often accomplished by the use of a helical spring mounted on the board with its axis horizontal and perpendicular to the direction of the wire. The assembly worker simply presses the wire end between two coils of the spring.

Once all the wires or cables have been laid (sometimes referred to as laid-in), they are bundled together using tie wraps, lacing, or split-conduit tubing or they are bound with electrical tape. Usually, one assembly worker completes all the operations involved in the construction phase. However, wire preparation usually requires special tools and is carried out in a separate earlier phase. In high-volume situations such as in the automobile industry, the assembly of cable harnesses may be carried out in assembly line fashion.

Here, the boards are transferred from station to station with one or two assembly workers completing a few operations at each station.

When complex harnesses are assembled, the connector receptacles are wired to a computer that continually tests whether the wires have been inserted properly. Such online testing is typically carried out in the automobile and defense industries, for example.

Usually, each end of a wire must eventually be connected. This is often accomplished using an intermediate item such as a connector or wire termination to which the wire is directly connected. The final connection of the connector or terminal is made during installation in the product. Alternatively, wires may be connected directly to an item such as a printed wiring board, a switch, or a terminal block.

At various stages of manufacture, each wire or cable must be cut to length, terminated, installed, and finally connected. The stage at which these operations are carried out is generally determined by the complexity of the wiring installation or wire harness assembly. Figure 4.5 illustrates the sequence of operations for low, normal, and high complexities.

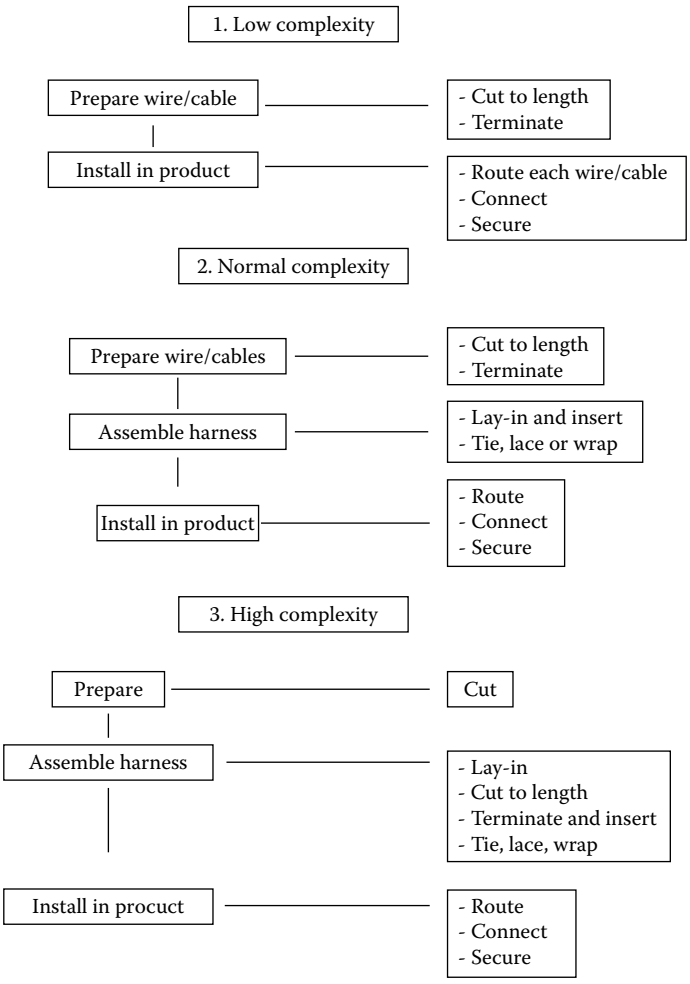

FIGURE 4.5
Classification of electrical interconnections.

For low complexity, where only a few wires are necessary, the wires (or cables) would first be cut to length and terminated. During the final assembly they would be installed separately into the product and be connected.

For normal complexity, typically occurring in the automobile, TV, and computer industries, the wires would first be cut and terminated, then laid on a board (laid-in) and tied, laced, or wrapped. After delivery to the product assembly station, they would be routed, connected, and finally secured.

High complexity refers to the type of harness used in the aerospace or defense industry. Here, the wire is arranged in position and then cut to length and terminated on the lay-in board.

The degree of automation used in wire harness assembly depends on the complexity of the harness and the quantity to be produced. However, automation is generally restricted to wire or cable preparation. Fully automatic machines are available that cut the wire to length and then strip and terminate both ends. Such machines are typically employed in the automobile industry but are finding increasing applications in lower volume production situations. More common is the semiautomatic procedure. Here the assembly worker transfers the wire to a series of special machines where individual operations such as cut, strip, and/or crimp are performed. All the wire handling is performed manually. Although some robotic cells have been developed for harness assembly, this operation is usually performed manually even in high-volume situations such as those in the automobile industry. Finally, installation is performed manually.

4.3 Types of Electrical Connections

Single conductors and cables are normally connected to terminals or connectors. The types of connections can be broadly classified into three categories, as shown in Figure 4.6.

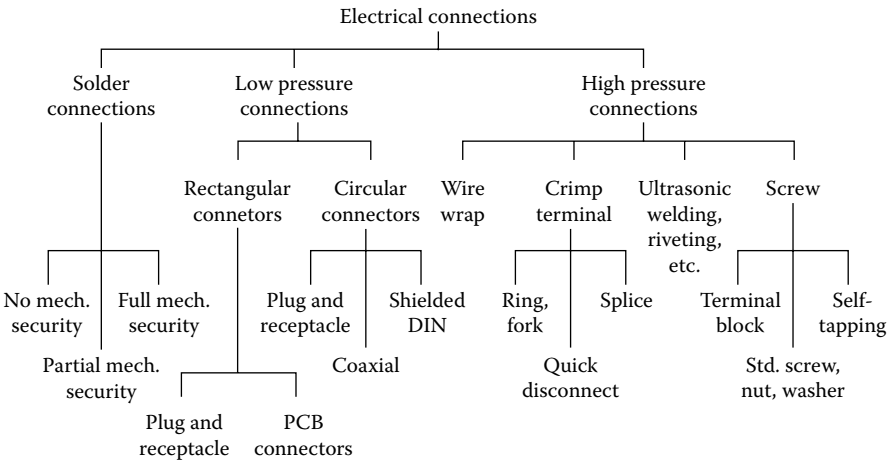

FIGURE 4.6
Types of electrical connections.

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4.3.1 Solder Connections

Although relatively expensive, soldering is one of the most versatile and reliable methods of joining wires to pins, terminals, and so on, and the main function of soldered-wire connections is to provide a mechanical joint and an electrically conductive path. Wires may be secured mechanically to terminals prior to soldering, depending on the criticality of the connections. Mechanically secured soldered wires involve additional assembly time, because the assembly worker needs to acquire a hand tool, move the tool to the wire, secure the wire to the terminal, and put aside the tool in addition to the subsequent soldering operation. A long-nose plier is often used for temporarily securing wires which are wrapped 180° in electronic wiring. For full mechanical security, a 360° wrap can be used.

When mechanical strength requirements are not important, wires can be soldered without prior securing, as with solder lugs. For this type of connection, the diameter of the wire should be slightly less than that of the hole in the lug.

4.3.2 Low-Pressure Connections

Low-pressure connections can be separated without the aid of a tool. Electrical and electronic connectors fall into this category. Besides providing a good solid connection, connectors are particularly convenient when frequent disconnection and reconnection are required; they also tend to minimize errors during servicing, because the wires remain in the correct sequence when disconnected. The general expectations from low-pressure connections are as follows [2]:

- Sufficient contact force for good conduction
- Good cleaning action during assembly
- Low resistance to mating of parts
- Low wear on parts
- Long life
- Ease in connecting and disconnecting

Some low-pressure connections have difficulty in meeting all the criteria stated above. For reliability, the higher the contact force, the better the connection. On the other hand, higher forces make a multicontact connector more difficult to connect and disconnect. Therefore, a compromise has to be maintained among the preceding criteria.

Low-pressure connections can be grouped by their construction (e.g., rectangular and circular connectors). One-piece card-edge connectors and two-piece plug and receptacle connectors such as socket and PCB connectors are classified as rectangular connectors. With a one-piece card-edge connector, the PCB foils extend to an edge of the board, which is inserted into the connector. Two-piece connectors come in the form of male and female halves. The male half consist of pins (male contacts) and the female part consist of sockets (female contacts). Coaxial, shielded DIN, and other circular plug and receptacle connectors are classified as circular connectors.

Rectangular and circular connectors have a variety of contact styles and the frequency of mating suggests the types of contacts to be used. The contacts can be machined or stamped, and they come in many shapes and sizes. Figure 4.7 shows pin and socket

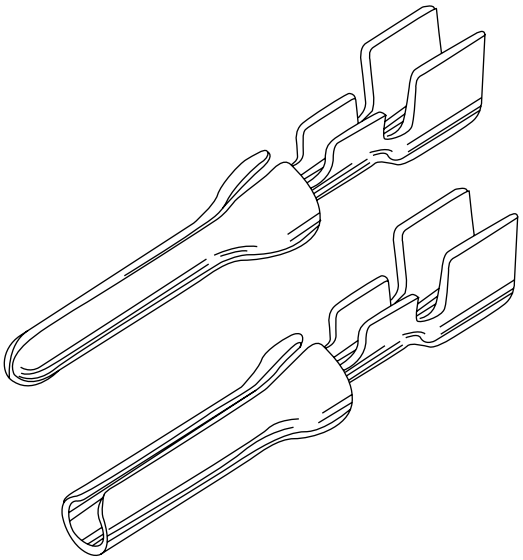

FIGURE 4.7
Pin and socket contacts.

contacts, a combination commonly used because of its low cost and ready availability. The disadvantages of these types of contacts are high-insertion forces and susceptibility to damage. Other types of contacts include blade and fork contacts and bellows contacts [2]. Some high-priced systems can provide as many as 100,000 high-compliance contacts without failure [3]. They are generally found on two-piece connectors. The points to consider when choosing a connector are the types of conductors to be terminated, the assemblies to be connected, the number of contacts required, the final product function, and the cost.

There are three methods used to connect wires to the connector contacts. In the first method, the pins or sockets could be crimped onto wires and then poked into the connector body with a cylindrical-shaped hand tool. The second method involves soldering the wires to the contacts. Soldering generally requires a skilled worker and has high-labor cost. The third method is the insulation displacement technique, where the insulation of the wire is pierced and displaced from the conductor. The conductor is then forced into the U-shaped contact in one operation, greatly reducing the time needed to connect a wire to the contact. This method is explained later when we consider multiwire flat cables that are terminated by insulation displacement.

Cable connectors that are used for high-frequency signals must be positively and firmly coupled. Coupling devices for both male and female connectors have been designed for use in applications where there is not enough access space to turn a coupling nut (see Figure 4.8). Other considerations involve the ability of the connector to stay coupled during shock and vibration conditions and to resist deterioration when used in a variety of environments. The commonly used methods of coupling circular connectors are screw-thread, push-on, or friction type and bayonet devices. The coupling devices used on rectangular connectors are latches or snap-on clips, locking clips, spring clips, or screws (Figure 4.8).

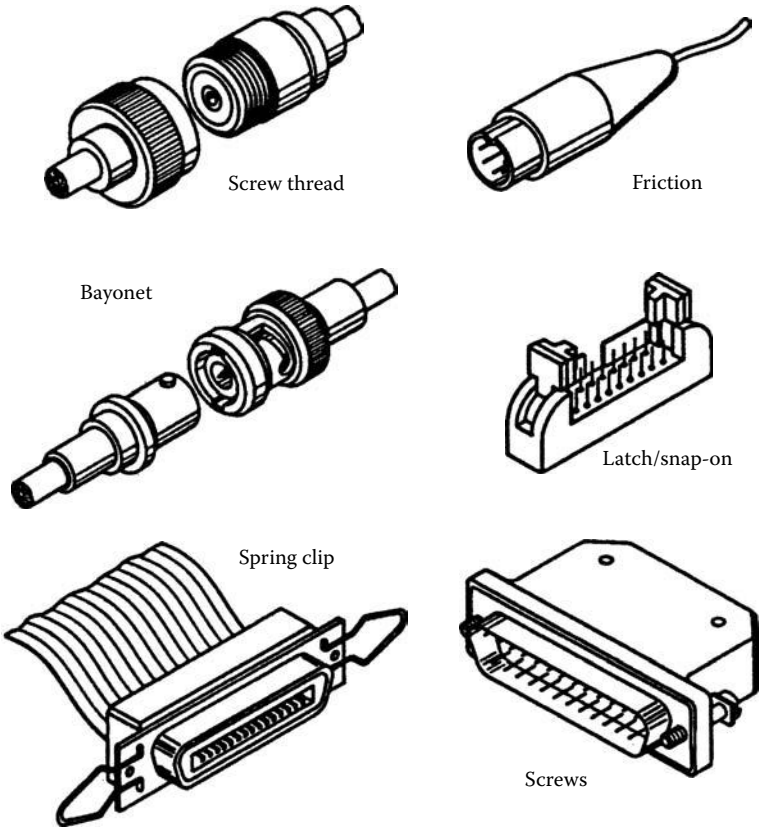

FIGURE 4.8
Coupling devices used on circular and rectangular connectors.

4.3.3 High-Pressure Connections

The high-pressure connection is one that requires a tool to create a metal-to-metal contact under pressure and/or plastic deformation. The most commonly used methods under this category are wire-wrap, crimp, and screw connections. Other methods are ultrasonic welding, riveting, and so on.

Wire wrap is the most reliable method for making point-to-point electrical connections between wires and terminals. It consists of wrapping the bare end of an insulated solid wire in a helix, tightly around a long terminal post having a square or rectangular cross-section. The resulting high-pressure metal-to-metal contacts produce a gas-tight connection that has a large contact area with low resistance. With time, the molecules of the post and wire start to diffuse at the joint and the bond strength of the joint increases to nearly that of a welded joint. Stranded wire cannot be used for this joining method. Wire wrap can be performed manually using a pneumatic- or electric-powered rotary tool. Alternatively, semiautomatic or automatic methods are available. A semiautomatic wire wrap can connect over 300 wires per hour with an error rate 10–20 times less than that of the manual method [2]. In the case of automatic wrapping, wrapping rates of 1000 wires per hour with a reject rate of 0.05% are achievable. Figure 4.9 shows the standard wire-wrap connection.

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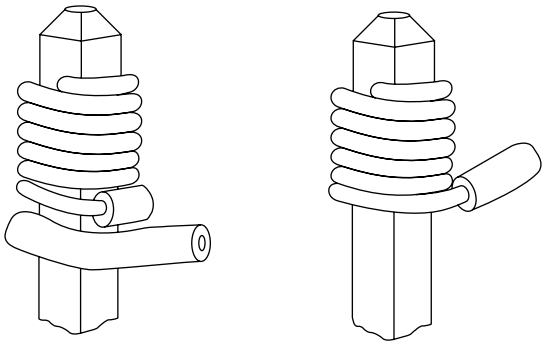

FIGURE 4.9
Wire-wrap termination.

A crimped terminal is a permanent connection and is used to connect individual wires to a terminal block with screws or it can be inserted into a connector block. Crimping can be done with hand tools or by machines. During crimping, pressure is applied to compress the terminal onto the wire to a critical depth. This depth is different for every terminal size and wire gauge. Two common configurations of the crimped terminal are the ring tongue and the fork tongue styles (see Figure 4.10). The fork tongue style can be connected and disconnected quickly and is used where mechanical security is not a major requirement.

The screw connection, probably the oldest type of mechanical connection, involves screwing down a metal screw or nut and clamping the wire under the screw head or nut. The wire is usually wrapped one turn around the screw or screwed post in a clockwise direction (Figure 4.10). This method is particularly advantageous where field installation requires fast and simple connections. However, screw connections may deteriorate under conditions of corrosion or severe vibration, and they have voltage and electrical frequency limitations.

Terminal blocks, with screws attached to each connecting point and separated by insulated partitions, are used to connect discrete wires. The wires may be connected directly onto the terminal block using the bare wire ends, or the wires may be provided with lugs. The type of lug may influence the assembly time. For example, the use of ring lugs would require the operator to totally unscrew the connecting point, whereas fork lugs eliminate this requirement (see Figure 4.10).

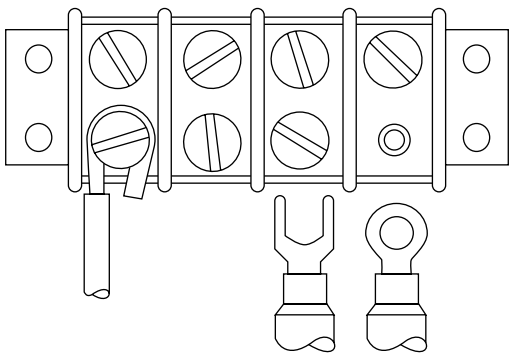

FIGURE 4.10
Attachment of wire, fork lug, and ring lug.

4.4 Types of Wires and Cables

Wire conductors are used to interconnect electrical and electronic systems to transmit current or signal and are selected for their current-carrying capacity, mechanical strength, type of insulation, and cost. Cables generally consist of two or more conductors within a common covering and are terminated by one or more connectors. Proper matching of the connector and cable is important to ensure reliable field performance. Electrical conductors that are commonly used include single solid or stranded wire, twisted pair and trio, multiconductor cables, coaxial cable, ribbon cable, and flexible flat cable. Soft, annealed copper is normally used for wires because of its high conductivity, ductility, and solderability.

Solid wire does not possess the flexibility characteristics or the fatigue life of stranded wire and tends to fracture even under mild flexing. Solid wire may be used for such applications as jumpers on printed-circuit boards where the leads are fixed securely and not subjected to vibration. The advantages of solid wires are their rigidity as well as efficiency at high frequencies. Solid and stranded wire is commonly designated by the American Wire Gauge (AWG) number, diameter of the wire in mils (thousandths of an inch), or cross-section in circular mils (square of the diameter expressed in mils).

A twisted pair consists of two-stranded conductor insulated wires twisted together. The number of twists per inch follows the engineering specification used in signal applications. The twist reduces noise, similar to the hum in a radio. A twisted trio is the same as a twisted pair except that it consists of three conductors.

Multiconductor cable consists of two or more color-coded rubber- or PVC-insulated conductors. Hemp cord may be used as a filler to add strength. The outer insulation or covering is made of neoprene rubber or PVC. Cable of this type is used to carry power from a source to the required areas within the unit or system.

Coaxial cable is used in radio-frequency circuits where the distributed capacity must be constant over the length of the cable. It consists of an insulated length of conductor enclosed in a conductive envelope of braided wire shield and an outer insulating jacket isolating the shield from ground.

Ribbon cable, sometimes called flat cable, consists of numerous conductors of the same gauge held side by side in flexible strips of insulation. The growing demand for the use of ribbon cables has resulted from the advantages of faster insulation stripping and mass termination at low cost. Mass termination is the process of simultaneously connecting a number of conductors to the same number of U-contacts of the connectors. During termination, using either manual or automatic equipment, the U-contact displaces the insulation and each conductor is then forced and wedged within a U-contact. The result is a high-pressure, gas-tight, solderless connection. It can be placed in narrow rectangular openings and used where great flexibility in one plane is needed. Wiring errors are eliminated, and the harness assembly is simplified when point-to-point wiring is required. Also, the ribbon cable has excellent characteristics for conveying high-speed digital signals and a more precise and fixed capacitance between conductors [3]. These characteristics are maintained in service, because the separation between cable conductors remains constant.

Flexible circuitry, which includes flexible cable, can be bent, rolled, or folded many times, depending on the material used. Flexible circuits are becoming widely used as a form of interconnection in applications requiring size and weight reduction, controlled impedance, reduced labor, and ease of assembly [4]. They can be used as one-to-one connectors

or as complex harnesses, allowing breakouts and special routing [5]. Replacing discrete wiring with flexible circuits can reduce the assembly time considerably. Other benefits are reliability and serviceability of the circuits. A number of companies have converted from the use of conventional backplanes, motherboards, and wire harnessing to flexible and rigid/flexible circuits [4].

4.5 Preparation and Assembly Times

In a study of preparation and assembly times [6] a variety of industrial time standards and published data were compared with onsite industrial studies and laboratory studies. The published data were taken from Refs. [7–10]. Information was obtained from two companies, referred to as Company 1 and Company 2 in the text and as Co.1 and Co.2 in the figures.

4.5.1 Preparation

Figure 4.11 presents the times for manually and semiautomatically stripping one end of a wire. The manual operation involves inserting the wire to the correct stripping length and into the proper station of a stripping tool. The tool is then closed thereby severing the insulation, which is removed by the tool. An average experimental time of 7.0 s was obtained for stripping one end of a wire and this agreed closely with published times [8,10] and those observed in Company 2 (see Figure 4.11). Machine stripping of wires involves grasping the wire and inserting the end into a stripping machine. This triggers the machine to strip off the insulation to the correct length. The stripping time obtained from published figures [10] suggests that an approximate time of 3 s can be assumed.

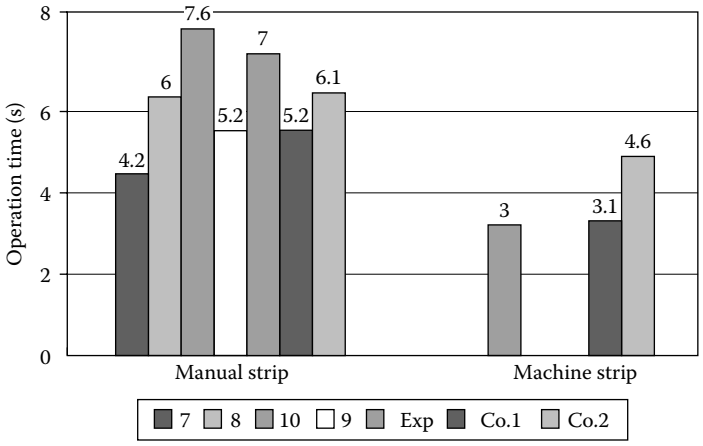

FIGURE 4.11
Results for stripping one wire end. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

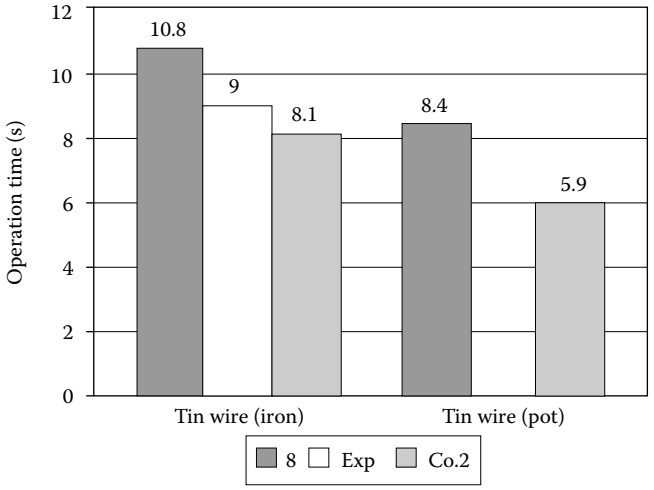

FIGURE 4.12
Results for tinning one wire end. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.12 presents the times for tinning one bare end of a wire. In an experiment, the wire was held by a fixture and the bare end tinned using a soldering iron held in one hand and solder held in the other hand. An experimental time of 9 s was obtained and is comparable to that given in [8] and observed in Company 2. If a solder pot is used for tinning the wire end, an average time of 7.2 s obtained from [8] and observed in Company 2 is recommended.

Figure 4.13 presents the times for crimping one terminal to the bare end of a wire. For manual crimping, a terminal is inserted into a color-coded notch of a crimping tool and

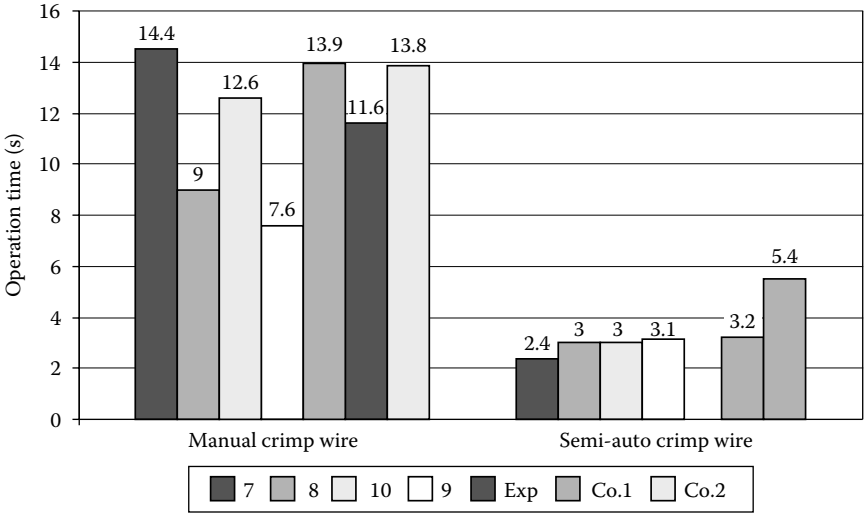

FIGURE 4.13
Results for crimping a terminal to one wire end. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

the bare end of the wire is placed into the barrel of the terminal. The tool is then closed to compress the barrel so that it clamps tightly onto the wire. The experimental time for the manual operation was found to be 13.9 s. This time compared well with [7,10] and with Company 2 but differed from that found from [8,9]. Crimp terminals come in various shapes and sizes and this may explain the wide variation in the times. The average experimental time of 13.9 s would seem to be a reasonable figure.

In the semiautomatic process of crimping terminals, the operation involves placing the bare end of the wire into the die set. This action triggers the crimping machine. After crimping, a new terminal advances automatically into the die set for the next crimping operation. It can be seen that the values obtained from various sources for the semiautomatic crimping operation agree closely, with the exception of the time observed in Company 2. A time of 3 s is suggested for this operation.

Semiautomatic machines are available that can strip the wire and crimp a terminal after the insertion of an unstripped wire into the machine. The insertion of wire is carried out manually, and from observations of machines that carried out these operations separately, a total time of 3.6 s is suggested for the combined operations. There are also machines capable of automatically cutting, stripping, and crimping terminals to wires in one operation. The production rates vary, depending on the make and model of the machine used. This automatic operation can be as fast as 1.8 s per wire end for a length of 10 ft (3 m) [11].

For multiconductor cable, the experimental time for stripping the outer insulation and then the inner insulation of all conductors within the cable is shown in Figure 4.14. It can be seen that the stripping times vary linearly with the number of conductors. A time of 30 s is required for stripping a multiconductor having two wires, and for each additional wire, a time of 6 s should be added. Also, the results indicate that the manual stripping of the outer insulation would take 18 s.

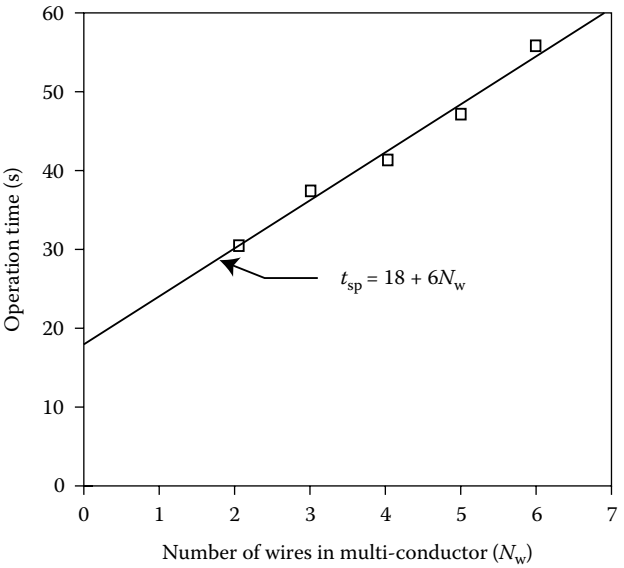

FIGURE 4.14
Experimental results for stripping a multiconductor cable: □, experimental. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

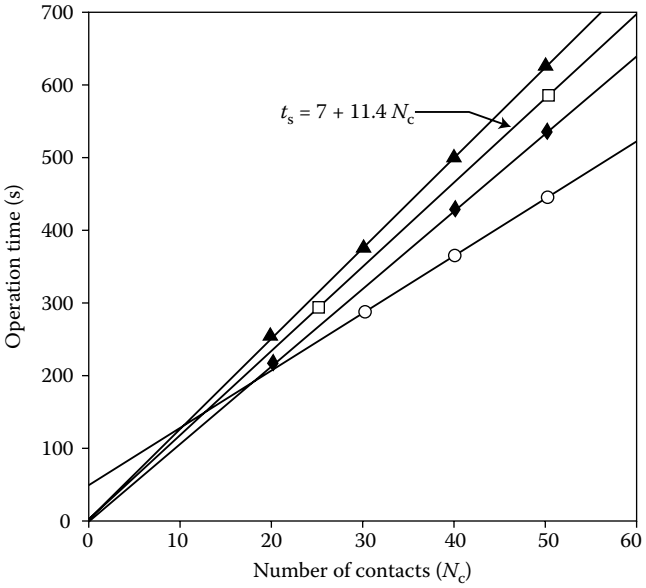

FIGURE 4.15
Manual assembly time for a connector with solder contacts: ○, (7); ◀, (9); □, experimental (total); ▲, Co.2. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.15 presents the manual assembly times for soldering the contacts of circular or rectangular connectors. The operation involves placing the connector into a fixture and filling all the solder cups. A handful of wires are then grasped using one hand, with the other hand holding the soldering iron. A solder cup is then reheated and simultaneously a bare wire is inserted. The wire is held in position until the solder solidifies. It can be seen that the times for filling solder cups and soldering wires to contacts vary linearly with the number of contacts to be soldered. The total experimental time t_s for assembling a rectangular or circular connector is the summation of the times for filling solder cups $(6.8 + 3.1N_c)$ and soldering wires $(0.2 + 8.3N_c)$ and was found to be

$$t_s = 7 + 11.4N_c \tag{4.1}$$

where N_c is the number of contacts.

The total time given by this equation does not include the cutting and stripping of the wires or assembling the connector.

It was noted that the design of connectors varied with different suppliers. The assembly of small mechanical parts is covered adequately by the methods in Chapter 3.

The total experimental time given by Equation 4.1 was found to be quite close to the time given in [9,10] and the time observed in Company 2.

Figure 4.16 gives the manual assembly times for crimping the contacts of circular or rectangular connectors. A contact is first inserted into a crimping tool and the bare end of the wire is then placed into the contact. The tool is squeezed so that the barrel of the contact grips the bare end of the wire as well as the insulation on the wire. The operation is repeated for each contact. With the connector clamped in a fixture, the wire contacts are

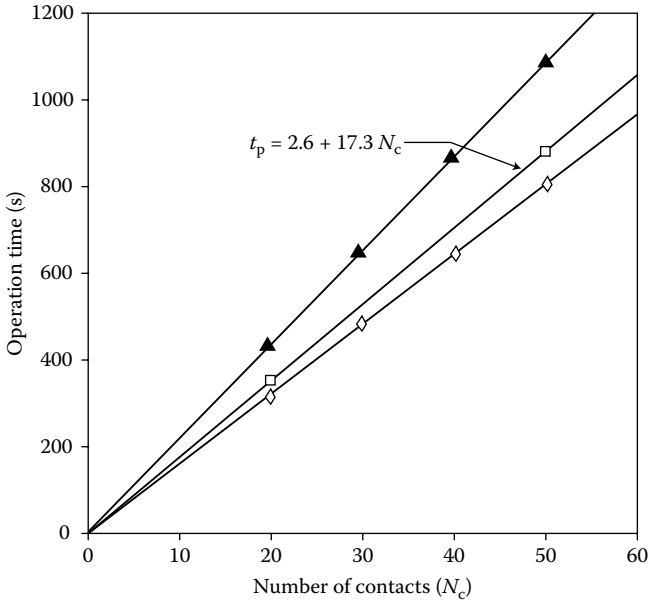

FIGURE 4.16
Manual assembly time for a connector with crimp contacts: □, experimental (total); ◇, Co.1; ▲, Co.2. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

then inserted one by one, using an insertion tool. The times for crimping contacts to wires ($1.5 + 12.4N_c$) and inserting wire contacts ($1.1 + 4.9N_c$) vary linearly with the number of contacts. The total experimental time t_p for assembling wires to a circular or rectangular connector is then given by

$$t_p = 2.6 + 17.3N_c \tag{4.2}$$

where N_c is the number of contacts.

The total time given by this equation does not include the cutting and stripping of the wires and the assembly of the connector.

For semiautomatic crimping of contacts to wires (3 s per contact) and manually inserting the crimped contacts into the connector ($1.1 + 4.9N_c$), a total time of 9 s for one contact is suggested. For installing more than one contact, an additional time of 7.9 s per contact should be added to the basic time.

Figure 4.17 presents the manual assembly times for one coaxial connector termination. The coaxial cable is cut to length, the outer insulation is stripped, and the polyethylene dielectric and shield braid are cut to the correct dimensions. The shield braid is then folded back smoothly and a plastic grommet assembled onto the cable. The contact is crimped to the conductor after it is assembled, flush against the dielectric. The connector body is then assembled, the braid clamp crimped, and the grommet pushed flush against the body. The experimental time for assembling a coaxial connector was 152 s. This time was much shorter than the figure of 290 s given by [9] (which included tinning of the center conductor) and longer than the 115 s given by [10] (which does not include measuring and cutting

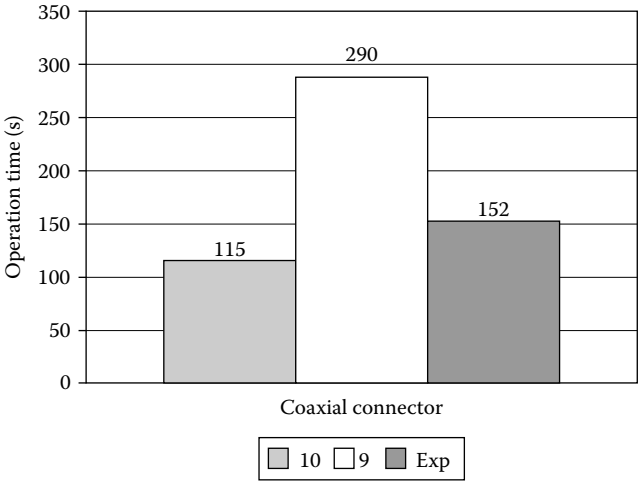

FIGURE 4.17
Manual assembly time for a coaxial connector. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

the cable). The large difference in assembly time could probably be a clue to the differences in connector construction.

Figure 4.18 presents the manual assembly time for mass termination of a flat cable. This operation first involves placing the body of the connector into the locator plate of a press. The flat cable is then positioned into the body of the connector and the mating connector cover is placed over the assembly. The U-contacts of the connector are forced into the flat cable conductors by operating the press. Finally, the cable connector is removed from the locator plate. The experimental time for flat cable connector termination was 30 s. The time

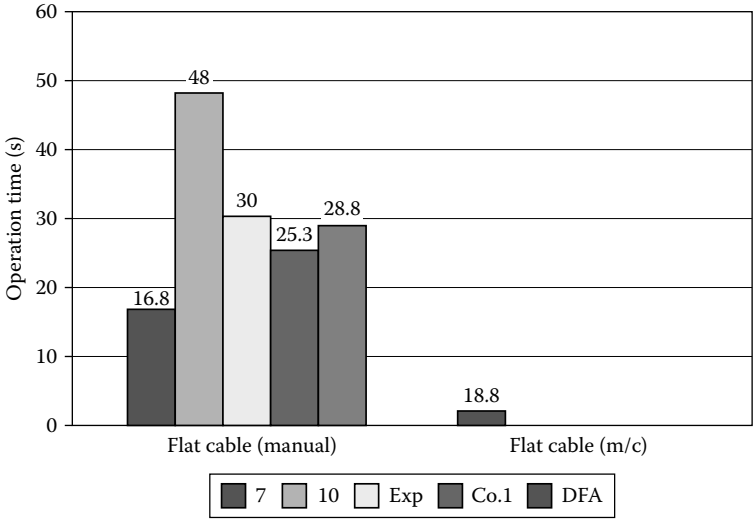

FIGURE 4.18
Manual assembly time for mass termination of a flat cable.

obtained from the observations in Company 1 agreed fairly closely with the experimental time. However, the times obtained from [7,10] were considerably lower and higher, respectively, than the experimental time. For flat cable connector termination using a press machine, a time of 2 s is suggested.

Insulation displacement connection methods involve placing a connector into a semiautomatic machine, spreading the wires, and simultaneously inserting one pair at a time into the connector's contacts [7]. The machine is then triggered and the pair of wires are pierced and cut. An operation time of 7.3 s for each pair of wires is given in [7].

4.5.2 Assembly and Installation

Figure 4.19 shows the times for point-to-point wiring (direct wiring) of the items in a chassis. After one end of the wire is attached, it is dressed neatly to follow the contour of the equipment chassis before the other end of the wire is attached. The dressing time does not include cutting and stripping the ends of the wire, adding the terminations, or attaching the terminated wire. The experimental times are lower than those observed in Company 2. The differences could be due to the degree of obstruction encountered while dressing the wire. The experimental time t_d for dressing the wire is given by

$$t_d = 3.4 + 1.2L_w$$

where L_w is the length of the wire measured in feet.

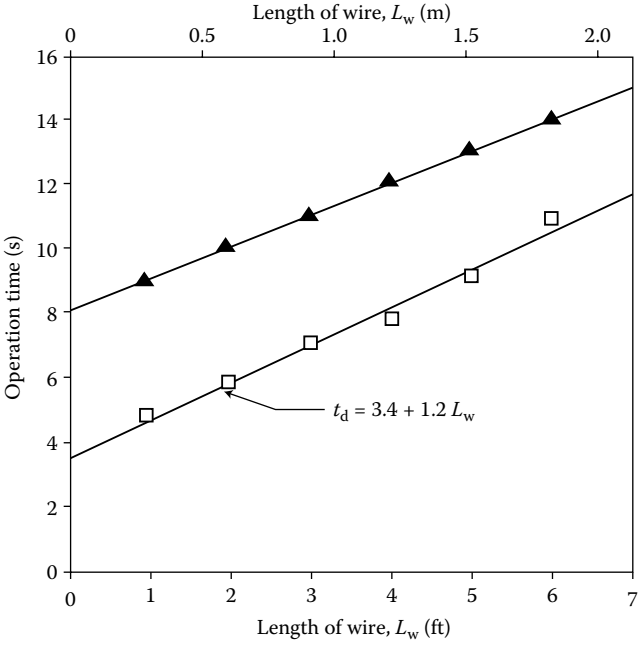

FIGURE 4.19
Results for point-to-point (direct) wiring: □, experimental; ▲, Co.2. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

or

$$t_d = 3.4 + 3.94L_w \tag{4.3}$$

where L_w is measured in meters.

Thus, for direct wiring, a time of 4.6 s is required for the first foot and an additional time of 1.2 s/ft (0.3 m) is added for a wire of length greater than 1 ft (0.3 m).

Figure 4.20 shows the times for dressing a wire in a U-channel. After the wire is attached at one end, it is inserted (dressed) into the U-channel before the other end of the wire is attached. The dressing time does not include cutting and stripping the ends of the wire, adding the terminations, or attaching the terminated wire. For a wire of length 3–4 ft, the experimental time obtained is comparable to that given in [9], A dressing time of 4.4 s is recommended for a wire 1 ft long, and an additional time of 1.7 s/ft should be added for a longer wire.

Figure 4.21 presents the times for laying a flat cable directly into the equipment chassis. The operation involves dressing the flat cable after the flat cable connector is attached onto its mating part. The experimental times obtained agreed fairly closely with those observed in Company 1. A time of 7.7 s is suggested for laying a flat cable 1 ft (0.3 m) long. An additional time of 1.6 s/ft should be added for a longer cable. The time for laying a flat cable does not include the time for bending and pressing of the cable so that it stays bent during laying. This operation is usually done before laying the flat cable, and a time of 15.1 s per bend should be added to the time for laying a flat cable.

Figures 4.22 and 4.23 present the times for laying wires onto a harness jig. A wire is first grasped and one end is attached to a holding device. The wire is then laid on the

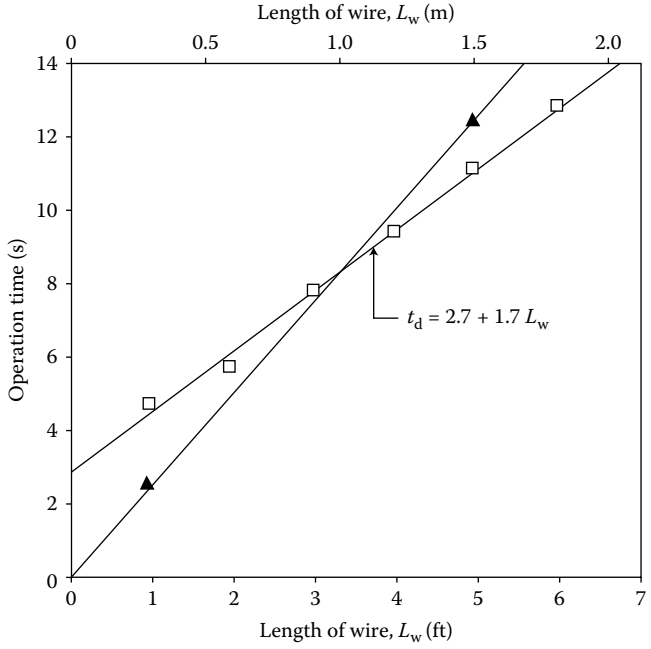

FIGURE 4.20
Results for dressing a wire into a U-channel: ▲, (9); □, experimental. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced* Manufacturing *Technology*, 6, 155–179, 1991.)

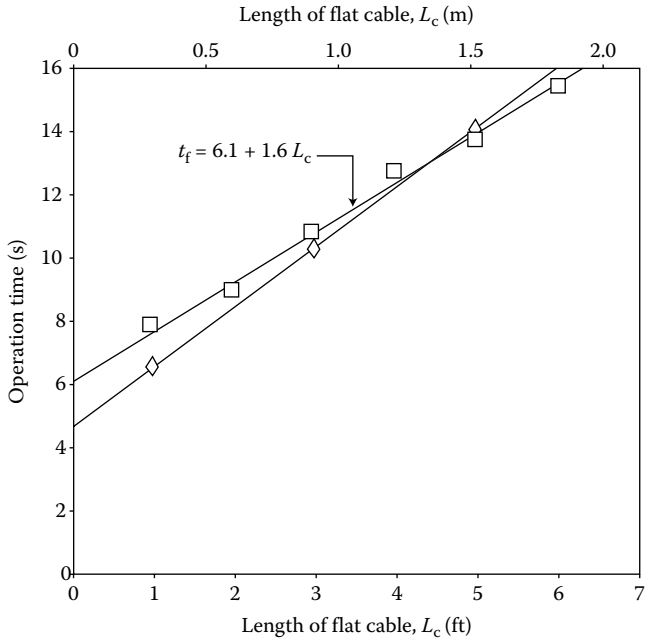

FIGURE 4.21
Results for laying a flat cable: □, experimental; ◇, Co.1. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

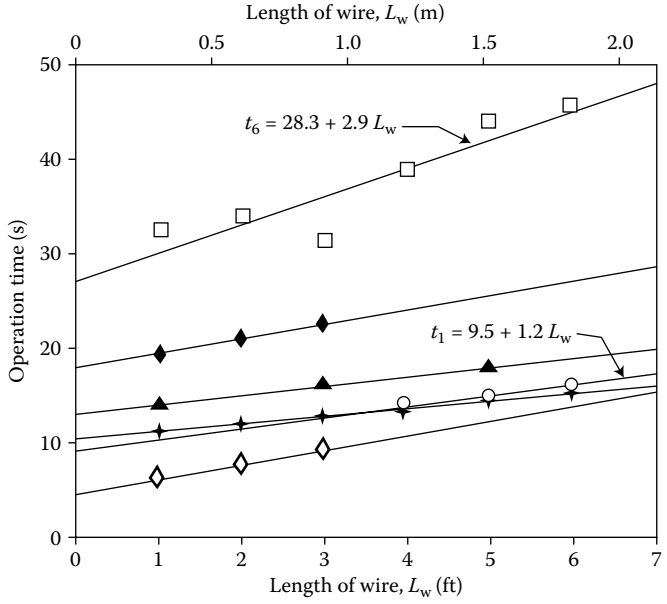

FIGURE 4.22
Results for laying a wire or six wires simultaneously onto a harness jig: ○, 1 wire (experimental); □, 6 wires (experimental); ✦, 1 (7); ◆, 6 (8); ◇, 1 (8); ▲, 1 (Co.2.)

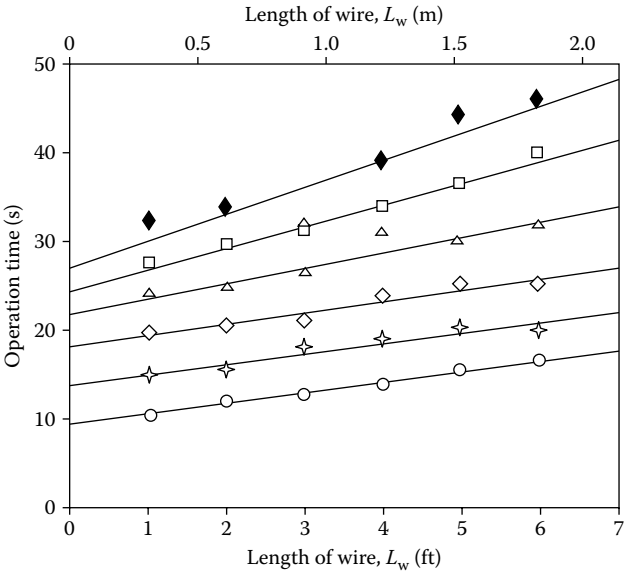

FIGURE 4.23
Experimental times for laying wires simultaneously onto a harness jig; ○, lay 1 wire; ✧, 2; ◇, 3; Δ, 4; □, 5; ◆, 6. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

board according to the wiring layout and finished, with the other end of the wire being attached to another holding device. Multiple wires can be laid simultaneously if the wires start and end at the same breakout. Figure 4.22 shows the comparisons of published results with experimental times for laying one wire or six wires simultaneously onto the harness jig.

Figure 4.23 shows further experimental results for laying one to six wires simultaneously onto a harness jig. From these results a general equation for the time t_n to assemble N_w wires simultaneously is

$$t_n = 6.4 + 3.8N_w + (0.5 + 0.4N_w)L_w \tag{4.4}$$

Figures 4.24 and 4.25 show the times for laying wires already connected to a connector onto a harness jig. The operations involve the selection of the wire(s) after the cable connector is installed on the harness jig, laying the wire(s) according to the wiring layout, and attaching the ends to a holding device. The times obtained do not include attaching the cable connector to its mating part on the harness jig. Figure 4.24 shows the comparison between the times obtained experimentally and those given by [8]. It was found that the experimental times were higher. Further experimental results are shown in Figure 4.25 and a general equation for the time t_m to assembly N_w wires simultaneously from a connector is

$$t_m = 6.9 + 2N_w + (0.5 + 0.3N_w)L_w \tag{4.5}$$

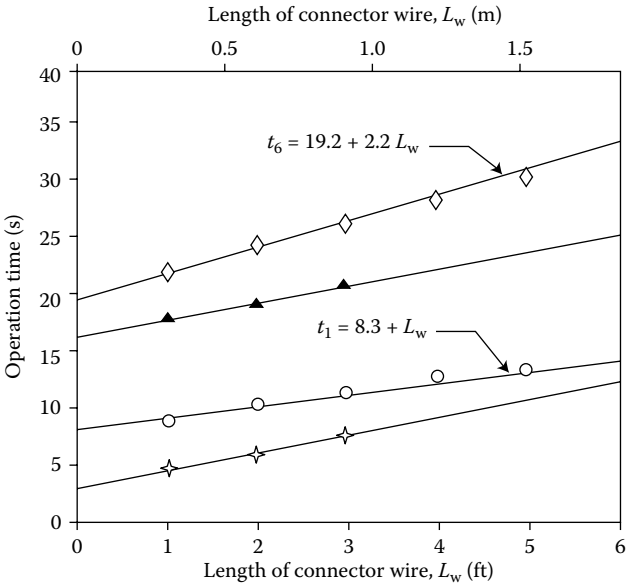

FIGURE 4.24
Results for laying wires simultaneously (from a connector) onto a harness jig; ○, 1 wire (experimental); ◇, 6 wires (experimental); ✧, 1 wire (8); ▲, 6 wires (8). (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

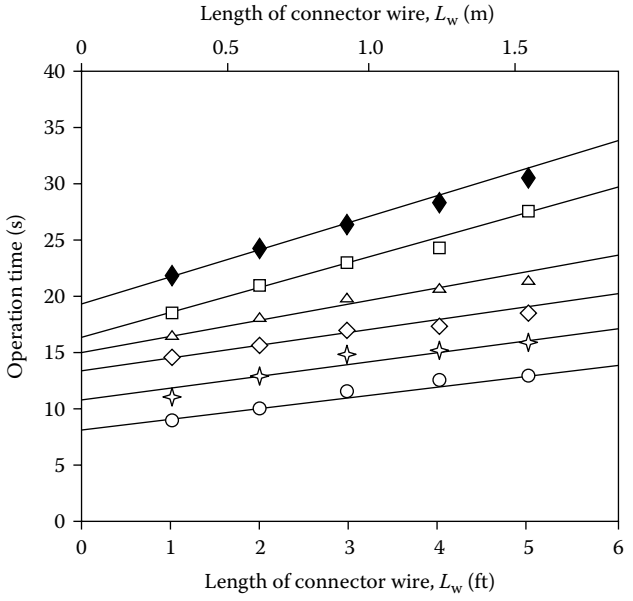

FIGURE 4.25
Experimental times for laying wires simultaneously (from a connector) onto a harness jig: ○, lay 1 wire; ✧, 2; ◇, 3; Δ, 4; □, 5; ◆, 6. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

4.5.3 Securing

Figure 4.26 presents the times for acquiring a tie cord, spot tying a bundle of wires, and cutting the excess cord with a pair of scissors. The experimental time of 16.6 s is comparable with times obtained from other sources.

Figure 4.27 shows the times for tying a cable tie or strap onto a bundle of wires. The operation involved acquiring a cable tie, looping the tapered end of the strap around the harness, and inserting it through the strap eyelet. The strap is pulled tightly and the excess is cut off with a tool. The experimental time of 14.4 s agreed closely with the times from all other sources with the exception of [7].

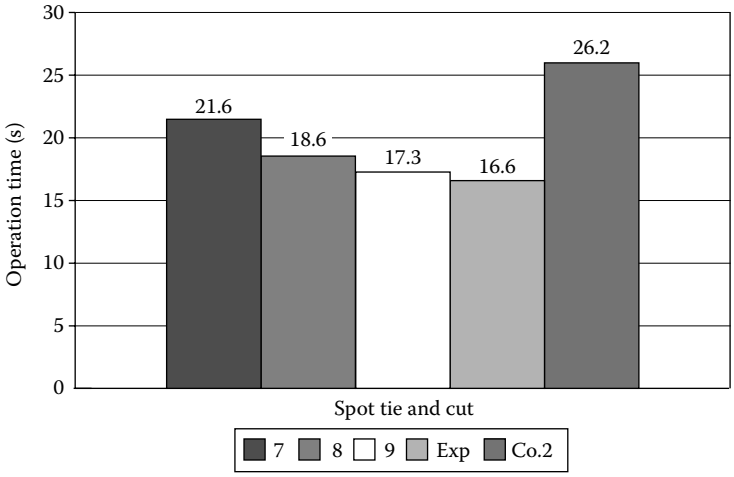

FIGURE 4.26
Results for spot tying a harness trunk/branch. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

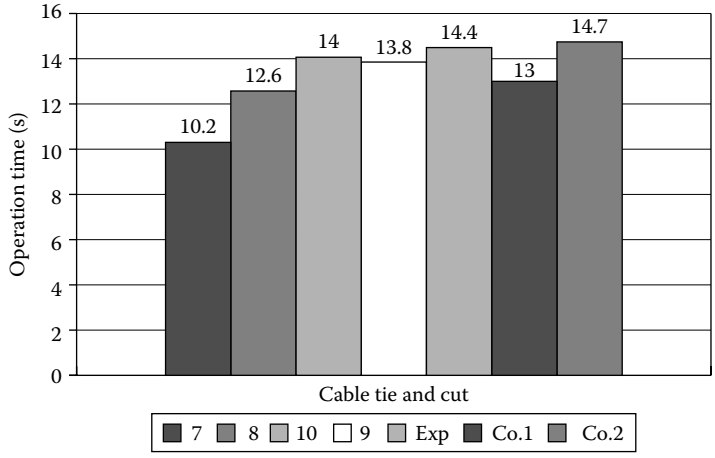

FIGURE 4.27
Results for tying a cable tie onto a harness trunk/branch. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

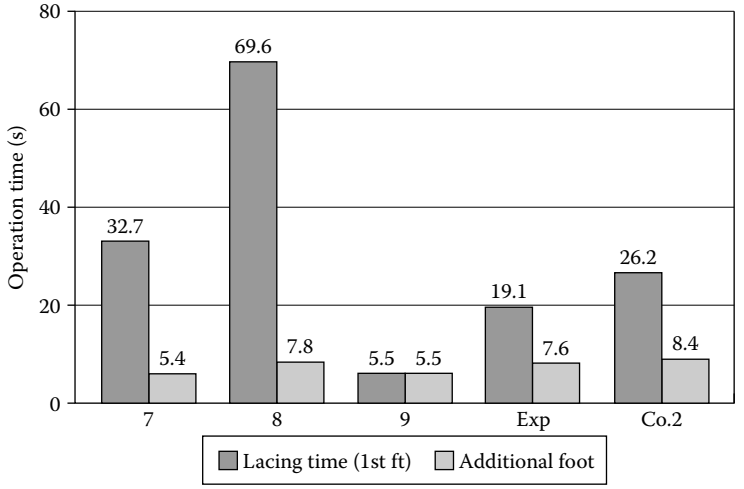

FIGURE 4.28
Results for lacing a harness trunk/branch. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.28 shows the times for lacing a wire harness. The operations involve acquiring a lacing cord and making an initial stitch (girth stitch) at one end of the trunk. To aid in lacing, a lacing bobbin (tool) may be used. The girth stitch is formed by wrapping one end of the lacing cord into a double loop. The free end of the cord and the bobbin are then passed through this loop. Tension is applied to the free ends of the cord to dress the girth stitch firmly. Additional stitches are formed and spaced uniformly at distances approximately equal to the diameter of the harness (but never less than 0.5 in. apart). The completion of the lacing terminates when the end of the cord is secured and trimmed. The experimental time t_{st} was found to be

$$t_{st} = 11.5 + 7.6N_{st}$$

where N_{st} is the number of stitches formed on the harness. Comparing the experimental results with those obtained from other sources, the variation in the lacing times arose at the first stitch. The first stitch took 69.6 s [8]. This large time probably included cutting a sufficient length of lacing cord and winding it onto the bobbin before the lacing operation.

Figure 4.29 gives the times for taping a bundle of wires. The operation involves obtaining a roll of tape, taping and wrapping to a specific location, and cutting the tape. For a tape 1 in. wide, the experimental time for taping 1 in. (25 mm) was 13.8 s for the first wrap and agreed closely with the data obtained from all the other sources. The taping of the second inch would involve more than one wrap of tape, due to the overlapping nature of the taping process. The wide variation in times given for taping an additional inch could be due to the number of wraps involved. In the experiment, three wraps of tape constituted about 1 in. (25 mm) and a time of 7 s per additional inch (25 mm) was considered acceptable.

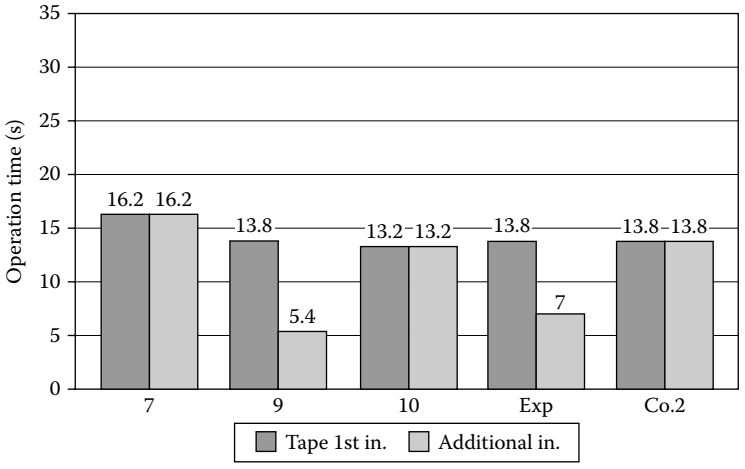

FIGURE 4.29
Results for taping a bundle of wires. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.30 presents the times for inserting a precut tube or sleeve over a bundle of insulated wires. The operation involved acquiring and arranging a bundle of wires and inserting the bundle into a tube or sleeve which is grasped with the free hand. The experimental time differed greatly from the times given by other sources. The ease of inserting the wires into the tube depends much on the amount of clearance between the inner wall of the tube and the bundle of insulated wires, and this probably explains the large differences in insertion times. The experimental time of 7.4 s for inserting the first inch (25 mm) of tube is suggested, and an additional time of 2.4 s per inch (25 mm) is added for a tube longer than 1 in. (25 mm).

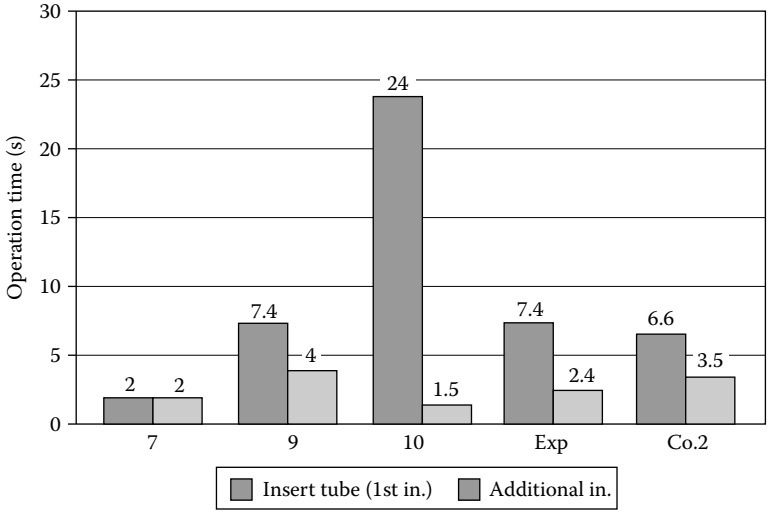

FIGURE 4.30
Results for inserting a precut tube or sleeve. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

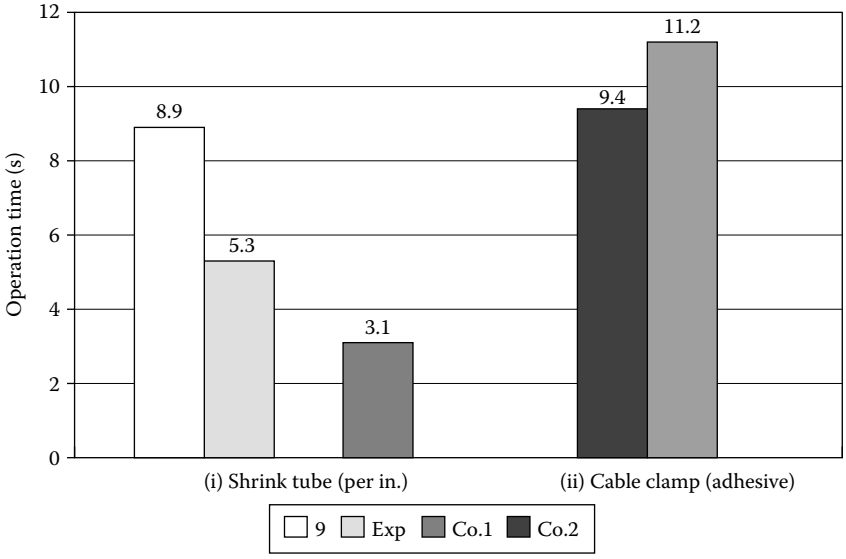

FIGURE 4.31
Results for (i) shrinking an inserted tube, and (ii) installing an adhesive cable clamp. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.31 shows two results for securing operations. The first involves heat shrinking the tube using a heat gun. The experimental time of 5.3 s per inch (25 mm) lies between those obtained from [9] and observations in Company 2. The wide variation in the heat-shrinking times could be attributed to the diameter of the tube to be shrunk. Also, a larger clearance between the inner diameter of the tube and the insulated wires prolong the shrinking time. The experimental time of 5.3 s per inch (25 mm) appears reasonable.

The second operation in Figure 4.31 involves acquiring an adhesive cable clamp, peeling off the protective layer, and pressing the clamp onto the equipment chassis. The experimental time of 9.4 s agreed fairly closely with observations in Company 2. For cable clamps that must be screwed onto the equipment chassis, a screwing-down operation into a tapped hole is necessary, and in Company 2, this operation took 27 s.

Figure 4.32 shows the times for labeling a wire. The operation involves peeling off a label and wrapping the label onto a wire. With the exception of [7], the times obtained from the various sources agreed fairly closely with the experimental time of 11.4 s. The time obtained from [7] (14.4 s) also involved labeling a cable with a marker.

4.5.4 Attachment

Figure 4.33 gives the times for the attachment of a bare wire to its mating part. The wire is first grasped with two hands (due to its length and flexibility), moved, positioned, and bent with a plier around its mating part. The mating part can be mounted in either a terminal block or a separate fastener such as a screw inserted into a tapped hole or a screw to be held in place with a nut. The wire is then secured. The attachment times for the various mating parts are shown in the figure, and the experimental times agreed closely with the times obtained from DFA (Chapter 3) with the exception of the time obtained for attaching a bare wire to a terminal block. The assembly time of 17.1 s can be assumed for attaching a

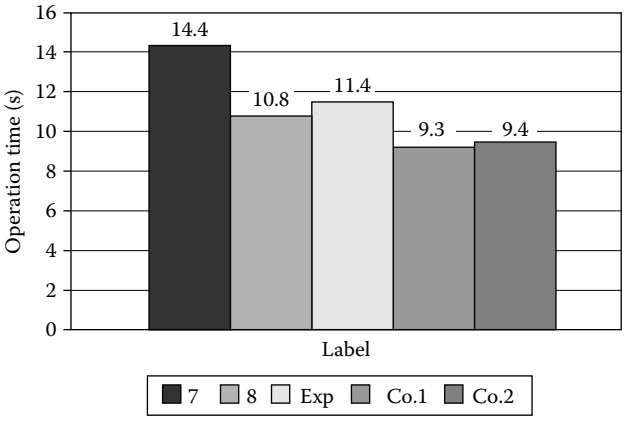

FIGURE 4.32
Results for labeling a wire. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

bare wire to a terminal block, 23.3 s for a bare wire/screw attachment and 30.6 for a bare wire/screw and nut attachment.

Figure 4.34 presents the times for soldering a bare wire to its mating part. The bare wire is first grasped, moved, and positioned to its mating part. The wire is then soldered with a soldering iron. Before soldering, the wire may be bent using pliers, in which case the bending time must be included. From preliminary observations, it can be deduced that the time for soldering depends very much on whether the wire needs to be bent and the area to be soldered. The experimental times agreed fairly closely with DFA (Chapter 3) in the case where the wire is not bent before soldering and with observations in Company 2 in the case where the wire is bent before soldering. An attachment time of 21.1 s can be assumed for soldering a bare wire without bending and a time of 26.6 s can be assumed if the wire is first bent.

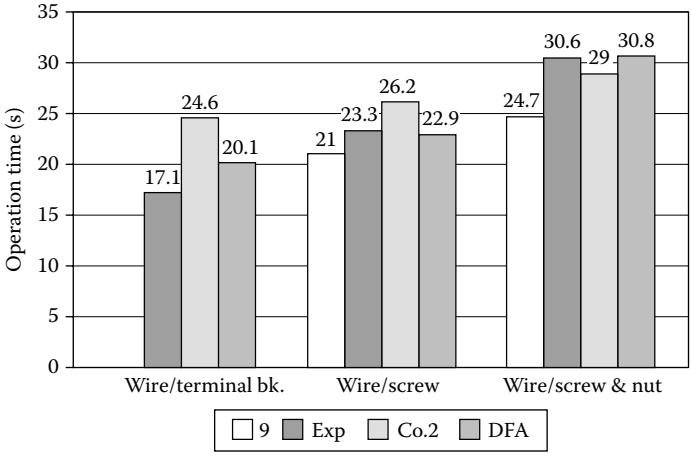

FIGURE 4.33
Results for attachment of bare wire to its mating part. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

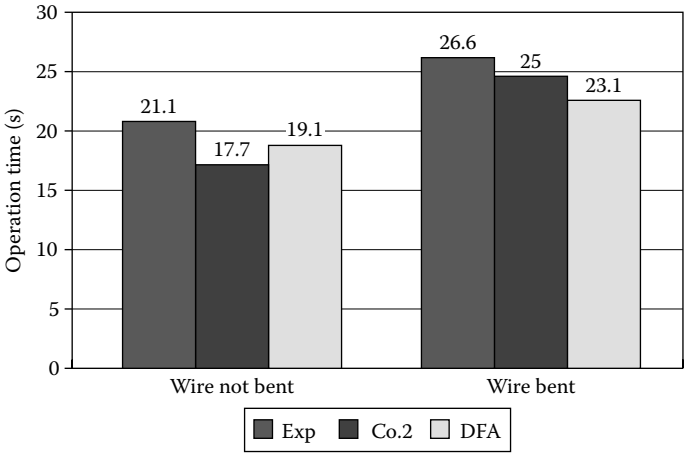

FIGURE 4.34
Results for soldering a bare wire to its mating part. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

Figure 4.35 presents the times for wire-wrapping a bare end of an insulated solid wire around a terminal post. The operation involves acquiring a prestripped wire and inserting it into the tip of the wire-wrapping tool. The tool is then positioned over the terminal and the trigger is squeezed. The tip of the tool spins the wire around the terminal to form the desired attachment. The average time to wire-wrap a terminal post is 13 s.

Figures 4.36 and 4.37 give the times for attaching a wire terminal to its mating part. A wire terminal is first grasped, moved, and positioned to its mating part. It can be a push-on

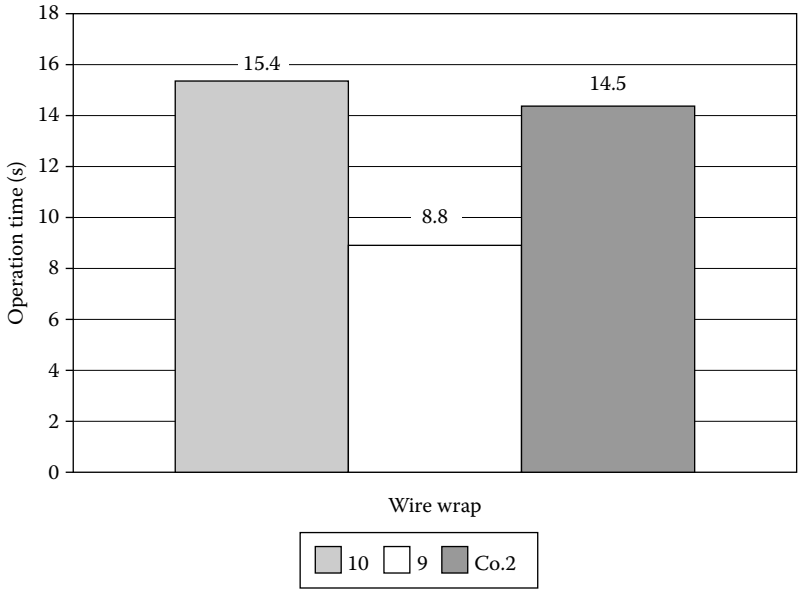

FIGURE 4.35
Results for wire-wrapping around a terminal post. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

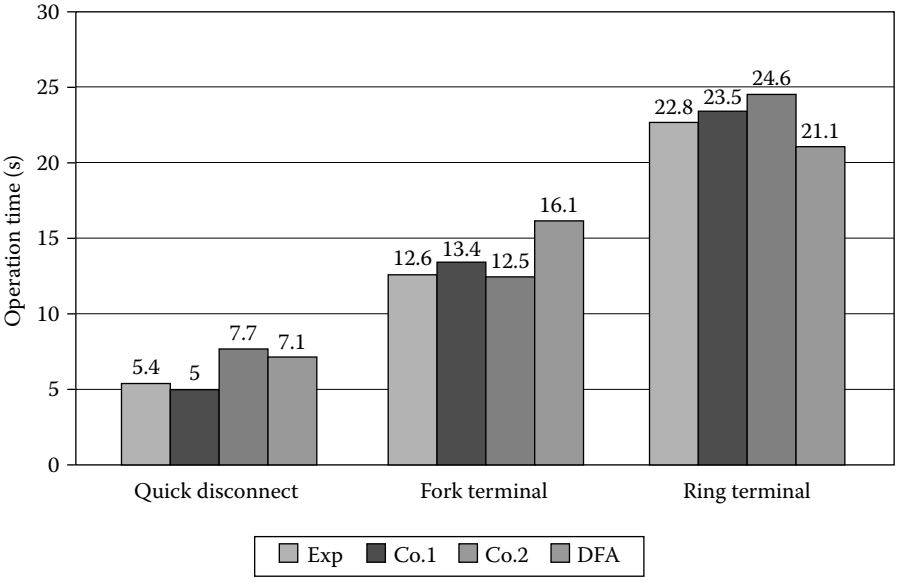

FIGURE 4.36
Results for attachment of a wire terminal to its mating part. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

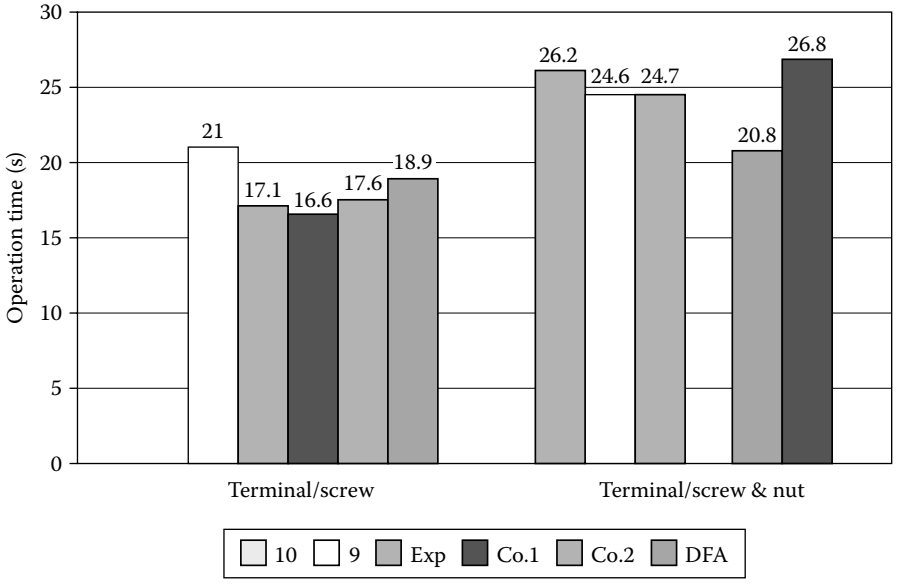

FIGURE 4.37
Results for attachment of a wire terminal to its mating part. (Adapted from Ong, N.S. and Boothroyd, G. *International Journal of Advanced Manufacturing Technology*, 6, 155–179, 1991.)

using a quick disconnect terminal or can be fastened on a terminal block using a ring or fork terminal. The wire terminal (fork or ring) can also be fastened using a screw or a screw and nut combination. From the figure, it can be seen that the times taken from the various sources are fairly close, except for the difference in the experimental and DFA times for attaching a fork terminal to a terminal block. Based on the experimental values, the following can be assumed:

- Attach a quick disconnect terminal—5.4 s.
- Attach a fork and ring terminals, respectively, to a terminal block—12.5 and 22.8 s.
- Attach a terminated wire and secure with a screw—17.1 s.
- Attach a terminated wire and secure with a screw and a nut—24.7 s.

Experiments were also performed on the various types of coupling devices found on connectors. The operation involved grasping a male cable connector (circular or rectangular) and inserting it into a female connector. Depending on the types of connector used, additional operations may be required to ensure that the connectors remain firmly coupled. No comparisons were made, since there was no information available from other sources. The average experimental times for attaching the various types of connectors were

Circular connector	
Install only	5.2 s
Bayonet type	5.2 s
Friction type	6.7 s
Screw thread type	11.3 s
Rectangular type	
Install only	6.5 s
Latch/snap-on type	8.1 s
Spring clip type	9.8 s
Screw (2 ×) type	24.0 s

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4.6 Analysis Method

A methodology has been developed [1] designed to allow estimates to be made of the labor involved in making electrical interconnections and in wire harness assembly. For a wire harness with normal complexity, there are three distinct steps:

1. *Preparation of the wires and cables*: This step includes cutting the wires or cables to length and terminating them. Connectors are sometimes attached to multiple wires at this stage. Also, some additional operations may be carried out such as marking, sealing, molding, sleeving, or labeling of the wires or connectors.

2. *Assembly of the harness on a board or jig*: This includes manually laying-in the wires and cables, inserting the wire ends into connectors if necessary, tying, taping, or lacing the bundles or wires, and/or sleeving the bundles. Testing is usually done at this stage and some labeling may also be carried out.
3. *Installation of the interconnections or the cable harness into the chassis or product*: This final step includes routing the wires or cables, insertion of the connectors into their mating parts, and the dressing and connection of any wire ends to appropriate terminals. Also included is the securing of the wires and cables to the chassis.

Sometimes, it is known exactly what steps are involved in the preparation, assembly, and installation of a particular wire harness assembly, including whether the preparation of the wires and cables are to be carried out manually, with the aid of semiautomatic equipment, or automatically. For the designer who wishes to obtain assembly cost estimates at the earliest stages of design, some of these details are unknown. To satisfy this need, it can be assumed, for example, that semiautomatic equipment will always be used for wire and cable preparation. This results in considerable simplification of the databases needed for the estimation of assembly time.

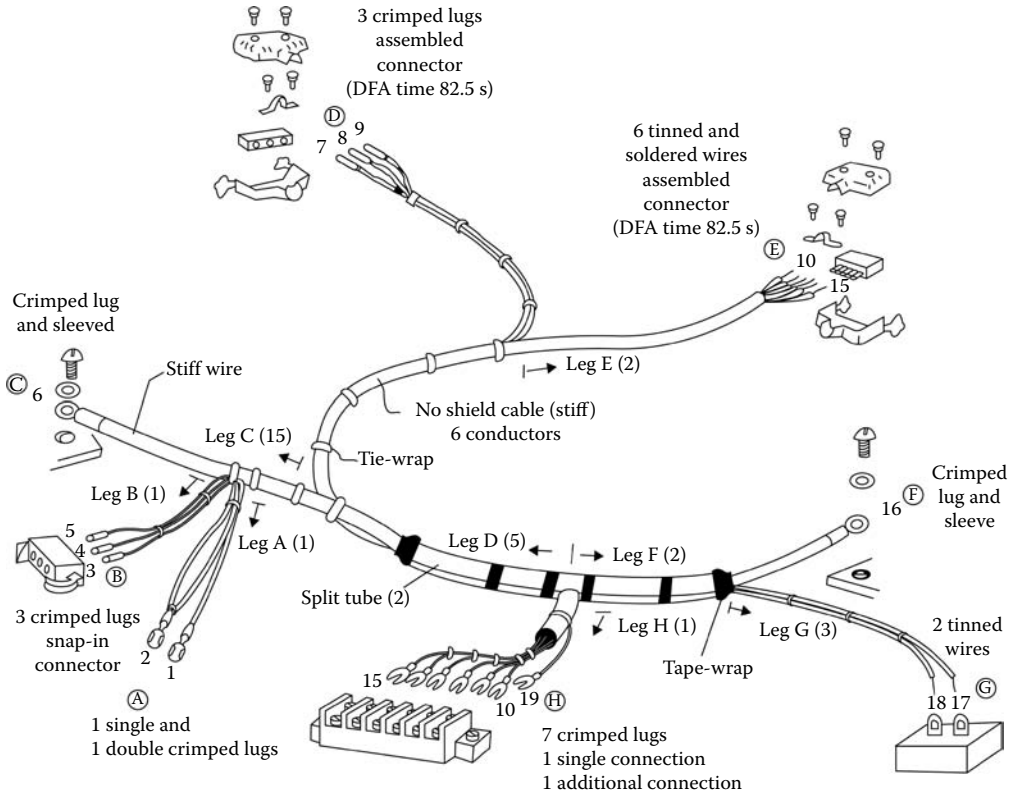
Ultimately, there is a need for two distinct procedures.

1. The procedure introduced here, which is intended for designers who require approximate estimates of preparation, assembly, and installation costs during the early stages of product design.
2. A detailed procedure for those wishing to study various methods for the preparation and assembly of wire harness assemblies.

In the DFA method for manual assembly (Chapter 3), one worksheet is sufficient to record both the handling and insertion times for each item in a subassembly. As we have seen, three distinct steps are necessary for electrical connections and cable harness assembly. In addition, to analyze some operations, such as preparing wire or cable ends, it is convenient to combine each group of wire ends with similar terminations. For other operations, such as laying in the wire on the board or jig, it is convenient to treat the complete lengths of wires or cables separately. For yet other operations, such as applying cable ties, it is convenient to account for these as one group in the later stages of analysis. This means that the overall analysis procedure is considerably more complicated than the DFA method for the manual assembly of mechanical parts.

4.6.1 Procedure

The analysis method involves the completion of worksheets using the data provided in the corresponding tables. The data is mainly derived from Ref. [6]. Many of the activities to be recorded on these worksheets may be performed at various stages of wire harness assembly, depending upon the specific application and complexity of design. For example, insertion of lugged wire ends into connectors may be performed during preparation, harness assembly, or even final installation of the wire harness.



Wires/Cables Run List								
Wires Cables Id	Wires/Cables Description	Wires Cables Length (Ft)	From			To		
			Con. Id	Ter. Id.	Termination Type	Con. Id.	Ter. Id.	Termination Type
W1	Single	5	A	1	Lug	D	7	Lug And Insert
W2	Single	2	A	2	Lug	B	3	Lug And Insert On Board
W3	Single	2	A	2	Lug	B	4	Lug And Insert On Board
W4	Single	4	B	5	Lug And Insert On Board	H	19	Fork Lug
W5	Single/Stiff	5	C	6	Ring Lug And Sleeve	F	16	Ring Lug And Sleeve
W6	Single	8	D	8	Lug And Insert	G	17	Tin
W7	Single	8	D	9	Lug And Insert	G	18	Tin
W8	No Shield Cable 6 Conductors Stiff	6	E	10.15	Tin And Solder	H	20–25	Fork Lug

FIGURE 4.38
Example harness and run list.

Therefore, to simplify the analysis procedure, 10 separate data tables and 11 associated worksheets have been developed [11]. This system of analysis has proved to be the most versatile and efficient method considering the wide range of applications that exist. It relieves the designer from having to consider the order in which individual activities may be performed. Additionally, specific activities that do not apply to a particular application may be omitted from the analysis by simply skipping the irrelevant worksheets.

Figure 4.38 shows an example harness assembly along with its associated run list. Figures 4.39 through 4.49 present the data and worksheets with appropriate entries made in the worksheets for the example harness.

By way of an example, Figure 4.45 shows data chart No. 7 and the corresponding worksheet for lug fastening. It can be seen that the leg of the harness is identified in the first column of the worksheet followed by the two-digit lug fastening code in the second column. This two-digit fastening code is obtained from the data chart and, in the example, the code 20 corresponds to the securing of one fork lug where the screw has previously been inserted into the terminal block and where there are no restrictions to the insertion and fastening operations. This code corresponds to an operation time of 10.4 s, which is entered into column 4 of the worksheet. The number of items to be fastened (six in the example) is placed in column 3 and the resulting total time of 62.4 s is entered into column 5.

4.6.2 Case Study

Figure 4.50 shows an installation consisting of 50 wires with 100 connections to be made. This example comes from a machine control unit manufactured in fairly small quantities. The various legs of the harness are lettered A through T.

Table 4.3 presents the wire run list showing, for each end of the wire, the harness leg, termination type, and connecting points. With the aid of such a chart and the drawing showing the location of wire ties, it is possible to complete the series of worksheets and obtain an estimate of the total wire preparation, harness assembly, and installation times. Table 4.4 shows the results of such an analysis where it can be seen that the three principal activities each contribute significantly to the total time of almost 1 h. Figure 4.51 shows a possible redesign employing ribbon cable and using mass termination techniques for the assembly of connectors onto the cable. In addition, the terminal block in the current design (Figure 4.50) where legs A and B were connected has been eliminated. Finally, the connections between the two printed circuit boards have been replaced with one ribbon cable. It was assumed in the redesign that all the standard items (switches, transformers, etc.) and their connection methods could not be changed. Also, it was assumed that the two printed circuit boards could not be combined.

The analysis of this new design gives the results presented in Table 4.5 where it can be seen that the total assembly time has been reduced to 24.2 mm and that harness assembly has been eliminated.

Clearly, further significant improvements could be made through a complete redesign including the elimination of soldered connections and combination of the printed circuit hoards, but this case study serves to illustrate how the effects of design changes can be quantified in order to guide the designer to less costly and more easily manufactured products.

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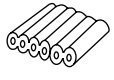
a b													
a) time for tool handling, strip cable jacket, setup machine b) time for each conductor end				Strip	Strip and crimp lug (4)	Strip-crimp lug & sleeve(4,6)	Strip and tin	Insulation displacement	Solder into connector Strip, tin and solder	Strip, tin solder & sleeve	Strip and solder	Strip, solder and sleeve (6)
				0	1	2	3	4	5	6	7	8
Single wire			0	0.0 0.8	2.2 3.9	6.2 18.2	2.2 6.1	32.0 2.1	9.2 19.8	13.2 34.1	7.0 14.5	11.0 28.8
Ribbon cable			1	2.2 0.0	4.4 3.1	8.4 17.4	6.6 5.3	13.8 0.0	13.6 19.0	17.6 33.3	9.2 13.7	13.2 28.0
Cable with multiple wires	No sheild		2	16.4 2.4	18.6 5.5	22.6 19.8	18.6 7.7	46.2 1.3	25.6 21.4	29.6 35.7	23.4 16.1	27.4 30.4
	Sheild (5)		3	38.4 2.4	40.6 5.5	44.6 19.8	40.6 7.7	68.2 1.3	47.6 21.4	51.6 35.7	45.4 16.1	49.4 30.4
Co-axial cable			4	38.4 2.4	40.6 5.5	44.6 19.8	40.6 7.7	68.2 1.3	47.6 21.4	51.6 35.7	45.4 16.1	49.4 30.4

CHART 1 WIRE/CABLE PREPARATION

FIGURE 4.39
Data Chart No. 1 for *Wire/Cable Preparation* and partially completed worksheet.

1. This analysis deals with the preparation of wire and cable ends. Individual legs of the harness are grouped by common preparation codes. The number of different termination styles and the total number of conductor ends to be prepared are then determined for each preparation code. Appropriate times from the chart are entered on the worksheet and a total preparation time calculated.
2. The number of different termination styles used in the legs of the harness, are classified by the preparation code entered in column 2.
3. Where possible, operations are assumed to be semi-automatic. However, certain operations can only be carried out manually. For example: insert wire into connector; remove binding from cable. Hence, if preparation involves any of these operations, the times in the chart include appropriate manual operation time.
4. If multiple wires are connected to one lug, allow the time for one lug on each wire.
5. The times in the chart include time for stripping the outer jacket and peeling back the braided shield. To separate and dress shielding braid, add 129 s.
6. Sleeving includes the time to place a small tube over the crimped connection and heat shrink it in place.

I.D. of leg	**Preparation code**	**Number of different termination styles (2)**	**Number of conductor ends to be prepared**	**Setup time per group of identical terminations (s)**	**Preparation time per conductor end (s)**	**Total preparation time (s)**
1	2	3	4	5	6	$(3 \times 5 + 4 \times 6)$
A, B D, H	01	3	10	2.2	3.9	45.6
C, F						
E						
G						
H						

FIGURE 4.39
Continued.

CHART 2 WIRE/CABLE HANDLING		Basic wire/cable handling time (s)	Additional handling time per foot (s)
Easy to lay-in (e.g. flexible single wire)	0	2.7	0.8
Difficult to lay-in (e.g. stiff wires, multi-wire cable)	1	4.7	1.2
Ribbon cable	2	4.7	1.6

1. This analysis deals with the handling (or laying-in) of wires and cables during assembly of the wire harness on a board or jig. Individual wires or cables are grouped by common handling codes.
2. Use the total length of all wires or cables laid that correspond to a given wire/cable handling code. If several wires having the same path are laid simultaneously, the path should be accounted for only once in determination of the total length of all wire/cable paths.

I.D. of wire or cable	Wire/cable handling code	Number of wires/ cables laid	Total length of all cable paths, ft (2)	Basic handling time (s)	Additional handling time per foot (s)	Total handling time (s)
1	2	3	4	5	6	$(3 \times 5) + (4 \times 6)$
w1, w2, w3, w4, w6, w7	0	6	27	2.7	0.8	37.8
w5, w8	1	2	11	4.7	1.2	22.6
						60.4

FIGURE 4.40
Data Chart No. 2 for *Wire/Cable Handling* and completed worksheet.

CHART 3 ASSEMBLY—INSERTION		No orientation required	Orientation required (4)	
		With alignment features and no resistance to insertion		No alignment features, resistance to, or blind insertion
		0	1	2
Single insertion or multiple insertions on one row	0	1.9	2.2	2.5
Multiple insertions on two rows (requiring two hands)	1	3.5	3.8	4.1
Multiple insertions on > two rows (requiring two hands)	2	3.9	4.2	4.5

1. This analysis deals with the times for the insertion of wire or cable ends into connectors or into temporary holding devices during harness assembly.
2. For insertion operations requiring a tool, add 2.7 s to the insertion time.
3. If a connector requires assembly after the connector ends have been inserted, a DFA time estimate should be added. A typical time would be 82.5 s.
4. For example, insert lug into rectangular snap-in connector. Or, insert previously assembled cable connector into test fixture on assembly board.

I.D. of leg	Insertion code	Number of items to be inserted	Insertion time per item (s)	Connector hardware assembly time (3) seconds	Total insertion time (s)
1	2	3	4	5	$(3 \times 4) + 5$
A	0	2	2.5	-	5.0

FIGURE 4.41
Data Chart No. 3 for *Assembly—Insertion* and partially completed worksheet.

CHART 4 WIRE DRESSING			Time per wire (s)	
			No restrictions	Restricted access (2)
			0	1
Flexible wire	1 wire	0	2.3	6.3
	2 – 5 wires	1	2.3	6.3
	6 – 26 wires	2	8.5	12.5
	> 26 wires	3	10.5	14.5
Stiff wire	1 wire	4	4.7	8.7
	2 – 5 wires	5	9.5	13.5
	6 – 26 wires	6	17.0	21.0
	> 26 wires	7	21.0	25.0

FIGURE 4.42
Data Chart No. 4 for *Dressing* and completed worksheet.

1. This analysis deals with the times for the selection and positioning of wire ends and dressing the ends of the wires or cables. Each item that must be individually positioned and dressed should be included. To determine the appropriate code, count the total number of wires or cables in the leg. For cables or groups of wires terminated in a connector, no dressing is required. Dressing may be needed in harness assembly or in final installation.
2. Restricted access means that restricted space available for positioning and dressing the wire causes a significant increase in time.

I.D. of leg	**Wire dressing code**	**Number of items to be dressed**	**Time per wire end (s)**	**Total dressing time (s)**
1	2	3	4	(3 × 4)
A,G	10	4	2.3	9.2
C,F	50	2	9.5	19.0
H	21	7	12.5	87.5
				115.7

FIGURE 4.42
Continued.

CHART 5 CONNECTOR FASTENING				Time per connector (s)	
				No restrictions	Restricted access (2)
				0	1
Circular connector	Bayonet		0	5.2	9.4
	Friction		1	6.7	10.7
	Screw thread		2	11.3	15.3
Rectangular connector	Latch or snap-on		3	8.1	12.1
	Spring clip		4	9.8	13.8
	With two screws (3)		5	24.4	28.4

FIGURE 4.43
Data Chart No. 5 for *Connector Fastening* and completed worksheet.

1. This analysis deals with the times for installation of connectors into their final location in the chassis (or parent assembly). Individual legs of the wire harness are grouped by common connector fastening codes.
2. Restricted access means that the space available for the insertion of the connector and positioning and dressing the associated wires causes a significant increase in time.
3. Includes tool handling time.

I.D. of leg	Connector fastening code	Number of items to be connected	Time per connector (s)	Total connector fastening time (s)
1	2	3	4	(3 × 4)
B	30	1	8.1	8.1
D,E	40	2	9.8	19.6
				27.7

FIGURE 4.43
Continued.

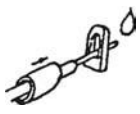
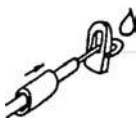
CHART 6 INSTALLATION—WIRE FASTENING				No restrictions		Restricted access (2)	
				Attachment of one wire	Attachment of each additional wire at the same location	Attachment of one wire	Attachment of each additional wire at the same location
				0	1	2	3
Mechanical connections	Insulation disp. cut & snap (3)		0	5.0	-	9.0	-
	Terminal block (4,5)		1	13.9	9.0	17.9	13.0
	Screw fasten (7)		2	20.2	16.5	28.2	24.5
	Screw and nut fasten (6)		3	28.3	16.5	40.3	28.5
	Wrap (7)		4	12.7	12.7	16.7	16.7
Solder connections	Solder (8)		5	13.5	16.5	21.5	24.5
	Solder and sleeve (9)		6	27.8	16.5	35.8	24.5
	Secure and solder		7	19.5	16.5	27.5	24.5
	Secure, solder & sleeve (10)		8	31.5	16.5	39.5	24.5

FIGURE 4.44
Data Chart No. 6 for *Installation—Wire Fastening* and completed worksheet.

1. This analysis deals with the times for connecting and securing separate wire ends. It does not include times for positioning the wires which should be accounted for using Chart 4 (wire dressing).
2. Restricted access means that the space available to insert and secure the wire ends causes a significant increase in time.
3. Includes the average time for either manual or semi-automatic cutting.
4. These times are consistent with the use of a manual screwdriver. If a power tool is used, subtract 2 s from the time per wire end.
5. Includes the time to partially unscrew the nut prior to insertion of the wire end.
6. The screw or nut is grasped and engaged before the wire is secured. An additional 7 s should be added for each washer.
7. For solid wire only.
8. Includes 4.2 s for tool handling.
9. Includes 8.2 s for tool handling.
10. Includes 4.0 s for tool handling.

I.D. of leg	**Wire fastening code**	**Number of items to be fastened**	**Time per wire end (s)**	**Total fastening time (s)**
1	2	3	4	(3 × 4)
G	50	2	13.5	27.0
				27.0

FIGURE 4.44
Continued.

CHART 7 INSTALLATION—LUG FASTENING				No restrictions		Restricted access (2)	
				Attachment of each lug	Attachment of each additional lug at same location	Attachment of each lug	Attachment of each additional lug at same location
				0	1	2	3
Quick connect	Connect		0	2.0	-	6.0	-
	Connect and solder (3)		1	14.0	-	18.0	-
Screw or nut previously inserted (4)	Fork lug (5)		2	10.4	11.0	14.4	15.0
	Ring lug w/screw (6)		3	19.8	18.0	27.8	26.0
	Ring lug w/nut (6)		4	14.6	5.0	22.6	13.0
Screw or nut not previously inserted (4)	Nut fasten (7)		5	13.0	5.0	21.0	13.0
	Screw fasten (7)		6	17.2	18.0	25.2	26.0
	Screw and nut fasten (7)		7	25.3	18.0	37.3	30.0

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FIGURE 4.45
Data Chart No. 7 for *Installation—Lug Fastening* and completed worksheet.

1. This analysis deals with the times for connecting and securing lugged wire ends. It does not include times for positioning the wires which should be accounted for using Chart 4 (wire dressing). Individual legs of the wire harness are grouped by common lug fastening codes.
2. Restricted access means that the space available to insert and secure the wire ends causes a significant increase in time.
3. This is an over secured connection and is not recommended.
4. These times are consistent with the use of a manual screwdriver. If a power tool is used, subtract 3 s from the time per wire end.
5. Includes the time to partially unscrew the screw or nut prior to insertion of the lug.
6. Includes the time to remove the screw or nut before inserting the lug.
7. The screw or nut is grasped and engaged before the lug is secured. An additional 7 s should be added for each washer.

I.D. of leg	**Lug fastening code**	**Number of items to be fastened**	**Time per lug (s)**	**Total fastening time (s)**
1	2	3	4	(3 × 4)
A	00	2	20	4.0
C,F	60	2	24.2	48.4
H	20	6	10.4	62.4
H	21	1	11.0	11.0
				125.8

FIGURE 4.45
Continued.

CHART 8 INSTALLATION—ROUTING

		Routing time (s)	Additional handling time per ft (s)
Easy to route (flexible wire)	0	4.2	0.8
Difficult to route (stiff wire, large bundle)	1	6.2	1.2
Ribbon cable	2	6.2	1.8

1. This analysis deals with the times for routing of the harness within the chassis (or parent assembly). Individual legs of the wire harness are grouped by common routing codes. For each code, the number of separate legs to be routed and the total length of all legs classified is determined. Using the appropriate values from the chart, a total routing time is calculated for each code. If the wire ends or connectors associated with a particular leg are easily connected with no routing required, the leg may be omitted from the analysis.
2. Does not include the time to grasp and secure the wire or cable ends or connectors.

I.D. of leg	Routing code	Number of separate legs to be routed	Total length of legs to be routed, ft (min. 1 ft)	Routing time per leg (s)	Additional time per ft (s)	Total routing time (s)
1	2	3	4	5	6	$(3 \times 5 + 4 \times 6)$
A,B,G	0	3	5	4.2	0.8	16.6
C,D,E F,H	1	5	11.5	6.2	1.2	44.8
						61.4

FIGURE 4.46
Data Chart No. 8 for *Installation—Routing* and completed worksheet.

CHART 9 ADDITIONAL OPERATIONS—A

			Constant time (s) (2)	Time per operation (s)
Label with sticker		0	0.0	10.0
Label with marker		1	2.0	12.4
Cable tie (4)		2	1.9	13.7
Tape—one wrap (4)		3	3.1	2.3
Tape—break out		4	3.1	8.0
Adhesive clamp		5	0.0	14.3
Screw clamp		6	0.0	31.0

1. This is the first of two analyses dealing with the times for additional operations that may be performed at any stage of wire harness assembly. The times for these activities are estimated per occurrence with an additional setup time for tool handling where appropriate. For each operation, the total number of occurrences is entered, together with the number of setups required. The total operation time is then calculated using the appropriate values from the chart.
2. Includes tool handling.

Additional operation code	Number of setups	Number of operations	Constant time (s)	Time per operation (s)	Total operation time (s)
1	2	3	4	5	$(2 \times 4 + 3 \times 5)$
2	1	24	1.9	13.7	330.7

FIGURE 4.47
Data Chart No. 9 for *Additional Operations—A* and partially completed worksheet.

CHART 10 ADDITIONAL OPERATIONS—B

			Constant time (s) (2)	Time per foot (s)
Lacing (stitch)		0	18.8	7.1
Tape a section of wires/cables		1	7.6	13.2
Install tube or sleeve		2	7.9	26.6
Install and shrink tube or sleeve		3	7.9	103.4
Install split tube or sleeve (3)		4	8.0	6.2

1. This is the second of two analyses dealing with the times for additional operations that may be performed at any stage of wire harness assembly. The times for these operations are estimated from the number of operations and the length of the part or section of the harness covered. The total operation time is then calculated using appropriate values from the chart.
2. Includes tool handling.
3. This does not include taping the tube.

Additional operation code	Number of operations	Length for all operations (ft)	Constant time (s)	Time per ft (s)	Total operation time (s)
1	2	3	4	5	$(2 \times 4 + 3 \times 5)$
4	1	2	8.0	6.2	20.4
					20.4

FIGURE 4.48
Data Chart No. 10 for *Additional Operations—B* and completed worksheet.

WIRE HARNESS SUMMARY DATA

	Worksheet	Total time seconds	Total time minutes
Preparation	1		
Assembly	2	60.4	1.0
	3		
Assembly or installation	4	115.7	1.9
Installation	5	27.7	0.5
	6	27.0	0.5
	7	125.8	2.1
	8	61.4	1.0
Additional operations	9		
	10	20.4	0.3

FIGURE 4.49
Wire harness summary data.

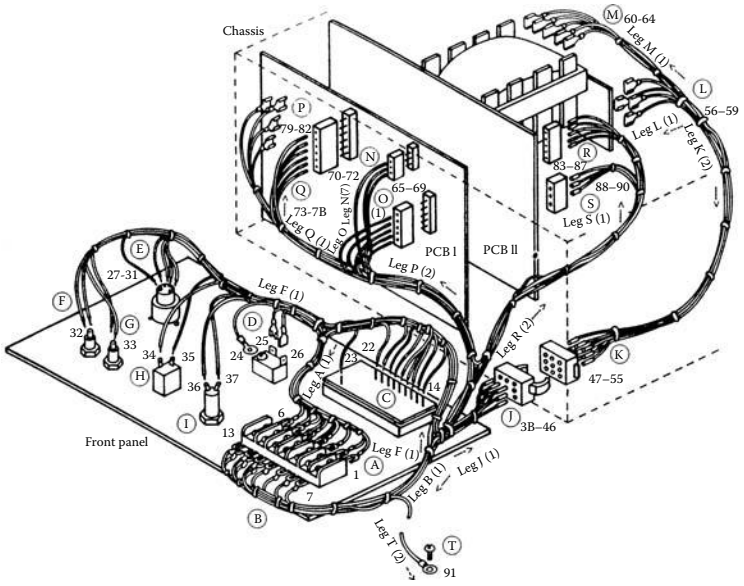

FIGURE 4.50
Current wiring design for a control unit (length in feet).

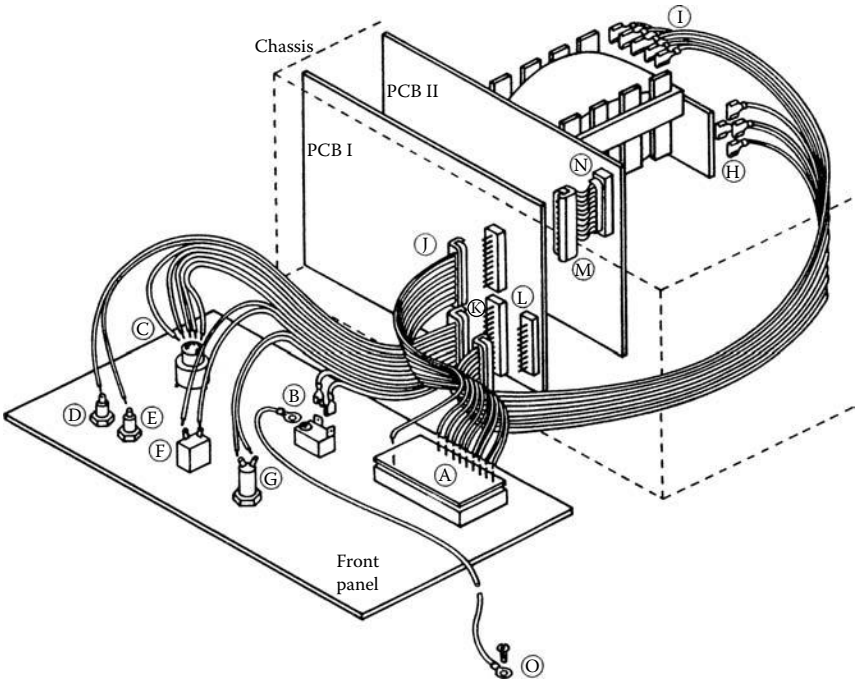

FIGURE 4.51
Proposed wiring design for a control unit.

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TABLE 4.3

Wire Run List for Current Design of Control Unit

		From			To		
Wire ID	**Length (ft)**	**Con. ID**	**No.**	**Termination Type**	**Con. ID**	**No.**	**Termination Type**
1–6	1	A	1–6	Fork lug	C	18–23	Tin (solder and sleeve)
7	1	A	4	Fork lug	D	26	Quick con. lug
8	1	A	5	Fork lug	1	37	Tin (solder)
9	1	A	6	Fork lug	D	24	Ring lug
10–11	1	B	7–8	Fork lug	J	38–39	Lug
12	1	B	3	Fork lug	J	40	Lug
13–15	1	B	10–12	Fork lug	J	41–43	Lug
16	2	B	10	Fork lug	S	88	Lug
17	2	B	11	Fork lug	S	90	Lug
18	2	B	12	Fork lug	S	83	Lug
19	3	B	13	Fork lug	T	91	Ring lug
20	1	B	13	Fork lug	E	31	Tin (solder)
21	2.5	C	15	Tin (solder and sleeve)	P	79	Quick con. lug
22–24	2.5	C	20–22	Tin (solder and sleeve)	P	80–82	Quick con. lug
25	1	D	25	Quick con. lug	I	36	Tin (solder)
26–27	2.5	E	27–28	Tin (solder and sleeve)	Q	73–74	Lug
28	1	E	29	Tin (solder and sleeve)	F	32	Tin (solder)
29	1	E	30	Tin (solder and sleeve)	G	33	Tin (solder)
30	3	F	32	Tin (solder)	Q	75	Lug
31	3	G	33	Tin (solder)	Q	76	Lug
32	3	H	34	Tin (solder)	Q	73	Lug
33	3	H	35	Tin (solder)	Q	78	Lug
34–36	1.5	J	44–46	Lug	N	70–72	Lug
37–40	1.5	K	47–50	Lugs	L	56–59	Quick con. lugs
41–45	2	K	51–55	Lugs	M	60–64	Quick con. lugs
46–50	3	O	65–69	Lugs	R	83–87	Lugs

TABLE 4.4

Analysis Results for Current Design of Control Unit

	Time (s)	**Time (min)**
Preparation	800.1	13.3
Assembly	1236.7	21.6
Installation	1350	22.5
Totals	3446.8	57.4

TABLE 4.5

Analysis Results for Proposed Design of Control Unit

	Time (s)	**Time (min)**
Preparation	576.8	9.6
Assembly	0	0
Installation	875.6	14.6
Totals	1452.4	24.2

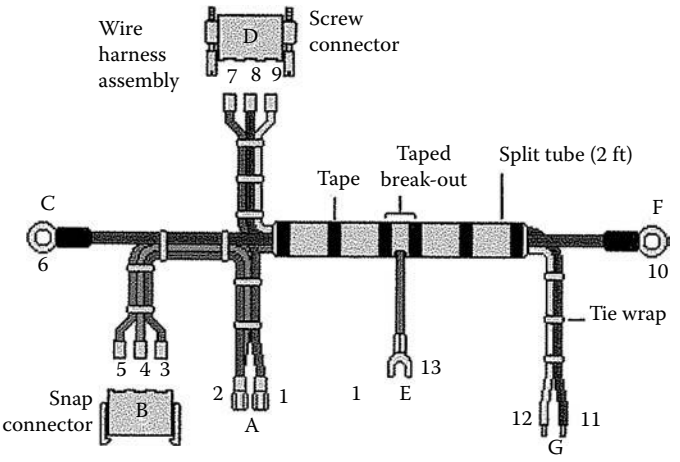

FIGURE 4.52
Sample harness assembly.

PROBLEMS

1. Complete all the partially completed worksheets for the sample analysis in this chapter.
2. Obtain the assembly time for the harness shown in Figure 4.52.

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5

Design for High-Speed Automatic Assembly and Robot Assembly

5.1 Introduction

Although design for assembly is an important consideration for manually assembled products and can reap enormous benefits, it is vital when a product is to be assembled automatically. The simple example shown in Figure 5.1 illustrates this. The slightly asymmetrical threaded stud would not present significant problems in manual handling and insertion, whereas for automatic handling an expensive vision system would be needed to recognize its orientation. If the part were made symmetrical, automatic handling would be simple. For economic automatic assembly therefore, careful consideration of product structure and component part design is essential. In fact, it can be said that one of the advantages of introducing automation in the assembly of a product is that it forces a reconsideration of its design—thus offering not only the benefits of automation, but also those of improved product design. Not surprisingly, the savings resulting from product redesign often outweigh those resulting from automation.

The example of the part in Figure 5.1 illustrates a further point. The principal problems in applying automation usually involve the automatic handling of the parts rather than their insertion into the assembly. To quote an individual experienced in the subject of automatic assembly "if a part can be handled automatically, then it can usually be assembled automatically." This means that, when we consider design for automation, we would be paying close attention to the design of the parts for ease of automatic feeding and orienting.

In considering manual assembly we were concerned with prediction of the time taken to accomplish the various tasks such as grasp, orient, insert, and fasten. From knowledge

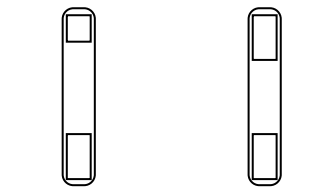


FIGURE 5.1
Design change to simplify automatic feeding and orienting.

of the assembly worker's labor rate we could then estimate the cost of assembly. In automatic assembly, the time taken to complete an assembly does not control the assembly cost. Rather, it is the rate at which the assembly machine or system cycles, because, if everything works properly, a complete assembly is produced at the end of each cycle. Then, if the total rate (cost per unit time) for the machine or system and all the operators is known, the assembly cost can be calculated after allowances are made for down-time. Thus, we shall be mainly concerned with the cost of all the equipment, the number of operators and technicians, and the assembly rate at which the system is designed to operate. However, so that we can identify problems associated with particular parts, we shall need to apportion the cost of product assembly between the individual parts and, for each part, and we shall need to know the cost of feeding and orienting and the cost of automatic insertion.

In the following discussion, we first look at product design for high-speed automatic assembly using special-purpose equipment and then we consider product design for robot assembly (i.e., using general-purpose equipment).

5.2 Design of Parts for High-Speed Feeding and Orienting

The cost of feeding and orienting parts depend on the cost of the equipment required and on the time interval between delivery of successive parts. The time between the delivery of parts is the reciprocal of the delivery rate and is nominally equal to the cycle time of the machine or system. If we denote the required delivery or feed rate F_r (parts/min), then the cost of feeding each part C_f is given by

$$C_f = \left(\frac{60}{F_r}\right) R_f \text{ cents} \tag{5.1}$$

where R_f is the cost (cents/s) of using the feeding equipment.

Using a simple payback method for estimation of the feeding equipment rate R_f, this is given by

$$R_f = \frac{C_F E_o}{(5760 P_b S_n)} \text{ cents/s} \tag{5.2}$$

where C_F is the feeder cost (\$), E_o is the equipment factory overhead ratio, P_b is the payback period in months, and S_n is the number of shifts worked per day. The constant 5760 is the number of available seconds in one shift working for one month divided by 100 to convert dollars to cents.

For example, if we assume that a standard vibratory bowl feeder costs \$5000 after installation and debugging, that the payback period is 30 months with 2 shifts working, and that the factory equipment overheads are 100% ($E_o = 2$), we get

$$R_f = \frac{5000 \times 2}{(5760 \times 30 \times 2)}$$
$$= 0.03 \text{ cent/s}$$

In other words, it would cost 0.03 cents to use the equipment for 1 s. Supposing that we take this figure as the rate for a "standard" feeder and we assign a relative cost factor C_r to any feeder under consideration, then Equation 5.1 becomes

$$C_f = 0.03\left(\frac{60}{F_r}\right)C_r \tag{5.3}$$

Thus, we see that the feeding cost per part is inversely proportional to the required feed rate and proportional to the feeder cost.

To describe these results in simple terms, we can say that for otherwise identical conditions it would cost twice as much to feed each part to a machine with a 6 s cycle compared with the cost for a machine with a 3 s cycle. This illustrates why it is difficult to justify feeding equipment for assembly systems with long cycle times.

For the second result, we can simply state that for otherwise constant condition, it would cost twice as much to feed a part using a feeder costing $10,000 compared with a feeder costing $5000.

If the feeding cost for a particular feeder is plotted against the required feed rate F_r on logarithmic scales, a linear relationship results, as shown in Figure 5.2. It appears that the faster the parts are required, the lower the feeding cost. This is true only as long as there is no limit on the speed at which a feeder can operate. Of course, there is always an upper limit to the feed rate obtainable from a particular feeder. We shall denote this maximum feed rate by F_m and consider the factors that affect its magnitude. However, before doing so, let us look at its effect through an example.

Suppose that the maximum feed rate from our feeder is 10 parts/min. Then if parts are required at a rate of 5 parts/min, the feeder can simply be operated more slowly involving an increased feeding cost as given by Equation 5.3 and illustrated in Figure 5.2. Suppose that parts are required at a rate of 20 parts/min. In this case two feeders could be used, each delivering parts at a rate of 10 parts/min. However, the feeding cost per part using two feeders to give twice the maximum feed rate would be the same as one feeder delivering parts at its maximum feed rate. In other words, if the required feed rate is greater than the maximum feed rate obtainable from one feeder, the feeding cost becomes constant and equal to the cost of feeding when the feeder is operating at its maximum rate. This is

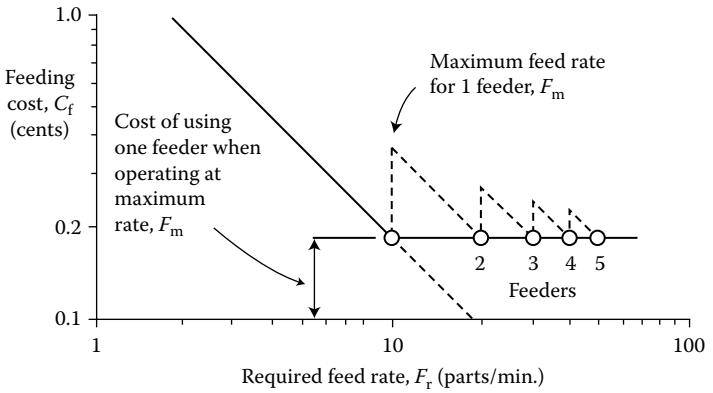


FIGURE 5.2
Effect of required feed rate on feeding cost.

shown in Figure 5.2 by the horizontal line. If multiple feeders are used for increased feed rates, then the line will be saw-toothed as shown. However, in practice, the line can be smoothed by spending more on feeders to improve their performance when necessary.

From this discussion, we can say that Equation 5.3 holds true only when the required feed rate F_r is less than the maximum feed rate F_m, and when this is not the case the feeding cost is given by

$$C_r = 0.03\left(\frac{60}{F_m}\right)C_r \tag{5.4}$$

Now the maximum feed rate F_m is given by

$$F_m = 1500\frac{E}{l} \text{ parts/min} \tag{5.5}$$

where E is the orienting efficiency for the part and l (mm) is its overall dimension in the direction of feeding and where it is assumed that the feed speed is 25 mm/s.

To illustrate the meaning of the orienting efficiency E, we can consider the feeding of dies (cubes with faces numbered 1–6). Suppose that if no orientation is needed, the dies can be delivered at a rate of 1 per second from a vibratory bowl feeder. However, if only those dies with the 6 side uppermost were of interest, a vision system could be employed to detect all other orientations and a solenoid-operated pusher could be used to reject them. In this case, the delivery rate would fall to an average of 1 die every 6 s or a feed rate of 1/6 per second. The factor 1/6 is defined as the orienting efficiency E and it can be seen that the maximum feed rate is proportional to the orienting efficiency (Equation 5.5).

Now let us suppose our dies were doubled in size and that the feed speed or conveying velocity on the feeder track were unaffected. It would then take twice as long to deliver each die. In other words, the maximum feed rate is inversely proportional to the length of the part in the feeding direction (Equation 5.5).

Equation 5.4 shows that when $F_r > F_m$, the feeding cost per part is inversely proportional to F_m. It follows that under these circumstances, the cost of feeding is inversely proportional to the orienting efficiency and proportional to the length of the part in the feeding direction.

This latter relationship illustrates why automatic feeding and orienting methods are only applicable to "small" parts. In practice, this means that parts larger than about 8 in. in their major dimension cannot usually be fed economically.

When considering the design of a part and its feeding cost, the designer would know the required feed rate and the dimensions of the part. Thus, F_r and l would be known. The remaining two parameters that affect feeding cost, namely, the orienting efficiency E and the relative feeder cost C_r, would depend on the part symmetry and the types of features that define its orientation. A classification system for part symmetry and features has been developed [1] and for each part classification the average magnitudes of E and C_r have been determined [2]. This classification system and data are presented in Figures 5.3 through 5.5. Figure 5.3 shows how parts are categorized into basic types, either rotational or nonrotational. For rotational parts, their cylindrical envelopes are classified as discs, short cylinders, or long cylinders. For nonrotational parts, the subcategories are flat, long, or cubic depending on the dimensions of the sides of the rectangular envelope.

Figure 5.3 gives the first digit of a three-digit shape code. Figure 5.4 shows how the second and third digits are determined for rotational parts (first digit 0, 1, or 2) and gives

Rotational	Discs	L/D < 0.8	0
	Short cylinders	0.8 ≤ L/D ≤ 1.5	1
	Long cylinders	L/D > 1.5	2
Nonrotational	Flat	A/B ≤ 3 A/C > 4	6
	Long	A/B > 3,	7
	Cubic	A/B ≤ 3 A/C ≤ 4	8

Notes:

1. A part whose basic shape is a cylinder or regular prism whose cross section is a regular polygon of five or more sides is called a rotational part. In addition, triangular or square parts that repeat their orientation when rotated about their principal axis through angles of 120° or 90°, respectively, are rotational parts.
2. L is the length and D is the diameter of the smallest cylinder that can completely enclose the part.
3. A is the length of the longest side, C is the length of the shortest side and B is the length of the intermediate side of the smallest rectangular prism that can completely enclose the part.

FIGURE 5.3
First digit of geometrical classification of parts for automatic handling. (From Boothroyd, G and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, Rl, 1986. With permission.)

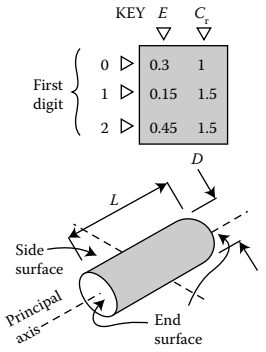
the corresponding values of the orienting efficiency E and the relative feeder cost C_r. Similarly, Figure 5.5 shows how the second and third digits are determined for nonrotational parts (first digit 6, 7, or 8). The geometrical classification system was originally devised by Boothroyd and Ho [1] as a means of cataloging solutions to feeding problems.

5.3 Example

Suppose that the part shown in Figure 5.6 is to be delivered to an automatic assembly station working at a 5 s cycle. We now use the classification system and database to determine the feeding cost and assume that the cost of delivering simple parts at 1 per second using our "standard" feeder is 0.03 cents per part.

First, we must determine the classification code for our part. Figure 5.6 shows that the rectangular envelope for the part has the dimensions $A = 30$ mm, $B = 20$ mm, and $C = 15$ mm.

Thus, $A/B = 1.5$ and $A/C = 2$. Referring to Figure 5.3, since A/B is less than 3 and A/C is less than 4, the part is categorized as cubic nonrotational and is assigned a first digit of 8. Turning to Figure 5.5, which provides a selection of data for nonrotational parts, we first determine that our example part has no rotational symmetry about any of its axes. Also, we must decide whether the part's orientation can be determined by one main feature. Looking at the silhouette of the part in the X direction, we see a step or projection in the basic rectangular shape and we realize that this feature alone can always be used to



			AUTOMATIC HANDLING-DATA FOR ROTATIONAL PARTS (first digit 0, 1 or 2)															
			Part is symmetrical about its principal axis (BETA symmetic) (see note 2)		Part is not BETA symmetric (code the main feature or features requiring orientation about the principal axis)													
					BETA asymmetric projections, steps, or chamfers (can be seen in silhouette)						BETA asymmetric grooves or flats (can be seen in silhouette)						Slightly asymmetric or small features less than D/10 and L/10 or holes or recesses which cannot be seen in outer shape of silhouette	
					On side surface only		On end surface(s) only		On both side and end surface(s)		Through groove or flat can be seen in end view		Through groove can be seen in side view					
													On end surface		On side surface			
			0		**2**		**3**		**4**		**5**		**6**		**7**		**8**	
Part is ALPHA symmetric (see note 1)		**0**	0.7	1	0.3	1	0.5	1	0.3	1	0.35	1	0.2	1	0.5	1	MANUAL HANDLING REQUIRED	
			0.7	1	0.15	1	0.2	1	0.15	1	0.2	1	0.2	1	0.2	1		
			0.9	1	0.45	1	0.9	2	0.45	1	0.9	1	0.9	2	0.9	2		
Part is not ALPHA symmetric (code the main feature or features requiring end-to-end orientation) (see note 1)	Part can be fed in a slot supported by large end or protruding flange	**1**	0.4	1	0.2	1	0.25	1	0.2	1	0.2	1	0.1	1	0.25	1		
			0.3	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1		
			0.9	1	0.45	1	0.9	2	0.45	1	0.9	1	0.9	2	0.9	1		
	BETA symmetric steps or chamfers on external surfaces (see note 3)	**2**	0.4	1	0.15	1	0.25	1	0.15	1	0.35	1	0.1	1	0.25	1		
			0.3	1	0.1	1.5	0.1	1.5	0.1	1.5	0.2	1.5	0.05	1.5	0.1	1.5		
			0.75	1	0.37	1.5	0.25	3	0.37	2.5	0.5	1	0.5	3	0.5	2		
	BETA symmetric groves holes or recesses (see note 3) — On both side and end surface(s)	**3**	0.5	1	0.15	1	0.25	1	0.15	1	0.2	1	0.1	3	0.25	1		
			0.2	1	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.05	1.5	0.1	1.5		
			0.85	1	0.48	1.5	0.25	2	0.43	1.5	0.5	1	0.5	2	0.5	2		
	BETA symmetric groves holes or recesses (see note 3) — On side surface only	**4**	0.5	1	0.15	1	0.25	1	0.15	1	0.2	1	0.1	1	0.25	1		
			0.1	1	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.05	1.5	0.1	1.5		
			0.85	1	0.43	1.5	0.25	2	0.13	1.5	0.5	1	0.5	2	0.5	2		
	BETA symmetric groves holes or recesses (see note 3) — On end surface(s) only	**5**	0.5	1	0.15	1	0.25	1	0.15	1	0.2	1	0.1	1	0.25	1		
			0.2	1	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.05	1.5	0.1	1.5		
			0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.15	1	0.45	2	0.45	2		
	BETA symmetric hidden features with no corresponding exposed features (see note 4)	**6**																
			0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
	BETA asymmetric features on side or end surface(s)	**7**					0.25	1	0.1	1			0.1	1	0.25	1		
					0.27	2	0.1	1.5	0.05	1.5	0.1	3	0.05	1.5	0.1	1.5		
							0.25	3	0.27	2			0.5	3	0.5	3		
	Slightly asymmetric or small features amount of asymmetry or feature size less than D/10 and L/10	**8**	MANUAL HANDLING REQUIRED															

Notes:

1. A rotational part is alpha symmetric if it does not require orienting end-to-end. If a part can only be inserted into the assembly in one direction then it is referred to as "not alpha symmetric."
2. A beta-symmetric part has rotational symmetry and therefore does not require orienting about its principal axis.
3. A beta-symmetric step, chamfer or groove is a concentric reduction or increase in diameter; its cross section can be circular or any regular polygon. Less significant features should be ignored.
4. Parts in this category have an alpha-symmetric external shape, but the internal surface (composed perhaps of cavities, counterbores, grooves, etc.) requires that the part be oriented end to end.

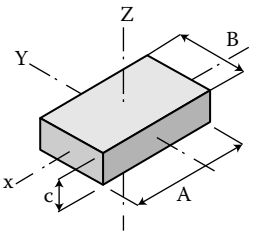
FIGURE 5.4
Second and third digits of geometrical classification for rotational parts. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

AUTOMATIC HANDLING-DATA FOR NON-ROTATIONAL PARTS
(first digit 6, 7 or 8)

KEY E C_r

First digit	E	C_r
6	0.7	1
7	0.45	1.5
8	0.3	2

		A > 1.1B and B > 1.1C	A ≤ 1.1B or B ≤ 1.1C (Code the main feature or features which distinguish the adjacent surfaces having similar dimensions)									
			Steps or chamfers (2) parallel to-			Through grooves (2) parallel to-			Holes for recesses > 0.1B (cannot be seen in silhouette)	Other including slight asymmetry (3), features too small etc
			X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Part has 180° symmetry about all three axes (1)	**0**	0.8 1 0.9 1 0.6 1	0.8 1 0.9 1 0.5 1	0.2 1 0.5 2 0.15 2	0.5 1 0.5 1.5 0.15 1.5	0.75 1 0.5 1 0.5 1	0.25 1 0.5 1.5 0.15 1	0.5 1.6 0.6 1 0.15 1.5	0.25 2 0.5 1 0.15 2	Manual handling required



			Code the main feature or if orientation is defined by more than one feature, then code the feature that gives the largest third digit							
			Steps or chamfers (2) parallel to-			Through grooves (2) parallel to-			Holes for recesses > 0.1B (cannot be seen in silhouette)	Other including slight asymmetry (3), features too small etc
			X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Part has 180° symmetry about one axis only (1)	About X axis	**1**	0.4 1 0.5 1 0.4 1	0.6 1 0.15 1 0.6 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.5 1 0.2 1	0.3 1 0.25 1 0.3 1	0.7 1 0.25 1.5 0.15 1	0.4 2 0.25 3 0.1 2	MANUAL HANDING REQUIRED
	About Y axis	**2**	0.4 1 0.4 1 0.5 1	0.3 1 0.2 1 0.15 1	0.4 1.5 0.25 2 0.5 2	0.5 1 0.4 1 0.2 1	0.3 1 0.25 1 0.15 1	0.4 1 0.25 1 0.15 2	0.4 2 0.25 2 0.15 2	
	About Z axis	**3**	0.4 1 0.3 1 0.4 1	0.3 1 0.2 1 0.2 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.3 1 0.2 1	0.3 1 0.25 1 0.15 1	0.1 1.5 0.25 2 0.15 2	0.4 2 0.25 2 0.15 2	
Part has no symmetry (code the main feature(s) that define the orientation) (4)	Orientation defined by one main feature	**4**	0.25 1 0.25 1 0.15 1	0.15 1 0.1 1.5 0.14 1	0.15 1.5 0.24 2 0.15 1	0.1 1 0.2 1 0.1 1	0.25 1 0.1 1.5 0.05 1	0.1 1.5 0.15 2 0.1 1.5	0.1 2 0.15 3 0.08 2	
	Orientation defined by two main features and one is a step, chamfer or groove	**6**	0.2 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 3 0.1 5 0.05 3	
	Other including slight asymmetry (3) etc.	**9**	MANUAL HANDLING REQUIRED							

Notes:

1. A rotational symmetry of 180° about an axis means that the same orientation of the part will be repeated only once by rotating the part through 180° about that axis.
2. Steps, chamfers, or through grooves are features that can be seen in silhouette.
3. Exposed features are prominent but the asymmetry caused by these features is less than 0.1 of the appropriate envelope dimension. For a part that has 180° rotational symmetry about a certain axis, slight asymmetry implies that the part has almost 90° rotational symmetry about that axis.
4. A part having no rotational symmetry means that the same orientation of the part will not be repeated by rotating the part through any angle less than 360° about any one of the three axes X, Y, or Z.

   A main feature is a feature that is chosen to define the orientation of the part. All the features that are chosen to completely define the orientation of the part should be necessary and sufficient for the purpose.

   Often, features arise in pairs or groups and the pair or group of features is symmetric about one of the three axes X, Y, or Z. In this case, the pair or group of features should be regarded as one main feature. Using this convention, two main features at most are needed to completely define the orientation of a part.

FIGURE 5.5
Second and third digits of geometrical classification for nonrotational parts. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

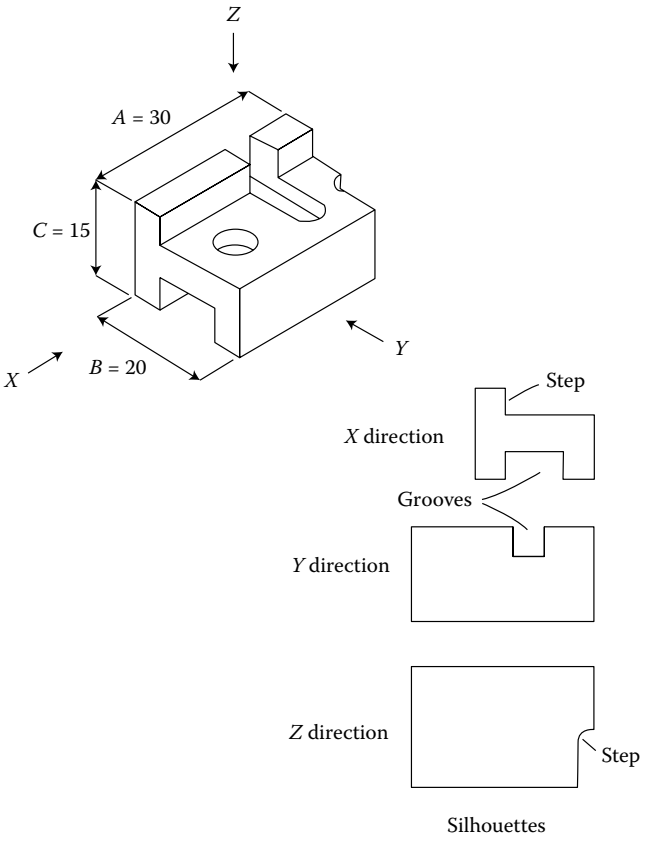


FIGURE 5.6
Sample part.

determine the part's orientation. This means that if the silhouette in the *X* direction is oriented as shown in Figure 5.6, the part can be in only one orientation and, therefore, the second digit of the classification is 4. However, either the groove apparent in the view in the *Y*-direction and the step seen in the view in the *Z*-direction could also be used to determine the part's orientation. The procedure now is to select the feature giving the smallest third classification digit; in this case it is the step seen in the *X*-direction. Thus, the appropriate column number in Figure 5.5 is 0. The three-digit code is thus 840 and corresponding values of orienting efficiency $E = 0.15$ and relative feeder cost $C_r = 1$.

Using the fact that the longest part dimension l is 30 mm and that the orienting efficiency E is 0.15, Equation 5.5 gives the maximum feed rate obtainable from one feeder; thus

$$\begin{aligned} F_m &= 1500\frac{E}{l} \\ &= 1500 \times \frac{0.15}{30} \\ &= 7.5 \text{ parts/min} \end{aligned}$$

Now, from the cycle time of 5 s the required feed rate F_r is 12 parts per min, which is higher than F_m. Therefore, since $F_r > F_m$ we use Equation 5.4 and since $C_r = 1$ we get a feeding cost of

$$\begin{aligned} C_r &= 0.03\left(\frac{60}{F_m}\right)C_r \\ &= 0.03\left(\frac{60}{7.5}\right)1 \\ &= 0.24 \text{ cents} \end{aligned}$$

5.4 Additional Feeding Difficulties

In addition to the problems of using the part's geometric features to orient it automatically, other part characteristics can make feeding particularly difficult. For example, if the edges of the parts are thin, shingling or overlapping may occur during feeding, which leads to problems with the use of orienting devices on the feeder track (Figure 5.7).

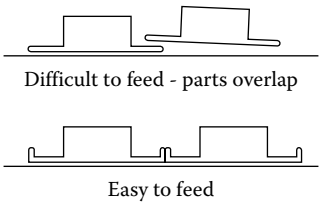


FIGURE 5.7
Parts that shingle or overlap on the feeder track.

Many other features can affect the difficulty of feeding the part automatically and can lead to considerable increases in the cost of developing the automatic feeding device. These features can also be classified as shown in Figure 5.8, where, for each combination of features, an approximate additional relative feeder cost is given that should be taken into account in estimating the cost of automatic feeding.

5.5 High-Speed Automatic Insertion

If a part can be sorted from bulk and delivered to a convenient location correctly oriented, a special-purpose mechanism or workhead can usually be designed that would place it in the assembly. Such workheads can generally be built to operate on a cycle as short as 1 s. Thus, for assembly machines operating on cycles greater than 1 s, the automatic insertion cost C_i is given by

$$C_i = \left(\frac{60}{F_r}\right)R_i \tag{5.6}$$

where F_r is the required assembly rate (or feed rate of parts) and R_i is the cost (cents/s) of using the automatic workhead.

AUTOMATIC HANDLING-ADDITIONAL FEEDER COSTS

Figures to be added to C_r					Parts will not tangle or nest				Tangle or nest but not severely					
					Not light		Light		Not light		Light			
					Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Severely tangle	Severely tangle
					0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Parts are small and non-abrasive	Parts do not tend to overlap during feeding	Not delicate	Non-flexible	**0**	0	1	2	3	2	3	3	4	MANUAL HANDLING REQUIRED	
			Flexible	**1**	2	3	4	5	4	5	5	6		
		Delicate	Non-flexible	**2**	1	2	3	4	3	4	4	5		
			Flexible	**3**	3	4	5	6	5	6	6	7		
	Parts tend to overlap during feeding	Not delicate	Non-flexible	**4**	2	3	3	4	4	5	4	5		
			Flexible	**5**	4	5	5	6	6	7	6	7		
		Delicate	Non-flexible	**6**	3	4	4	5	5	6	5	6		
			Flexible	**7**	5	6	6	7	7	8	7	8		

		Very small parts					Large parts				
		Rotational		Non-rotational			Rotational		Non-rotational		
		L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3 A/C > 4	A/B > 3	A/B ≤ 3 A/C ≤ 4	L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3 A/C > 4	A/B > 3	A/B ≤ 3 A/C ≤ 4
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Parts are very small or large but are nonabrasive	**8**	2	2	2	2	2	9	9	9	9	9

		Parts will not severely tangle or nest									
		Small parts					Large parts		Very small parts		
		Orientation defined by geometric features			Orientation defined by non-geometric features		Orientation defined by geometric features	Orientation defined by non-geometric features	Orientation defined by geometric features	Orientation defined by non-geometric features	Severely tangle or nest
		Non-flexible		Flexible							
		Do not overlap	Overlap		Do not overlap	Overlap					
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Abrasive parts	**9**	2	4	4			9		4		

Notes:

Flexible: A part is considered flexible if the part cannot maintain its shape under the action of automatic feeding so that orienting devices cannot function satisfactorily.

Delicate: A part is considered delicate if damage may occur during handling, either due to breakage caused by parts falling from orienting sections or tracks onto the hopper base, or due to wear caused by recirculation of parts in the hopper. When wear is the criterion, a part would be considered delicate if it couid not recirculate in the hopper for 30 min and maintain the required tolerance.

Sticky: If a force, comparable to the weight of a nontangling or nonnesting part, is required to separate it from bulk, the part is considered sticky.

Light: A part is considered too light to be handled by conventional hopper feeders if the ratio of its weight to the volume of its envelope is less than 1.5 kN/m^3.

FIGURE 5.8

Additional relative feeder costs for a selection of feeding difficulties. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

Overlap: Parts will tend to overlap in a feeder when an alignment of better than 0.2 mm is required to prevent shingling or overlapping during feeding in single file on a horizontal track.

Large: A part is considered to be too large to be readily handled by conventional hopper feeders when its smallest dimension greater than 50 mm or if its maximum dimension is greater than 150 mm. A part is considered to be too large to be handled by a particular vibratory hopper feeder if L > d/8, where L is the length of the part measured parallel to the feeding direction and d is the feeder or bowl diameter.

Very small: A part is considered to be too small to be readily handled by conventional hopper feeders when its largest dimension is less than 3 mm. A part is considered to be too small to be readily handled by a particular vibratory hopper feeder if its largest dimension is less than the radius of the curved surface joining the hopper wall and the track surface measured in a plane perpendicular to the feeding direction.

Nest: Parts are considered to nest if they interconnect when in bulk, causing orientation problems. No force is required to separate the parts when they are nested.

Severely nest: Parts are considered to severely nest if they interconnect and lock when in bulk and require a force to separate them.

Tangle: Parts are said to tangle if a reorientation is required to separate them when in bulk.

Severely tangle: Parts are said to severely tangle if they require manipulation to specific orientations and a force is required to separate them.

Abrasive: A part is considered to be abrasive if it may cause damage to the surface of the hopper feeding device unless these surfaces are specially treated.

FIGURE 5.8
Continued.

Again, using a simple payback method for estimation of the equipment rate R_i, this is given by

$$R_i = \frac{W_c E_o}{(5760 P_b S_n)} \text{ cents/s} \tag{5.7}$$

where W_c is the workhead cost (\$), E_o is the equipment factory overhead ratio, P_b is the payback period in months, and S_n is the number of shifts worked per day.

If we assume that a standard workhead costs \$10,000 after installation and debugging, that the payback period is 30 months with two shifts working, and the factory equipment overheads are 100% ($E_o = 2$), we get

$$R_i = \frac{10,000 \times 2}{(5760 \times 30 \times 2)}$$
$$= 0.06 \text{ cents/s}$$

In other words, it would cost 0.06 cents to use the equipment for 1 s. If we take this figure as the rate for a "standard" workhead and we assign a relative cost factor W_r to any workhead under consideration, then Equation 5.6 becomes

$$C_i = 0.06\left(\frac{60}{F_r}\right)W_r \tag{5.8}$$

Thus, the insertion cost is inversely proportional to the required assembly rate and proportional to the workhead cost.

When considering the design of a part, the designer knows the required assembly rate F_r. For the presentation of relative workhead costs, a classification system for automatic insertion similar to that for manual insertion was devised [2] and is shown in Figure 5.9. It can be seen that this classification system is similar to that of manual insertion of parts except that the first digit is determined by the insertion direction rather than whether obstructed access or restricted vision occurs.

AUTOMATIC INSERTION - RELATIVE WORKHEAD COST, W_c

Key:

Part added but not secured

Part secured immediately

Separate operation

Assembly process where all solid parts in place or non-solids added or parts are manipulated

		After assembly no holding down required to maintain orientation and location (5)				Holding down required during subsequent process(es) to maintain orientation and location (5)			
		Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)	
		No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)
		0	**1**	**2**	**3**	**6**	**7**	**8**	**9**
No final securing is taking place (2)	Straight line insertion — From vertically above	**0**	1	1.5	1.5	2.3	1.3	2	2	3
	Straight line insertion — Not from vertically above (3)	**1**	1.2	1.6	1.6	2.5	1.6	2.1	2.1	3.3
	Insertion not straight line motion (4)	**2**	2	3	3	4.6	2.7	4	4	6.1

		No screwing operation or plastic deformation immediately after insertion (snap of press fits, etc.)		Plastic deformation immediately after insertion						Screwing immediately after insertion	
				Plastic bending			Rivetting of similar plastic deformation				
				Easy to align and position (6)	Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)	Not easy to align or position (no features provided for the purpose)			
		Easy to align and position (6) no resistance to insertion	Not easy to align or position and/or resistance to insertion		No resistance to insertion	Resistance to insertion (7)		No resistance to insertion	Resistance to insertion (7)	Easy to align and position (6) no resistance to screwing	Not easy to align or position and/or resistance to screwing (7)
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Addition of any part (1) where final securing is taking place	Straight line insertion — From vertically above	**3**	1.2	1.9	1.6	2.4	3.6	0.9	1.4	2.1	0.8	1.8
	Straight line insertion — Not from vertically above (3)	**4**	1.3	2.1	2.1	3.2	4.8	1	1.5	2.3	1.3	2
	Insertion not straight line motion (4)	**5**	2.4	3.8	3.2	4.8	7.2	1.8	2.8	4.2	3.6	3.6

		Mechanical fastening processes (parts already in place)				Non-mechanical fastening processes (parts already in place)				Non- fastening processes	
		None or localized plastic deformation				Metallurgical processes					
							Additional material required				
		Bending or similar processes	Rivetting or similar processes	Screwing or other processes	Snap fit, snap clip, press fit, etc.	No additional of material (friction or resistance welding, etc.)	Soldering processes	Welding or brazing	Chemical processes (adhesive bonding etc.)	Manipulation of parts or sub-assembly (orienting, fitting, adjustment etc.)	Other processes (liquid insertion etc.)
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Assembly process where all solid parts in place or non-solids added or parts are manipulated		**9**	1.6	0.9	0.8	1.6	1.2	1.1	1.1	0.8	1.5	

FIGURE 5.9
Relative workhead costs W_r for a selection of automatic insertion situations. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

Notes:

1. A part is a solid or nonsolid element of an assembly added during an assembly process. A subassembly is considered a part if it is added to an assembly. However, adhesive, fluxes, fillers, and so on, used for joining parts are not considered to be parts.
2. Part addition involves part placing or insertion processes only. Part may be a fastener that is not securing any other part or parts immediately.
3. Placing or insertion of the part into the assembly necessitates access motions from a direction other than vertically above (e.g., from the side or from below, etc.).
4. Part cannot be placed or inserted by a simple single-axis straight-line motion, for example, part access may be obstructed requiring a change in the direction of motion during insertion.
5. Part is unstable after placement or insertion or during subsequent operations an will require gripping realignment or holding down until it is finally secured. *Holding down* refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to or during the next assembly operation or during transfer of the assembly to the next workstation. A part is *located* if it will not require holding down or realignment for subsequent operations, and it is only partially secured.
6. A part is easy to align and position if the position of the part is established by locating features on the part, or on its mating part, and insertion is facilitated by well-designed chamfers or similar features.
7. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For exmaple, a press fit is an interferences fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

FIGURE 5.9
Continued.

5.6 Example

If the part shown in Figure 5.6 is inserted horizontally into the assembly in the direction of the arrow Y and it is not easy to align and position and not secured on insertion, then the appropriate classification is row 1, column 2 in Figure 5.9. The automatic insertion code is thus 12, giving a relative workhead cost of 1.6.

For a cycle time of 5 s, the assembly rate F_r is 12 parts/min and Equation 5.8 gives an insertion cost of

$$\begin{aligned} C_i &= 0.06\left(\frac{60}{F_r}\right)W_r \\ &= 0.06\left(\frac{60}{12}\right)1.6 \\ &= 0.48 \text{ cents} \end{aligned}$$

Thus, the total handling and insertion cost C_t for this part is

$$\begin{aligned} C_t &= C_f + C_i \\ &= 0.24 + 0.48 \\ &= 0.72 \text{ cents} \end{aligned}$$

5.7 Analysis of an Assembly

To facilitate the analysis of a complete assembly, a worksheet similar to that used for manual assembly analysis can be employed. Figure 5.10 shows the exploded view of a simple assembly before and after redesign which is to be assembled at a rate of 9.6 per minute and Figure 5.11 presents the completed worksheets for automatic assembly analysis.

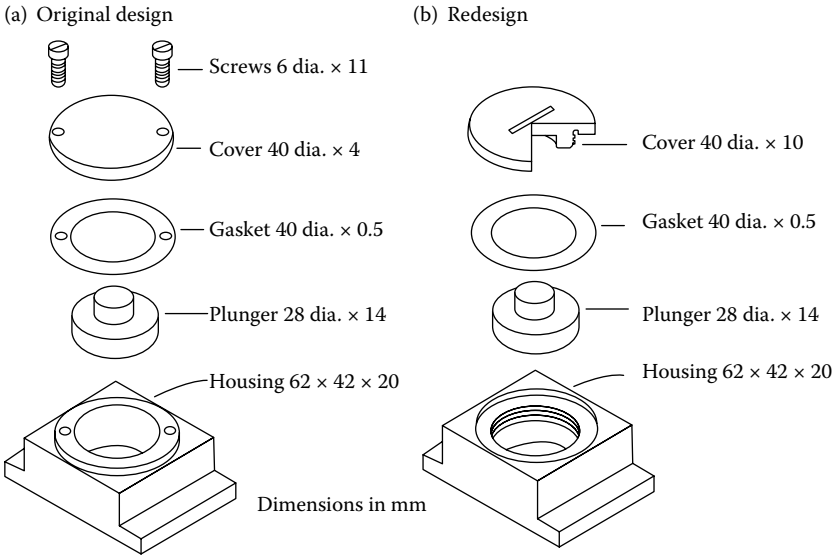


FIGURE 5.10
Simple assembly.

5.8 General Rules for Product Design for Automation

The most obvious way in which the assembly process can be facilitated at the design stage is by reducing the number of different parts to a minimum. This subject was covered in the previous chapter dealing with manual assembly, where it was emphasized that simplification of the product structure can lead to substantial savings in assembly cost and parts cost. When considering product design for automation, it is even more important to consider a reduction in the number of separate parts. For example, the elimination of a part would eliminate a complete station on an assembly machine—including the parts feeder, the special workhead, and the associated portion of the transfer device. Hence, the reduction in necessary investment can be substantial when product structure is simplified.

Apart from product simplification, automation can be facilitated by the introduction of guides and chamfers that directly facilitate assembly. Examples of this are given by Baldwin [3] and Tipping [4] in Figures 5.12 and 5.13. In both examples, sharp corners are removed so that the part to be assembled can be guided into its correct position during assembly, which requires less control by the placement device or can even eliminate the need for a placement device.

(a) Original design

Item no.	Name	Repeat count	Feed code	Orient efficiency E	Relative feeder cost C_r	Max. feed/ min. F_m	Feeding cost C_f	Insertion code	Relative workhead cost W_c	Insertion cost C_i	Total cost C_t	Min. parts
1	Housing	1	83100	0.2	1	7.1	0.25	00	1	0.38	0.63	1
2	Plunger	1	02000	0.4	1	21.4	0.19	02	1.5	0.56	0.75	1
3	Gasket	1	00840			Manual assembly required					7.13	0
4	Cover	1	00800			Manual assembly required					6.67	1
5	Screw	2	21000	0.9	1	122.7	0.19	39	1.8	0.68	1.74	0
		6									16.92	3

(b) Redesign

Item no.	Name	Repeat count	Feed code	Orient efficiency E	Reletive feeder cost C_r	Max. feed/ min. F_m	Feeding cost C_f	Insertion code	Relative workhead cost W_c	Insertion cost C_i	Total cost C_t	Min. parts
1	Housing	1	83100	0.2	1	7.1	0.25	00	1	0.38	0.63	1
2	Plunger	1	02000	0.4	1	21.4	0.19	02	1.5	0.56	0.75	1
3	Gasket	1	00040	0.7	3	26.3	0.56	00	1	0.38	0.94	0
4	Cover	1	02000	0.4	1	15	0.19	38	0.8	0.3	0.49	1
		4									2.81	3

FIGURE 5.11
Completed worksheets for high-speed automatic assembly analysis of the assemblies in Figure 5.10.

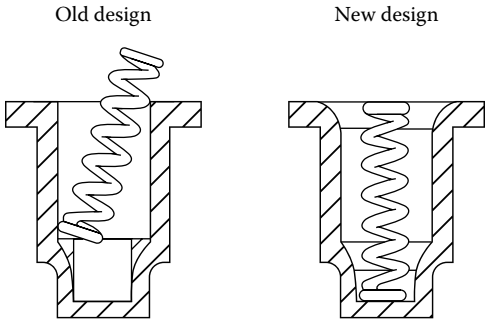


FIGURE 5.12
Redesign of part for the ease of assembly. (Adapted from Baldwin, S.P. How to make sure of easy assembly, *Tool Manufacturing and Engineering*, p. 67, May 1966.)

Further examples in this category can be found in the types of screws used in automatic assembly. Screws that tend to centralize themselves in the hole give the best results in automatic assembly; Tipping [4] summarizes and grades the designs of screw points available as follows (Figure 5.14):

1. Rolled thread point: very poor location; will not centralize without positive control on the outside diameter of the screws
2. Header point: only slightly better than (1) if of correct shape

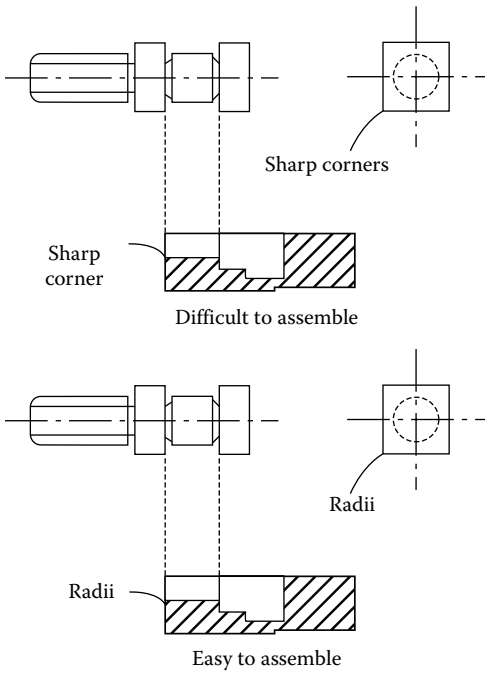


FIGURE 5.13
Redesign to assist assembly. (Adapted from Tipping, W.V. *Component and Product Design for Mechanized Assembly*, Conference on Assembly, Fastening and Joining Techniques and Equipment, PERA, 1965.)

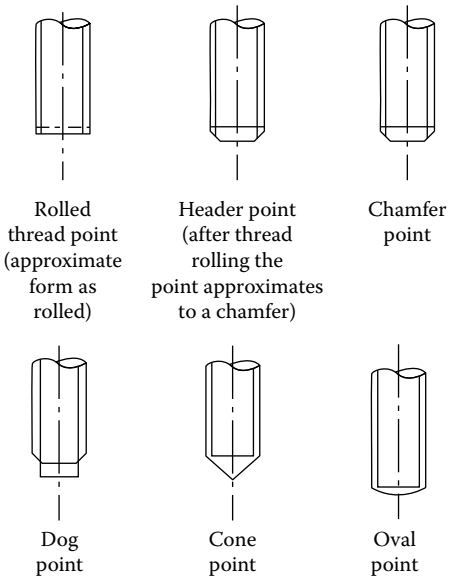


FIGURE 5.14
Various forms of screw points. (Adapted from Tipping, W.V. *Component and Product Design for Mechanized Assembly*, Conference on Assembly, Fastening and Joining Techniques and Equipment, PERA, 1965.)

3. Chamfer point: reasonable to locate
4. Dog point: reasonable to locate
5. Cone point: very good to locate
6. Oval point: very good to locate

Tipping recommends that only cone and oval point screws be used in automatic assembly. However, industrial practice now favors dog point screws since these tend to be self-aligning once inserted.

Another factor to be considered in design is the difficulty of assembly from directions other than directly above. The designer should aim to allow assembly in sandwich or layer fashion, each part being placed on top of the previous one. The biggest advantage of this method is that gravity can be used to assist in the feeding and placing of parts. It is also desirable to have workheads and feeding devices above the assembly station, where they would be accessible in the event of a fault due to the feeding of a defective part. Assembly from above may also assist in the problem of keeping parts in their correct positions during the machine index period, when dynamic forces in the horizontal plane might tend to displace them. In this case, with proper product design using self-locating parts, the force due to gravity should be sufficient to hold the part until it is fastened or secured.

If assembly from above is not possible, it is probably wise to divide the assembly into subassemblies. For example, see the exploded view of a British power plug shown in Figure 5.15; in the assembly of this product it would be relatively difficult to position and drive the two cord grip screws from below. The remainder of the assembly (apart from the main holding screw) can be conveniently built into the base from above. In this example

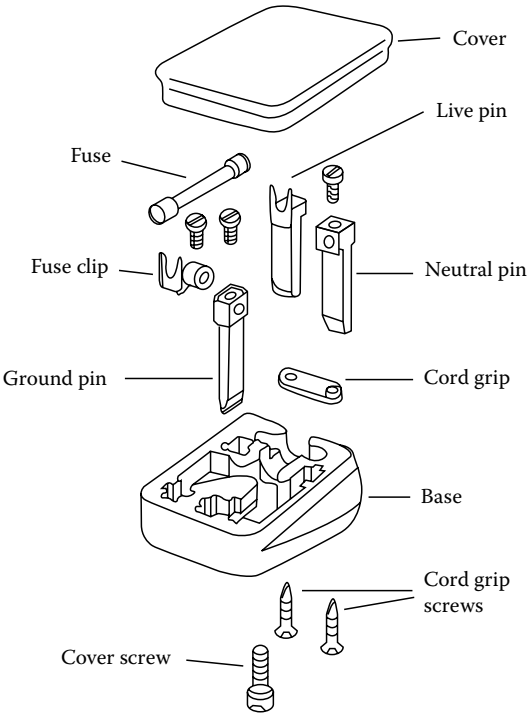


FIGURE 5.15
Assembly of three-pin power plug.

the two screws, the cord grip, and the plug base could be treated as a subassembly dealt with prior to the main machine assembly.

It is always necessary in automatic assembly to have a base part on which the assembly can be built. This base part must have features that make it suitable for quick and accurate location on the work carrier. Figure 5.16a shows a base part for which it would be difficult

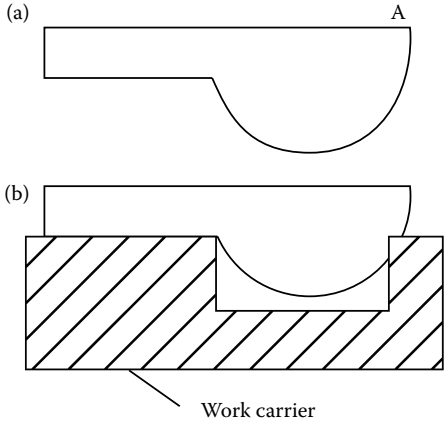


FIGURE 5.16
Design of base part for mounting on work carrier.

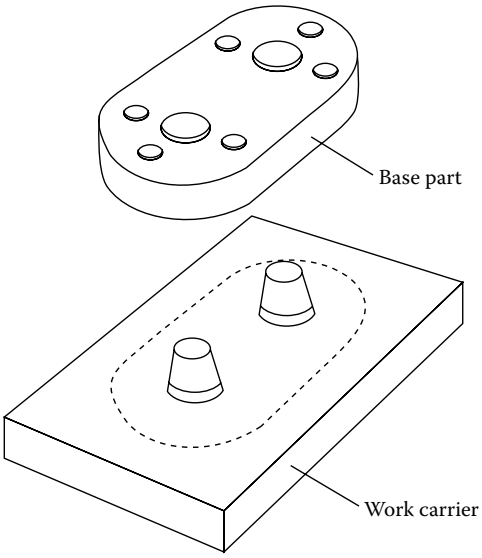


FIGURE 5.17
The use of tapered pegs to facilitate assembly.

to design a suitable work carrier. In this case, if a force were applied at *A*, the part would rotate unless adequate clamping was provided. One method of ensuring that a base part is stable is to arrange that its center of gravity be contained within flat horizontal surfaces. For example, a small ledge machined into the part allows a simple and efficient work carrier to be designed (Figure 5.16b).

The location of the base part in the horizontal plane is often achieved by dowel pins mounted in the work carrier. To simplify the assembly of the base part onto the work carrier, the dowel pins can be tapered to provide guidance, as in the example shown in Figure 5.17.

5.9 Design of Parts for Feeding and Orienting

Many types of parts feeders are used in automatic assembly; but most feeders are suitable for feeding only a very limited range of part shapes and are not generally relevant when discussing the design of parts for feeding and orienting. The most versatile parts feeder is the vibratory bowl feeder, and the following section mainly deals with the aspects of the design of parts that facilitate feeding and orienting in these devices. Many of the points made, however, apply equally to other feeding devices. Three basic design principles can be enumerated:

1. Avoid designing parts that would tangle, nest, or shingle.
2. Make the parts symmetrical.
3. If parts cannot be made symmetrical, avoid slight asymmetry or asymmetry resulting from small or nongeometrical features.

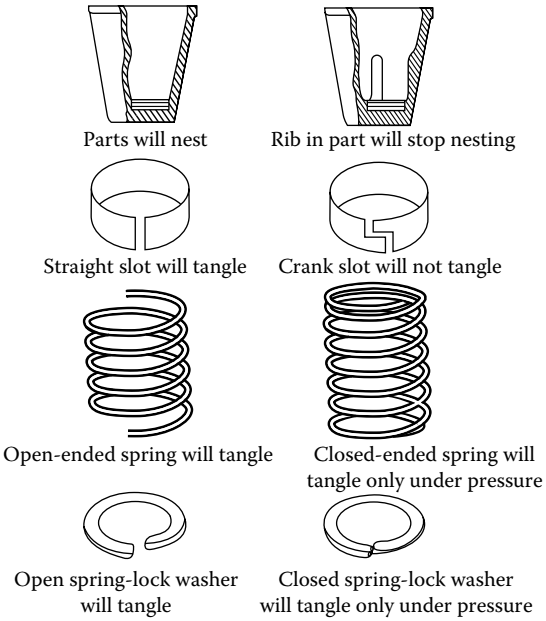


FIGURE 5.18
Examples of redesign to prevent nesting or tangling. (Adapted from Iredale, R. *Metalwork Production*, April 8, 1964.)

If parts tend to tangle or nest when stored in bulk, it can be almost impossible to separate, orient, and feed them automatically. Often, a small, nonfunctional change in design prevents this occurrence, and some simple examples of this are illustrated in Figure 5.18.

While the asymmetrical feature of a part can be exaggerated to facilitate orientation, an alternative approach is to deliberately add asymmetrical features for the purpose of orienting. The latter approach is more common, and some examples, given by Iredale [5], are reproduced in Figure 5.19. In each case, the features that require alignment are difficult to utilize in an orienting device, so corresponding external features are deliberately added.

In the portion of the coding system shown in Figure 5.4, those parts with a high degree of symmetry have codes representing parts that are easy to handle. There are, however, a wide range of codes representing parts that would probably be difficult to handle automatically; these parts create problems for designers unless assistance is provided.

Figure 5.20a shows a part that would be difficult to handle and Figure 5.20b shows the redesigned part, which could be fed and oriented in a vibratory bowl feeder at a high rate. The subtle change in design would not be obvious to the designer without the use of the coding system. In fact, it might not have occurred to the designer that the original part was difficult to handle automatically.

It should be pointed out that, although the discussion above dealt specifically with automatic handling, parts that are easy to handle automatically would also be easy to handle manually. A reduction in the time taken for an assembly worker to recognize the orientation of a part and then reorient it results in considerable cost savings.

Clearly, with some parts, it would not be possible to make design changes that would enable them to be handled automatically: for example, very small parts or complicated

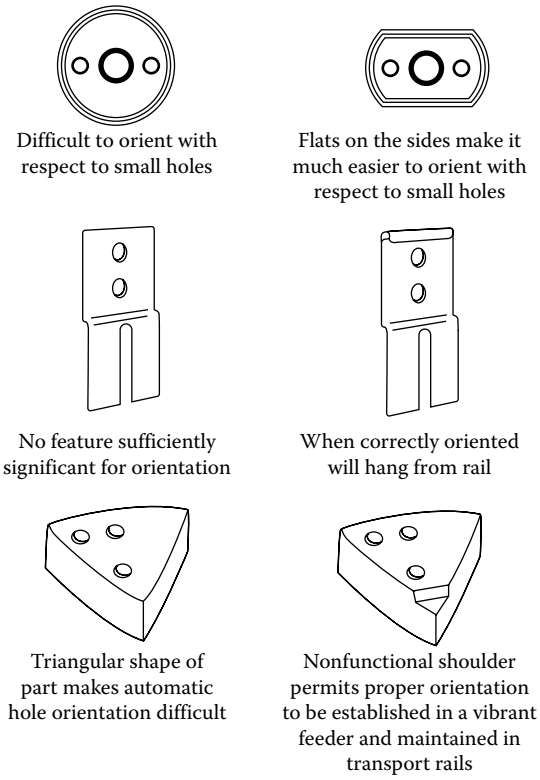


FIGURE 5.19
Provision of asymmetrical features to assist in orientation. (Adapted from Iredale, R. *Metalwork Production*, April 8, 1964.)

shapes formed from thin strips are difficult to handle in an automatic environment. In these cases, it is sometimes possible to manufacture the parts on the assembly machine or to separate them from the strip at the moment of assembly. Operations such as spring winding or blanking out thin sections have been successfully introduced on assembly machines in the past.

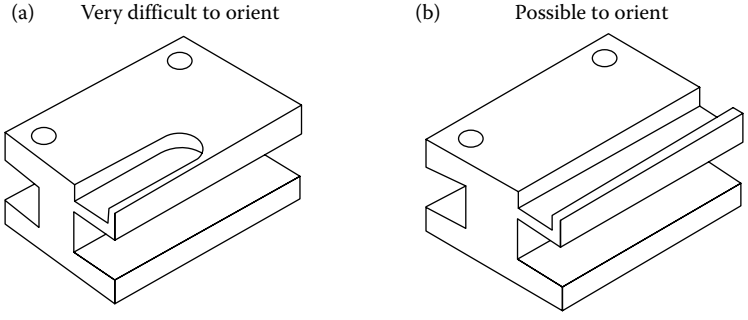


FIGURE 5.20
Less obvious example of a design change to simplify feeding and orienting.

5.10 Summary of Design Rules for High-Speed Automatic Assembly

The various points made in this discussion of parts and product design for automatic assembly, are summarized below in the form of simple rules for the designer.

5.10.1 Rules for Product Design

1. Minimize the number of parts.
2. Ensure that the product has a suitable base part on which to build the assembly.
3. Ensure that the base part has features that enable it to be readily located in a stable position in the horizontal plane.
4. If possible, design the product so that it can be built up in layers, each part being assembled from above and positively located so that there is no tendency for it to move under the action of horizontal forces during the machine-index period.
5. Try to facilitate assembly by providing chamfers or tapers that help to guide and position the parts in the correct position.
6. Avoid expensive and time-consuming fastening operations, such as screw fastening, soldering, and so on.

5.10.2 Rules for the Design of Parts

1. Avoid projections, holes, or slots that cause tangling with identical parts when placed in bulk in the feeder. This may be achieved by arranging the holes or slots to be smaller than the projections.
2. Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency.
3. If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features that can be used to orient the parts.

5.11 Product Design for Robot Assembly

As with product design for high-speed automatic assembly, one objective with robot assembly is to provide the designer with a means of estimating the cost of assembling the product—but in this case using robots. However, several important design aspects are affected by the choice of robot assembly system; a choice which, in turn, is affected by various production parameters such as production volume and the number of parts in the assembly. Three representative types of robot assembly systems can be considered, namely:

1. Single-station with one robot arm
2. Single-station with two robot arms
3. Multistation with robots, special-purpose workheads, and manual assembly stations as appropriate

For a single-station system, parts that required manual handling and assembly, and that must be inserted during the assembly cycle, present special problems. For reasons of safety it would usually be necessary to transfer the assembly to a location or fixture outside the working environment of the robot. This can be accomplished by having the robot place the assembly on a transfer device that carries the assembly to the manual station. After the manual operation has been completed, the assembly can be returned in a similar manner to within reach of the robot.

The use of special-purpose workheads for insertion or securing operations presents similar problems to those for manual assembly operations. Two different situations can be encountered. The first involves the insertion or placement of the part by the robot without it being secured immediately. This operation is then followed by a transfer of the assembly to an external workstation to carry out the securing operation; a heavy press fit would be an example. The second situation is where a special-purpose workhead is engineered to interact directly at the robot workfixture. This might take the form of equipment activated from the sides of or underneath the workfixture to carry out soldering, tab bending, or twisting operations, spin riveting, and so on, while the robot has to place and, if necessary, manipulate the part.

These major problems with single-station systems do not occur with a multistation system, where manual operations or special-purpose workheads can be assigned to individual stations as necessary. This illustrates why it is important to know the type of assembly system likely to be employed when the product is designed.

In order to determine assembly costs, it is necessary to obtain estimates of the following:

1. The total cost of all the general-purpose equipment used in the system, including the cost of robots and any transfer devices and versatile grippers—all of which can be employed in the assembly of other products if necessary.
2. The total cost of all the special-purpose equipment and tooling, including special-purpose workheads, special fixtures, special robot tools or grippers, special-purpose feeders, and special magazines, pallets, or part trays.
3. The average assembly cycle time—that is the average time to produce a complete product or assembly.
4. The cost per assembly of the manual labor involved in machine supervision, loading feeders, magazines, pallets, or part trays and performing any manual assembly tasks.

Classification systems and databases have been developed for the purpose of cost estimating [2]. The information presented allows these estimates to be made and includes one classification and data chart for each of the three basic robot assembly systems. In these charts, insertion or other required operations are classified according to difficulty. For each classification, and depending on the difficulty of the operation, relative cost and time factors are given that could be used to estimate equipment costs and assembly times. These costs and time estimates are obtained by entering data from the appropriate chart onto a worksheet for each part insertion and separate operation.

Figures 5.21 through 5.23 show the classification system and database for each type of robot assembly system. The selection of the appropriate row (first digit) depends on the direction of insertion—an important factor influencing the choice of robot because the 4 degree-of-freedom Selective Assembly Compliance Robot Arm (SCARA) robot can only perform insertions along the vertical axis. The selection of the appropriate column (second

ROBOT ASSEMBLY DATA FOR A SINGLE-STATION ONE-ARM SYSTEM

AR	TP
AG	TG

TP - Relative affective basic operation time

AR - Relative robot cost

AG - Relative additional gripper or tool cost

TG - Relative time penalty for gripper or tool change

			Part can be gripped and inserted using standard gripper or gripper used for previous part								Part requires change to special gripper							
			No holding down				Part requires temporary holding or clamping				No holding down				Part requires temporary holding or clamping			
			Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align	
			0		1		2		3		4		5		6		7	
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07
			0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1
	Using motion along or about a non-vertical axis	1	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.0
			0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1
	Involving motion along or about more than one axis	2	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9
			0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1

			Force or torque levels within robot capability												Special workhead operation	
			Part can be gripped and inserted using standard gripper or gripper used for previous part						Part requires change to special gripper							
			Snap or push fit				Push and twist or other simple manipulation		Snap or push fit or simple manipulation				Screw fastening or nut running			
			Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Robot positions part
			0		1		2		3		4		5		6		7		8	
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0	1.0	1.0	1.07	1.0	1.15	1.0	1.2	1.0	1.0	1.0	1.07	1.0	1.25	1.0	1.3	1.0	1.0
			0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.0	2.1
	Using motion along or about a non-vertical axis	4	1.5	1.0	1.5	1.07	1.5	1.15	1.5	1.2	1.5	1.0	1.5	1.07	1.5	1.25	1.5	1.3	1.5	2.0
			0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.0	2.1
	Involving motion along or about more than one axis	5	1.5	1.8	1.5	1.9	1.5	2.0	1.5	2.1	1.5	1.8	1.5	1.9					15	2.8
			0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1					4.0	2.1

			Operation can be carried out using standard gripper or gripper used for previous operation						Operation requires change to special gripper or tool								Special workhead operation	
			Snap or push fit		Push and twist or simple manipulation		Reorient or unload assembly		Snap or push fit		Screw or nut tighten		Solder		Apply liquid or adhesive		Reorient or unload assembly		Robot positions part
			0		1		2		3		4		5		6		7		8	
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0	0.75	1.0	0.85	1.0	1.0	1.0	0.75	1.0	0.8	1.0	0.9	1.0	1.2	1.0	1.0	1.0	1.0
			0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1
	Using motion along or about a non-vertical axis	7	1.5	0.75	1.5	0.85	1.5	1.0	1.5	0.75	1.5	0.8	1.5	0.9	1.5	1.2	1.5	1.0	1.5	2.0
			0	0	0	0	0	0	1.5	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1
	Involving motion along or about more than one axis	8	1.5	1.4	1.5	1.6	1.5	1.8	1.5	1.4	1.5	1.5	1.5	1.7	1.5	2.0	1.5	1.8	1.5	3.2
			0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1

FIGURE 5.21
Classification system and database for a single-station one-arm robot assembly system. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

ROBOT ASSEMBLY DATA FOR A SINGLE-STATION TWO-ARM SYSTEM

AR	TP
AG	TG

TP - Relative affective basic operation time

AR - Relative robot cost

AG - Relative additional gripper or tool cost

TG - Relative time penalty for gripper or tool change

			Part can be gripped and inserted using standard gripper or gripper used for previous part								Part requires change to special gripper							
			No holding down				Part requires temporary holding or clamping				No holding down				Part requires temporary holding or clamping			
			Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align	
			0		1		2		3		4		5		6		7	
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0	0.55	1.0	0.6	1.5	0.85	1.5	0.9	1.0	0.6	1.0	0.6	1.5	0.85	1.5	0.9
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
	Using motion along or about a non-vertical axis	1	1.5	0.55	1.5	0.6	1.5	0.85	1.5	0.9	1.5	0.6	1.5	0.6	1.5	0.85	1.5	0.9
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
		2	1.5	1.05	1.5	1.1	1.5	1.3	1.5	1.4	1.5	1.05	1.5	1.1	1.5	1.3	1.5	1.4
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
	Involving motion along or about more than one axis																	

			Force or torque levels within robot capability														Special workhead operation	
			Part can be gripped and inserted using standard gripper or gripper used for previous part								Part requires change to special gripper							
			Snap or push fit				Push and twist or other simple manipulation				Snap or push fit or simple manipulation				Screw fastening or nut running				Robot positions part
			Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		
			0		1		2		3		4		5		6		7		8	
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0	0.55	1.0	0.6	1.0	0.7	1.0	0.75	1.0	0.6	1.0	0.65	1.0	0.7	1.0	0.8	1.0	1.15
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	Using motion along or about a non-vertical axis	4	1.5	0.55	1.5	0.6	1.5	0.7	1.5	0.75	1.5	0.6	1.5	0.65	1.5	0.7	1.5	0.8	1.5	1.15
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	Involving motion along or about more than one axis	5	1.5	1.05	1.5	1.1	1.5	1.16	1.5	1.2	1.5	1.05	1.5	1.1					1.5	1.6
			0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7					4.0	0.7

			Operation can be carried out using standard gripper or gripper used for previous operation						Operation requires change to special gripper or tool								Special workhead operation	
			Snap or push fit		Push and twist or simple manipulation		Reorient or unload assembly		Snap or push fit		Screw or nut tighten		Solder		Apply liquid or adhesive		Reorient or unload assembly		Robot positions part
			0		1		2		3		4		5		6		7		8	
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0	0.45	1.0	0.5	1.0	0.6	1.0	0.45	1.0	0.5	1.0	0.55	1.0	0.7	1.0	0.6	1.0	0.15
			0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	Using motion along or about a non-vertical axis	7	1.5	0.45	1.5	0.85	1.5	0.6	1.5	0.45	1.5	0.5	1.5	0.55	1.5	0.7	1.5	0.6	1.5	1.16
			0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.5	0.7
	Involving motion along or about more than one axis	8	1.5	0.8	1.5	0.9	1.5	1.05	1.5	0.8	1.5	0.85	1.5	1.0	1.5	1.15	1.5	1.05	1.5	1.8
			0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.5	0.7

FIGURE 5.22
Classification system and database for a single-station two-arm robot assembly system. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

ROBOT ASSEMBLY DATA FOR A MULTI-STATION SYSTEM

AR TP
AG

TP - Relative affective basic operation time

AR - Relative robot cost

TG - Relative additional gripper or tool cost

			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper				Special workhead operation
			No holding down		Part requires temporary holding or clamping		No holding down		Part requires temporary holding or clamping		
			Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	
			0	1	2	3	4	5	6	7	8
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0 1.0 0	1.0 1.1 0	1.0 1.05 1.0	1.0 1.15 1.0	1.0 1.0 0.5	1.0 1.1 0.5	1.0 1.05 1.5	1.0 1.15 1.5	
	Using motion along or about a non-vertical axis	1	1.5 1.0 0	1.5 1.1 0	1.5 1.05 1.0	1.5 1.15 1.0	1.5 1.0 0.5	1.5 1.1 0.5	1.5 1.05 1.5	1.5 1.15 1.5	
	Involving motion along or about more than one axis	2	1.5 1.8 0	1.5 1.9 0	1.5 1.85 1.0	1.5 1.95 1.0	1.5 1.8 0.5	1.5 1.9 0.5	1.5 1.85 1.5	1.5 1.95 1.5	

			Force or torque levels within robot capability								
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper				Special workhead operation
			Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulation		Screw fastening or nut running		
			Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	
			0	1	2	3	4	5	6	7	8
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0 1.0 0	1.0 1.1 0	1.0 1.1 0	1.0 1.2 0	1.0 1.0 0.5	1.0 1.1 0.5	1.0 1.25 0.5	1.0 1.3 0.5	0 1.0 4.0
	Using motion along or about a non-vertical axis	4	1.5 1.0 0	1.5 1.1 0	1.5 1.1 0	1.5 1.2 0	1.5 1.0 0.5	1.5 1.1 0.5	1.5 1.25 0.5	1.5 1.3 0.5	0 1.0 5.0
	Involving motion along or about more than one axis	5	1.5 1.8 0	1.5 1.9 0	1.5 2.0 0	1.5 2.0 0	1.5 2.8 0.5	1.5 1.9 0.5			0 1.5 6.0

			Operation can be carried out using standard gripper or gripper used for previous operation			Operation requires change to special gripper or tool					Special workhead operation
			Snap or push fit	Push and twist or simple manipulation	Reorient or unload assembly	Snap or push fit	Screw or nut tighten	Solder	Apply liquid or adhesive	Reorient or unload assembly	
			0	1	2	3	4	5	6	7	8
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0 0.75 0	1.0 0.85 0	1.0 1.0 0	1.0 0.75 0.5	1.0 0.8 0.5	1.0 0.9 0.5	1.0 1.2 0.5	1.0 1.0 0.5	0 1.0 3.5
	Using motion along or about a non-vertical axis	7	1.5 0.75 0	1.5 0.85 0	1.5 1.0 1.0	1.5 0.75 0.5	1.5 0.8 0.5	1.5 0.9 0.5	1.5 1.2 0.5	1.5 1.0 0.5	0 1.0 4.0
	Involving motion along or about more than one axis	8	1.5 1.4 0	1.5 1.6 0	1.5 1.8 0	1.5 1.4 0	1.5 1.5 0.5	1.5 1.7 0.5	1.5 2.0 0.5	1.5 1.8 0.5	0 1.5 4.5

FIGURE 5.23
Classification system and database for a single-station one-arm robot assembly system. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

digit) depends on whether the part needs a special gripper, clamping temporarily after insertion, and whether it tends to align itself during insertion. All these factors affect either the cost of the tooling required or the time for the insertion operation, or both.

When the row and columns have been selected for a particular operation, the figures in the box allow estimates to be made of the robot cost, the gripper tool cost, and the total time for the operation.

Let us suppose that a part is to be inserted along a horizontal axis, which does not require a special gripper, but requires temporary clamping, and is easy to align. For this operation, on a single-station one-arm robot system (Figure 5.21), the code would be 12. In this case, the relative robot cost AR is 1.5. This means that if the basic capital cost of an installed standard 4 degree-of-freedom robot (including all controls, sensors, and so on, and capable of only vertical insertions) is \$60,000, a cost of \$90,000 is assumed. This figure allows a more sophisticated robot, able to perform operations from directions other than above. In other words, there is a cost penalty of \$30,000 for the basic equipment in the system because the "standard robot" cannot perform the operation required.

The value of the relative additional gripper or tool cost AG is 1.0. Since the part needs temporary clamping, special tooling mounted on the workfixture would be required. Thus, if the standard tooling or gripper cost \$5000, the additional tooling needed would represent a cost penalty of \$5000 in the form of special-purpose equipment.

The value of the relative basic operation time TP is 1.0. In this analysis method, the basis for time estimates is the average time taken by the robot to move approximately 0.5 m, grasp the part, return, and insert the part when the motion is simple and no insertion problems exist. For a typical present-generation robot, this process might take 3 s. If this figure is used in the present example, then this is the basic time for the robot to complete the operation.

Finally, since the relative time penalty for gripper or tool change is zero, no additional time penalty is incurred and the total operation time is 3 s. A further time penalty must be added when the part to be inserted is not completely oriented by the part presentation device. In this case, the robot arm must perform final orientation with the aid of a simple vision system and an additional 2–3 s must be added to the operation time.

In addition to the cost of the robot and the special tools or grippers, the costs of the part presentation must be estimated. Before this can be accomplished, it must be decided which part presentation method is to be used for each part. In practice, there are usually only two choices: the special-purpose feeder or the manually loaded magazine, pallet, or part tray.

The costs associated with part presentation can be divided into:

1. *Labor costs*: which include material handling (loading parts feeders or magazines), system tending (freeing jams in feeders, handling parts trays, etc.), and system changeover costs (changing of workfixture, feeders, and magazines and robot reprogramming);
2. *Equipment costs*: including feeder depreciation and the depreciation of special fixtures, special tooling, magazines, pallets, or part trays.

It can be assumed that the bulk material handling costs (i.e., dumping parts in bulk into feeder hoppers) are negligible compared to the cost of manually loading individual parts one-by-one into magazines, pallets, or part trays.

There are thus only three significant factors needed to estimate the cost of part presentation:

1. *Special-purpose feeders:* The cost of a special-purpose feeder, fully tooled and operating on the robot system, is assumed to be a minimum of $5000. The actual cost of a feeder, for a particular part, can be obtained from the data presented earlier in this chapter where feeding and orienting costs were considered in detail.
2. *Manually loaded magazines:* The cost of one set of special magazines, pallets, or part trays for one part type is assumed to be $1000. For large parts, this figure may considerably underestimate the actual cost and extra allowance should be made.
3. *Loading of magazines:* The time needed to hand-load one part into a magazine can be estimated to be the part-handling time, obtained from the data in Chapter 3, plus 1 s. Alternatively, a typical value of 4 s may be used.

It can be seen that the use of the classification systems and database allows the total cost of equipment and the cost of any manual assembly work to be estimated together with the assembly time for each part. These results provide the data necessary to predict assembly costs using each of the three robot assembly systems.

5.11.1 Summary of Design Rules for Robot Assembly

Many of the rules for product design for manual assembly and high-speed automatic assembly also apply to product design for robot assembly. However, when considering the suitability of a proposed design for robot assembly, careful consideration should be given to the need for any special-purpose equipment such as special grippers or special feeders. The cost of this equipment must be amortized over the total life volume of the product and for the mid-range volumes where robot assembly might be applied, and this can add considerably to the cost of assembly.

The following are some specific rules to follow during product design [2]:

1. Reduce part count—this is a major strategy for reducing assembly, manufacture, and overhead costs irrespective of the assembly system to be used.
2. Include features such as leads, lips, chamfers, and so on, to make parts self-aligning in assembly. Because of the relatively poor repeatability of many robot manipulators—when compared to dedicated workhead mechanisms—this is a vitally important measure to ensure consistent fault-free part insertions.
3. Ensure that parts which are not secured immediately on insertion are self-locating in the assembly. For multistation robot assembly systems, or one-arm single-station systems, this is an essential design rule. Holding down of unsecured parts cannot be carried out by a single robot arm, and so special fixturing is required which must be activated by the robot controller. This adds significantly to special-purpose tooling and, hence, assembly costs. With a two-arm single-station system, one arm can, on principle hold down an unsecured part while the other continues the assembly and fastening processes. In practice, this requires one arm to change the end-of-arm tooling to a hold-down device; the system then proceeds with 50% efficiency while one arm remains immobile.

4. Design parts so that they can all be gripped and inserted using the same robot gripper. One major cause of inefficiency in robot assembly systems is the need for gripper or tool changes. Even with rapid gripper or tool change systems, each change to a special gripper and then back to the standard gripper is approximately equal to two assembly operations. Note that the use of screw fasteners always results in the need for tool changes, since robot wrists can seldom rotate more than one revolution.
5. Design products so that they can be assembled in layer fashion from directly above (*z*-axis assembly). This ensures that the simplest, least costly, and most reliable 4 degree-of-freedom robot arms can accomplish the assembly tasks. It also simplifies the design of the special-purpose workfixture.
6. Avoid the need for reorienting the partial assembly or for manipulating previously assembled parts. These operations increase the robot assembly cycle time without adding value to the assembly. Moreover, if the partial assembly has to be turned to a different resting aspect during the assembly process, then this will usually result in increased workfixture cost and the need to use a more expensive 6 degree-of-freedom robot arm.
7. Design parts that can be easily handled from bulk. To achieve this goal, avoid parts that
   - Nest or tangle in bulk
   - Are flexible
   - Have thin or tapered edges that can overlap or "shingle" as they move along a conveyor or feed track
   - Are so delicate or fragile that recirculation in a feeder would cause damage
   - Are sticky or magnetic so that a force comparable to the weight of the part is required for separation
   - Are abrasive and will wear the surfaces of automatic handling systems
   - Are light so that air resistance would create conveying problems (less than 1.5 N/m^3 or 0.01 $lb/in.^3$)
8. If the parts are to be presented using automatic feeders, then ensure that they can be oriented using simple tooling. Follow the rules for ease of part orientation discussed earlier. Note, however, that feeding and orienting at high speed is seldom necessary in robot assembly, and the main concern is that the features that define part orientation can be easily detected.
9. If parts are to be presented using automatic feeders, then ensure that they can be delivered in an orientation from which they can be gripped and inserted without any manipulation. For example, avoid the situation where a part can only be fed in one orientation from which it must be turned over for insertion. This would require a 6 degree-of-freedom robot and special gripper, or a special 180° turn delivery track—both solutions leading to unnecessary cost increases.
10. If the parts are to be presented in magazines or part trays, then ensure that they have a stable resting aspect from which they can be gripped and inserted without any manipulation by the robot. If the production conditions are appropriate, the use of robots holds advantages over the use of special-purpose workheads and some design rules can be relaxed. For example, a robot can be programmed to

acquire parts presented in an array—such as in a pallet or part tray which has been loaded manually, thus avoiding many problems arising with automatic feeding from bulk. However, when making economic comparisons, the cost of manual loading of the magazines must be taken into account.

PROBLEMS

1. Eight different small parts are shown in Figure 5.24. Using the classification charts shown in Figures 5.3 through 5.8, determine the feeding and orienting five-digit codes for these parts.
2. The part shown in Figure 5.25 is to be delivered to a workhead on an automatic assembly machine at a rate of 13 per minute. Estimate the cost of feeding and orienting each part assuming that the cost of using a standard feeder for 1 s is 0.05 cents.

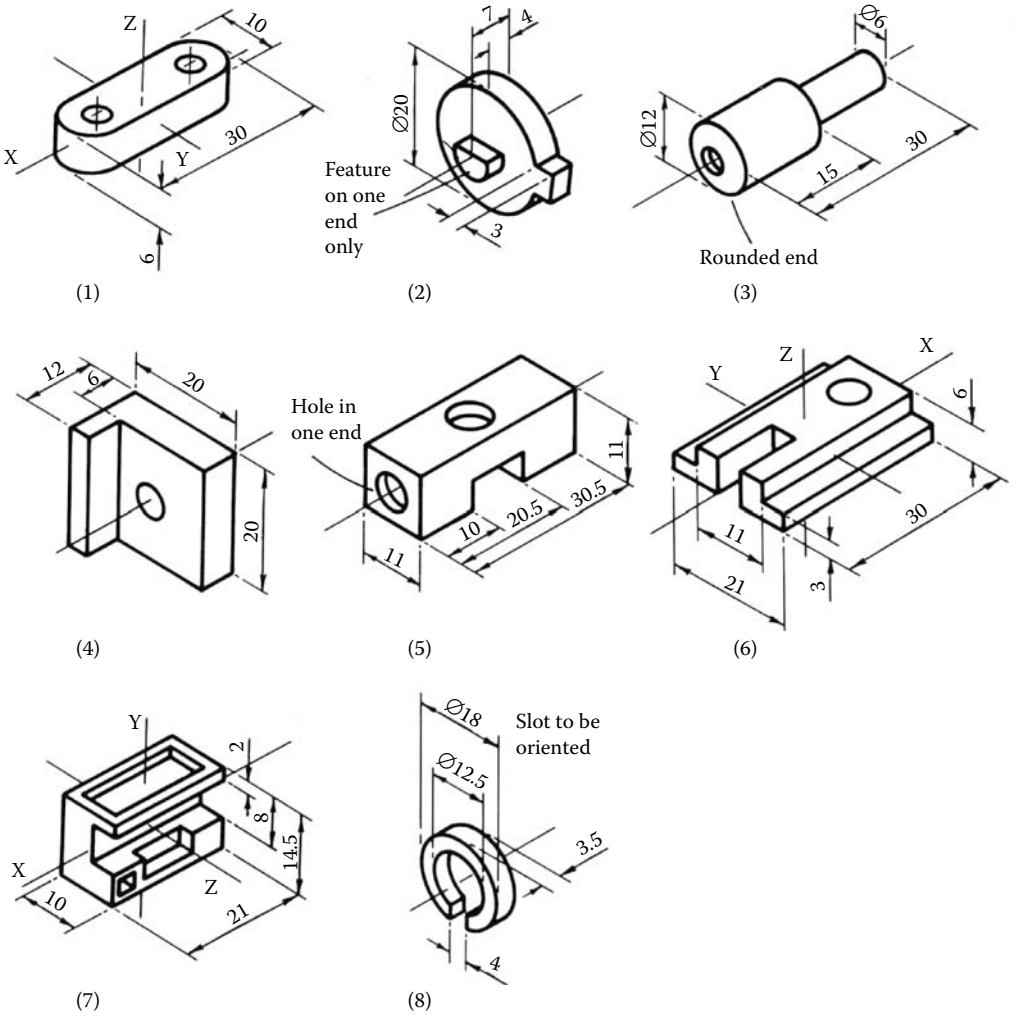


FIGURE 5.24
Small parts for feeding and orienting. *Note:* All dimensions are mm.

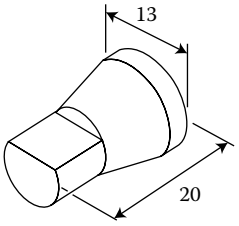


FIGURE 5.25
Part for feeding and orienting (dimensions in mm).

3. The final operation in the automatic assembly of a small mechanism, involves the insertion of an adjusting screw, as shown in Figure 5.26. The screw is inserted with a straight-line motion from the side and has a pilot point which makes it easy to align and position in the hole. The assemblies are required at a rate of 4 per minute, estimate the cost of automatic insertion of the screw, assuming that the cost rate of using a standard workhead for 1 s is 0.06 cents.
4. The part shown in Figure 5.27 is a coupling in a motorcycle gearbox, which is to be assembled automatically at a rate of 5 per minute. The features of this part which can be used for automatic orienting are the symmetric groove in the cylindrical body of the part, and the grooves across the end faces. Estimate the following items for automatic handling of this part:
   i. The maximum feed rate which would be obtained from a standard vibratory bowl feeder capable of delivering 25 mm symmetrical cubes at the rate of 1 per second.
   ii. The estimated automatic handling cost per part assuming 0.03 cents/s as the rate for a standard feeder.

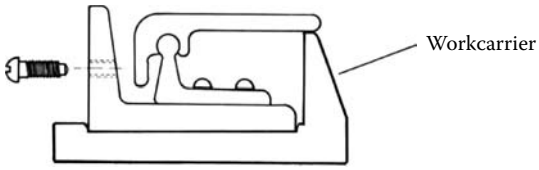


FIGURE 5.26
Latch mechanism assembly.

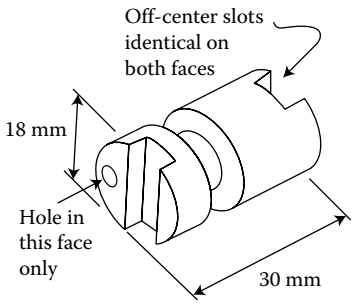


FIGURE 5.27
Part from a motor cycle gearbox coupling.

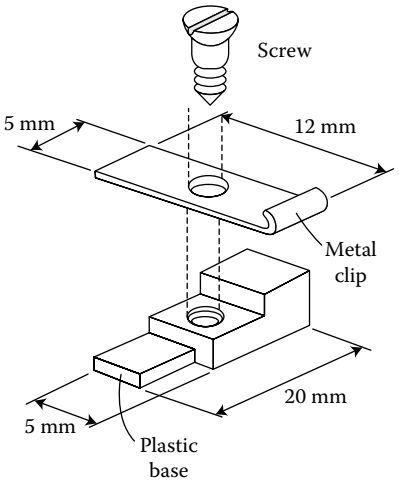


FIGURE 5.28
Three-part assembly.

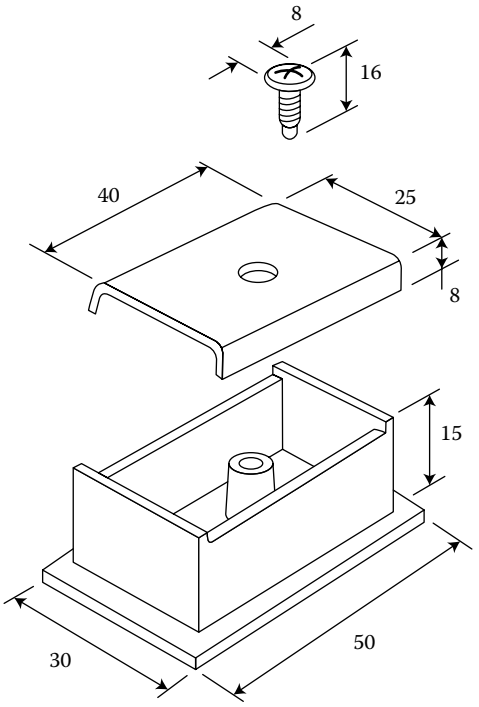


FIGURE 5.29
Box assembly. *Note:* Dimensions in mm.

iii. The approximate cost of a feeder to deliver the part at the required rate of 5 per minute.
iv. The estimated insertion cost per part assuming 0.06 cents/s as the rate for a standard pick and place workhead. The part is easy to assemble and is inserted directly from above.

The gearbox designer decides that the slots must be moved to the center position in the end faces. If this were the only design change, what effect would it have on automatic handling of the part? If this design change is essential, what other changes would you recommend to improve the design for automatic handling?

5. Figure 5.28 shows a small three-part assembly that is to be assembled automatically. Carry out an analysis of this assembly for high-speed automatic assembly and from this determine the estimated assembly cost. The assemblies are required at a rate of 10 per minute. The cost of using a standard feeder for 1 s is 0.03 cents and the cost of using a standard workhead for 1 s is 0.06 cents. The screw has a pilot point and so is easy to align and position into the screw hole.
6. Figure 3.59 shows an exploded view of the diaphragm assembly for a gas flow meter. Carry out an analysis for high-speed automatic assembly, including determination of the theoretical minimum number of parts. The assembly sequence begins with the insertion of the nuts into a suitably designed work carrier and ends with the insertion of the two screws. The cost of using a standard feeder for 1 s is 0.03 cents and the cost of using a standard workhead for 1 s is 0.06 cents. From the analysis, determine the assembly cost for each assembly. The required rate of assembly is 30 per minute.

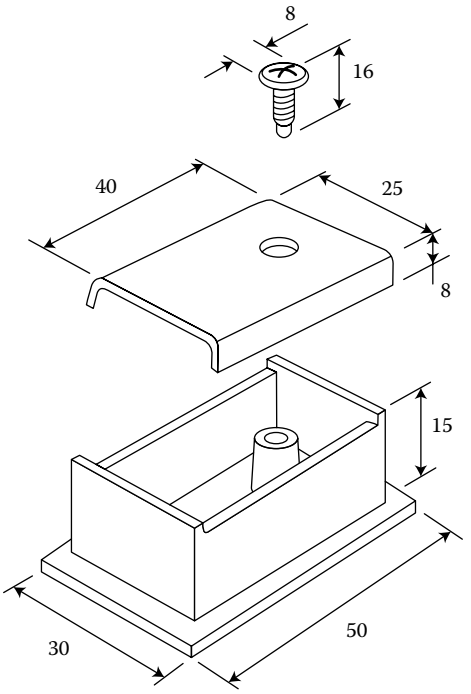


FIGURE 5.30
Redesigned box assembly. *Note:* Dimensions in mm.

Note: The diaphragm plate may be difficult or impossible to feed and orient automatically. If it is decided that this part must be assembled manually, use the data in Chapter 3 to estimate the assembly cost of this item, assuming a manual labor rate of $36/h.

7. For the diaphragm assembly used in the previous problem, suggest changes to the diaphragm plate that would allow easier feeding and orienting automatically. Carry out an analysis for high-speed automatic assembly with the redesigned diaphragm plate. Estimate the assembly cost per assembly and compare this with cost in Problem 3.
8. Develop a redesign of the diaphragm assembly in Problem 6 that uses fewer parts and is suitable for high-speed automatic assembly. Estimate the assembly cost for this new design and compare this cost to costs in Problems 6 and 7.
9. The box shown in Figure 5.29 is to be assembled at a rate of 40 per minute on a high-speed rotary indexing machine. The clearance between the cover and the walls of the base is sufficient for the cover to be easy to align and insert. In addition, the screw has a pilot point for the ease of alignment. The base and cover are both symmetrical about the vertical axis.

   Complete a Design for Automatic Assembly Worksheet and hence estimate the assembly cost and the assembly efficiency for this design. The cost of using a standard feeder for 1 s is 0.03 cents and the cost of using a standard workhead for 1 s is 0.06 cents. Note that all three parts can be oriented with a single feature visible in the external silhouette, and that the relative workhead cost for a single-spindle vertical screwdriver head is 0.9.

   A second version of the box assembly is proposed in which the boss in the molded base and the hole in the cover are offset as shown in Figure 5.30. Would this offset make any difference to the efficiency of automatic assembly?

References

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6

Printed Circuit Board Design for Manufacture and Assembly

6.1 Introduction

Printed circuit boards (PCBs) are electronic circuits created by mounting electronic components onto a nonconductive board and creating conductive connections between them. The creation of circuit patterns is accomplished using both additive and subtractive methods. The conductive circuit is generally copper, but other metals are sometimes used. There are three basic varieties of PCBs: single sided, double sided, and multilayered. Printed circuit boards are widely employed in the manufacture of business machines and computers, as well as many other products including communications, control, and home entertainment equipment.

There has been a dramatic growth in the output of printed circuit boards (PCBs) in recent decades. This trend is symptomatic of the increased replacement of previously mechanical functions in products by electronics. A typical example of this change is the domestic washing machine, which a few years ago would have been controlled by an electromechanical cam timer, but which is now controlled electronically by a PCB. Similarly, the control of the spark timing and fuel intake of an automobile engine is now carried out through PCBs.

It is equally necessary to consider manufacturability at the early design stages for PCBs as it is for mechanical products. The use of quantitative tools to assess manufacturing difficulties and costs early in the design process is of great importance. PCB manufacture is a rapidly developing field. New PCB designs, new component packaging, and new assembly techniques are continually being introduced. Manufacturers are constantly striving to achieve higher component densities, which make assembly increasingly difficult. Boards using through-hole mounted components are being replaced by boards that utilize surface-mounted devices (SMDs) [1–3]. In addition new techniques such as tape-automated bonding (TAB) and chip-on-board are increasingly being used. Tools used for assessing the manufacturability issues for PCBs must be capable of expansion to account for these newer developments. For the time being, the discussion in this chapter is restricted to through-hole and surface-mount components, as these make up the majority of devices currently used.

6.2 Design Sequence for Printed Circuit Boards

Design procedures for PCBs differ considerably from those used for mechanical devices. In addition, the use of computer-aided design techniques has in general been much further

developed and integrated into the design process than for mechanical products. The sequence for the design of a PCB is as follows:

1. Development of a functional circuit schematic diagram to meet the design specification and performance of the circuit.
2. Circuit layout design—this leads to the artwork for the circuit, including component layout, routing of conductors, and component selection.

   Layout design is a complex task involving many interrelated considerations, including

   Component area

   Number of sides

   Number of boards

   Volume computing (volumetric space taken up by the board)

   Actual layout design, including component placement and conductor routing

A number of computer aids have been developed to assist with these design tasks, including autoplacement and routing, artwork preparation, and so on. However, many of these tasks are carried out without any assessment of costs until much later in the overall design process.

6.3 Types of Printed Circuit Boards

Printed circuit boards are manufactured in a variety of types and configurations. The choice of board type depends upon a number of factors, including:

1. The function of the board
2. Space available, related to component density
3. Component availability
4. Cost
5. Working environment
6. Any standards applied to the board

Circuit boards are produced with copper circuit traces on an insulating backing material. The following variations of board types can be identified.

6.3.1 Number of Sides

Printed circuit boards may be referred to as single sided or double sided. In the first case, the circuit is applied to only one side of the board and in the second case the circuit is laid down on both sides of the board. A further variation is that holes in the board may either be plated through to connect circuits on both sides or not plated through.

6.3.2 Number of Layers

Printed circuit boards may be single or multilayered. Single-layer boards have the circuit connections applied to one layer of insulation material only. Multilayer boards are built up from several layers of insulation material, with portions of the circuit laid down between the layers. For two- or three-layer boards, which are relatively common, the intermediate layers may serve only as ground and power planes. In some extreme cases the number of layers may be as high as 20 or more, but this is exceptional. The separate insulation boards are made separately and then laminated together to form a multilayer board.

6.3.3 Board Materials

Various materials are used for the insulating layers of the board. The majority of boards are made from a reinforcing material and a thermosetting resin, but some ceramic boards are also used, particularly in military applications. The common combinations of resin and reinforcing materials are as follows:

Resin	Reinforcing Material
Phenolics	Paper
	Cotton fabric
	Glass cloth
	Nylon
Epoxy	Paper
	Glass cloth
	Aramid cloth
Polymide	Glass cloth
	Aramid cloth
Alkyds	Glass material
Silicones	Glass cloth

There are a number of standard board materials [1] and some of these are as follows:

FR-2: Laminated paper impregnated with phenolic resin. Paper laminates are not only the least expensive, but also the least durable. The main uses are for low-cost consumer electronic products, such as radios, calculators, and toys.

FR-3: Laminated paper impregnated with an epoxy-resin binder. This material is stronger than FR-2. The main uses are in computers, televisions, and communications applications.

FR-4: Laminated layers of woven glass cloth impregnated with epoxy resin. This is a very durable material and widely used because of its very good physical properties. Around 80% of the boards produced utilize FR-4 material.

FR-5: Laminated layers of woven glass cloth impregnated with polyfunctional epoxy resin, which results in better heat resistance than FR-4.

PL: Laminated layers of woven glass impregnated with polyimide resin. This material has good thermal stability and low thermal expansion.

GPO: Polyester resin-based laminate with random glass mat as a filler. Lower in cost than FR-4 and suitable for less critical applications.

CEM-1: A composite material made up of a paper core with woven glass layers on the surfaces and impregnated with epoxy resin.

CEM-3: A composite material made up of a nonwoven glass core with woven glass cloth on the surfaces and impregnated with epoxy resin. CEM-3 is more durable and costlier than CEM-1.

6.3.4 Device Types

The discrete electronic components may be attached to the board in a variety of ways. The two main device types used are through-hole mounted and surface mounted. For through-hole devices, attachment is by means of separate leads that pass through holes in the board and are soldered to the circuit on the opposite side of the board. For surface-mounted devices, attachment is to pads on the same side of the board as the device is placed. Until recently, the use of through-hole mounted devices predominated, but now surface-mounted devices are more commonly used, mainly because of the higher component densities that can be achieved. In general, it is easier from a manufacturing viewpoint if only through-hole or only surface-mounted devices are used, but many boards are still made with a mixture of both types of device.

6.3.5 Copper Weight

The circuit traces are usually made from copper foil on the surface of the laminates, with a thickness ranging from 10 to 100 μm. The copper thickness is usually expressed by a number that represents the weight of material uniformly spread on a fixed area, for example, ounce per square foot. A copper weight of 1 ounce per square foot results in a copper thickness of 0.0014 in or 35 μm. Thus, to convert the thicknesses in inches to copper weight in ounces per square foot, divide the thickness by 0.0014. Similarly, to convert the thicknesses in micrometer to copper weight in ounces per square foot, divide the thickness by 35. The choice of thickness depends on the electrical requirements of the circuit, for example, power circuits require thicker foils (larger copper weight). Internal circuit layers on multilayer boards may have different copper weights than the external circuits.

6.4 Bare Board Manufacture

The first step in the production of a PCB assembly is the manufacture of the bare printed wiring board (PWB) onto which the electronic components are to be mounted. The manufacture of PWBs requires numerous steps, including the selective etching of flat circuits of copper onto the nonconductive sheets. PWBs have circuits on the external faces and for multilayer boards on the internal layers (cores) also. For multilayer boards, the inner layer circuits are produced first and then the layers are laminated together using a laminating press. After this, the external circuits are produced. Depending on the size of boards, several are produced together from standard panels. The individual boards are sheared from the panels at some stage in processing and this may be after the assembly of the finished PCBs.

The basic sequence of processes for producing the circuits is essentially the same for both internal and external circuits [1,4,5]. The starting point is a nonconductive sheet

laminated with a thin layer of copper foil. The following basic sequence produces the circuits:

- The laminates are coated with a UV-sensitive photo-resist.
- The track pattern is imaged onto each side of the base board, using overlays (masters) and UV light.
- The photo-resist is developed; leaving photo-resist only where copper is required.
- The laminates are put in an acid bath, to etch away exposed copper, forming the track pattern.
- The bare board with tracks and pads is cleaned.
- Each circuit layer is usually inspected using automated optical inspection (AOI) prior to lamination.

Other operations involved in PWB manufacture include hole drilling, using automated (NC) drilling machines, and electro-less copper plating to join the various circuits by means of plated through holes, together with various cleaning processes and solder tinning of the circuit pads, and so on. The final stage includes automated circuit testing for which suitable test fixtures and programs must be prepared.

6.4.1 Basic Bare Board Costs

The main cost drivers in the manufacture of bare PWBs are:

- Number of layers
- Board thickness
- Copper weight
- Minimum conductor spacing
- Minimum trace width
- Gold-plated edge connectors
- Number of holes in the board

Figure 6.1 [6] shows the approximate cost per unit area for different types of board as a guide to selection. In Table 6.1 [7], the cost influence of the number of board layers is shown, using a double-sided board as the baseline.

Based on this information an overall cost factor for PWBs can be developed. Fitting a relationship to the data given in Table 6.1 gives the following relationship for the basic cost factor:

$$F_{\mathrm{PWB}} = 0.33 n_{\mathrm{L}} + 0.3 \tag{6.1}$$

This basic cost factor can be increased incrementally for the other factors as indicated in Table 6.2 [7].

In this way, the basic cost per unit area of the PWB can be estimated from the main design parameters of the board. This cost estimate includes the costs of material, circuit etching, lamination, and inspection of the circuit layers. Additional costs result from the

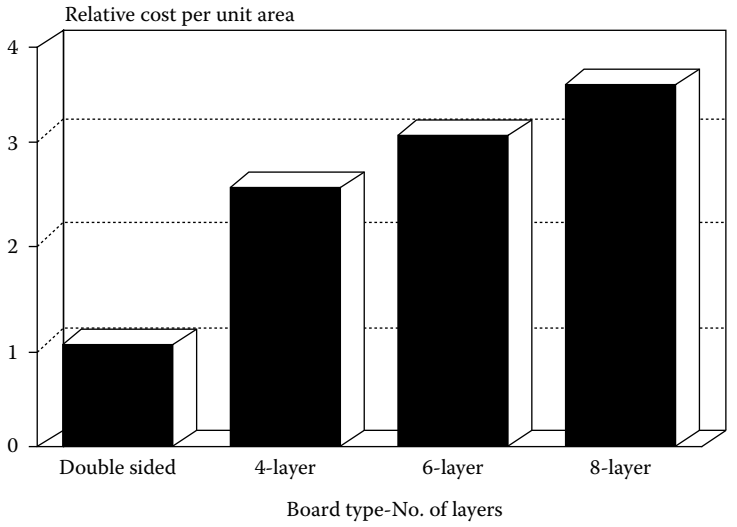


FIGURE 6.1
Approximate cost per unit area of bare boards. (Adapted from Grezesik, A. *Layer Reduction Techniques, Circuit Design*, August 1990, p. 21.)

TABLE 6.1

Influence of Number of Layers (n_L) on PWB Costs

Number of Layers	Cost Factor
Single-sided	0.67
Double-sided	1.00
4-layer	1.75
6-layer	2.25
8-layer	3.00
10-layer	3.50
12-layer	4.25
14-layer	5.25

drilling of holes, solder mask deposition, legend printing, and final board testing. These can be calculated separately.

EXAMPLE

A six-layer board has a thickness of 0.062 in., with a 0.5 oz copper weight, minimum trace width of 0.005 in., and 600 holes in the board. Determine the cost factor for this board. Since the number of layers is 6, the basic cost factor is given by $0.33 \times 6 + 0.3 = 2.28$. Increments to this factor from Table 6.2 should be added and the final Cost Factor becomes $2.28 + 0.1 + 0.05 + 0.1 + 0.05 = 2.58$. The cost per unit area for this board is 2.58 times the cost per unit area for a simple double-sided board of the same material.

TABLE 6.2

Increments to Basic Cost Factor for PWBs

Condition	Cost Factor Increment
Thickness > 0.062 (1.58 mm)	0.1
Thickness > 0.092 (2.34 mm)	0.05
Copper weight > 0.5 oz	0.05
Copper weight > 1.0 oz	0.05
Minimum conductor spacing < 0.006 (0.152 mm)	0.1
Minimum trace width < 0.006 (0.152 mm)	0.1
Number of holes > 500	0.05
Number of holes > 800	0.05
Gold-plated edge connectors	0.05

6.4.2 Number of Boards per Panel

Printed wiring boards are usually made from standard panels, with one or more boards arranged in the panel. The boards usually remain within the panel until after population with electronic components, at which time the separate boards are sheared from the panel.

The number of boards per panel (n_p) is determined from the size of the boards and the size of the panel, with suitable clearances between each board and at the edges of the panel.

$$n_p = n_{lp} n_{wp} \tag{6.2}$$

where n_{lp} is the number of boards along the length of the panel and n_{wp} is the number of boards along the width of the panel. There are two possible arrangements for boards in the panel [3]; one with the board length, l_b, parallel to the panel length, l_p, and the second with l_b parallel to the panel width, w_p. Thus, the number of boards along the panel length, n_{lp}, is given by

$$n_{lp} = \left[\frac{l_p + s_b - 2s_e}{l_b + s_b} \right] \tag{6.3}$$

for the board length parallel to the panel length or

$$n_{lp} = \left[\frac{w_p + s_b - 2s_e}{l_b + s_b} \right] \tag{6.4}$$

for the board length parallel to the panel width, where w_p is the panel width, w_b is the board width, s_b is the spacing between boards and s_e is the spacing required between the edge of the panel and the edge of the board. The [ ] parentheses represent truncation to the integer part of the result.

Similarly, the number of boards along the panel width is given by

$$n_{wp} = \left[\frac{w_p + s_b - 2s_e}{w_b + s_b} \right] \tag{6.5}$$

for the board length parallel to the panel length or

$$n_{wp} = \left[\frac{l_p + s_b - 2s_e}{w_b + s_b} \right] \tag{6.6}$$

The result that gives the greatest value for Equation 6.2 is the number of boards per panel.

6.4.3 Hole Drilling

Holes through the board are usually produced with programmable NC drilling machines [1]. Usually several panels are drilled together in a stack. The drills are small in diameter and the board material is quite abrasive. The panel stack includes entry and exit film layers. The entry film provides lubrication for the drill and the exit layer is necessary to reduce breakout defects as the drill penetrates the undersurface of the bottom panel of the stack.

The number of panels in the stack, n_{ps}, is given by

$$n_{ps} = \left[\frac{H_{st} - t_{enl} - t_{exl}}{t_b} \right] \tag{6.7}$$

where

H_{st} = the maximum stack height
t_{enl} = the entry film layer thickness
t_{exl} = the exit film layer thickness
t_b = the board thickness.

Again, the [] parentheses represent truncation to the integer part of the result.

The time to load and unload the board panels and film layers onto the drilling machine is

$$T_{ld} = T_{lp}(n_{ps} + 2) \tag{6.8}$$

where T_{lp} = the time to load and unload each panel.

The drilling cost per board, C_{dl}, is given by

$$C_{dl} = \frac{M_{dl}(T_{st} + T_{ld})}{(n_{pl} + n_p)3600} \tag{6.9}$$

in which M_{dl} = the operating cost of the drilling machine in \$/hour and $T_{st} = n_{hl} n_p t_{dl}$, where n_{hl} is the number of holes per board and t_{dl} is the time to drill one hole.

Additional costs for machine setup and programming are also required.

6.4.4 Optional Bare Board Processes

Two optional processes that are usually included are solder mask application and legend (text) printing. Curing and cleaning operations are also required.

Solder masking is a process in which the entire board area, except solder pads and through holes, is selectively coated with an organic polymer. This is done to prevent short

circuits in the circuit traces from subsequent assembly and soldering processes. Silk screening and other processes are used for laying down this polymer film. Since solder masking is an additional operation it increases the manufacturing costs of the PWB. For single-sided boards, only one side of the board needs to be treated. Solder masking can sometimes be eliminated if circuit trace clearances are large.

Legend screen printing is a process in which component names, symbols, and other identification marks are printed on the board surface. This printing must be legible and able to withstand all manufacturing processes, together with being visible after all parts are installed. Screen printing is an additional process that increases the board manufacturing costs. Unless the board is manually assembled or there is a specific field-service requirement it may be possible to eliminate legend screen printing.

The screens for mask application and legend printing are made from a dry type of photoimageable film. The film is cut to size and exposed to UV light to define the stencil or screen image. The stencils are then usually laid onto two rigid mesh screens for subsequent printing.

The costs for solder masking and legend printing included the cost of loading and unloading panels, the processing cost for each side treated, together with a setup cost and the cost of the printing screens used. The processing cost per board, C_{sl}, is given by

$$C_{sb} = \frac{M_{sl} n_{sm} (T_{lp} + T_{sm})}{3600 n_p} \tag{6.10}$$

where

M_{sl} = operational cost in \$/h
n_{sm} = the number of sides processed
T_{sm} = processing time per side in s.
T_{lp} = loading and unloading time per panel
n_p = number of boards per panel.

6.4.5 Bare Board Testing

Finally, the bare PWB must be tested for circuit defects and so on. A suitable test fixture must be developed for the board and the cost of this is spread over the total number of boards to be produced.

6.5 Terminology

For those not familiar with the terms used in PCB manufacture, a glossary is included at the end of this chapter.

The term *insertion* is used to describe the process of placing a through-hole electrical component onto a printed circuit board so that its leads pass through the correct holes in the board or the placing of a surface-mounted component onto the board in the required position. There are in general three methods of insertion: (1) dedicated automatic insertion machines, (2) manual assembly workers and semiautomatic insertion, and (3) robots.

The automatic insertion of axial (variable center distance, or VCD) components involves several operations including preforming of the leads, inserting the component and then

cutting and clinching the leads. Preforming and cut and clinch are done automatically as part of the insertion cycle and do not add to the cycle time or decrease the rate of insertion. Automatic insertion of dual in-line package components (DIPs) does not involve lead forming or cutting.

Most surface mount components can be inserted with high-speed pick and place machines. With such placement machines, the insertion rates, particularly for small components, can be very high.

With manual insertion and semiautomatic insertion, all the operations are performed manually in sequence. Thus, the preforming before insertion and then cut and clinch after insertion add to the total time for the insertion operation.

Robot insertion involves moving the robot arm to the component, grasping the component, realigning it if necessary, moving it to the correct board location, and insertion. If the component feeders or presenters cannot completely orient the component, then robot insertion will include final realignment and this will increase the cycle time. As with manual assembly, preforming and cut and clinch are usually done separately.

Robots are generally used only to insert nonstandard components that otherwise would have been inserted manually, except that multistation robot assembly lines are sometimes used for surface-mounted component placement. Nonstandard components or odd-form components are large or odd-shaped components that cannot be inserted by special-purpose machinery.

Before introducing the cost analysis for printed circuit board assembly, the assembly procedure will be described. The following section explains the various steps that can be included in a PCB assembly process; these steps are automatic, manual, and robotic insertion of components.

6.6 Assembly of Printed Circuit Boards

After manufacture the bare PWB, it must be populated with electronic components that are soldered to the board circuit pads. Two basic types of technology are used for PCBs: pin through hole (PTH) and surface mount device (SMD) technology. Figure 6.2 shows some of the standard PTH and SMD packages that are in common use. The glossary at the end of the chapter includes short descriptions of these and other devices. Through hole technology electronic components with leads are passed through holes in the board and clinched for temporary securing before being soldered to the circuits, usually by automated wave soldering. This is an older technology but is still used for many PCBs for which high circuit density is not required because of the lower overall costs. There is a large range of standard electronic components and package styles available. Many of the standard PTH components can be inserted using high-speed automatic equipment, but odd form and large components must be inserted manually or robotically.

A large proportion of PCBs now use SMD technology. Surface mount components are soldered onto pads on the board surface and result in higher component densities than PTH boards. The trend toward even smaller electronic products has to some extent been possible because of the increased use of SMD technology to miniaturize PCB assemblies. Again there is a large number of standard SMD package styles and most of these are inserted using special purpose high-speed equipment. Soldering is usually achieved by reflow soldering, for which the bare boards are screen printed with solder paste in appropriate places

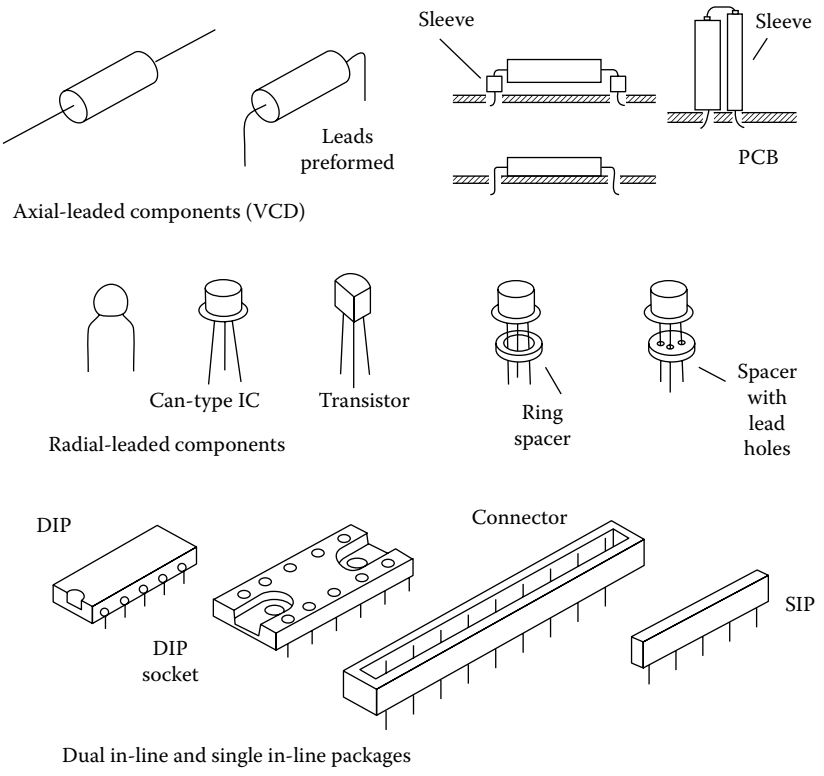


FIGURE 6.2
Various electronic components (not to scale).

prior to placement of the electronic components. Many boards are produced using a mixture of PTH and SMD components, which generally complicates the assembly sequence, but is often necessary because all component types are not widely available in surface mount package styles.

For high production volumes, most manufacturers use a combination of both automatic and manual insertion, because odd-shaped or nonstandard components cannot be handled by the automatic insertion machines. However, it is desirable to use automatic insertion machines wherever possible, since they can operate much faster and with greater reliability than manual workers. For those PCBs manufactured in small batches and where the applications involve severe working environments, such as military applications, assembly is still sometimes entirely by hand.

Later in this chapter, data and equations are presented that can be used to estimate the cost of component insertion and soldering by dedicated automatic insertion machines, manual assembly workers, or robots.

6.6.1 Assembly Operations for Through-Hole Printed Circuit Boards

Through hole components can be inserted with dedicated automatic insertion equipment, robotically or manually depending on the type of component [8].

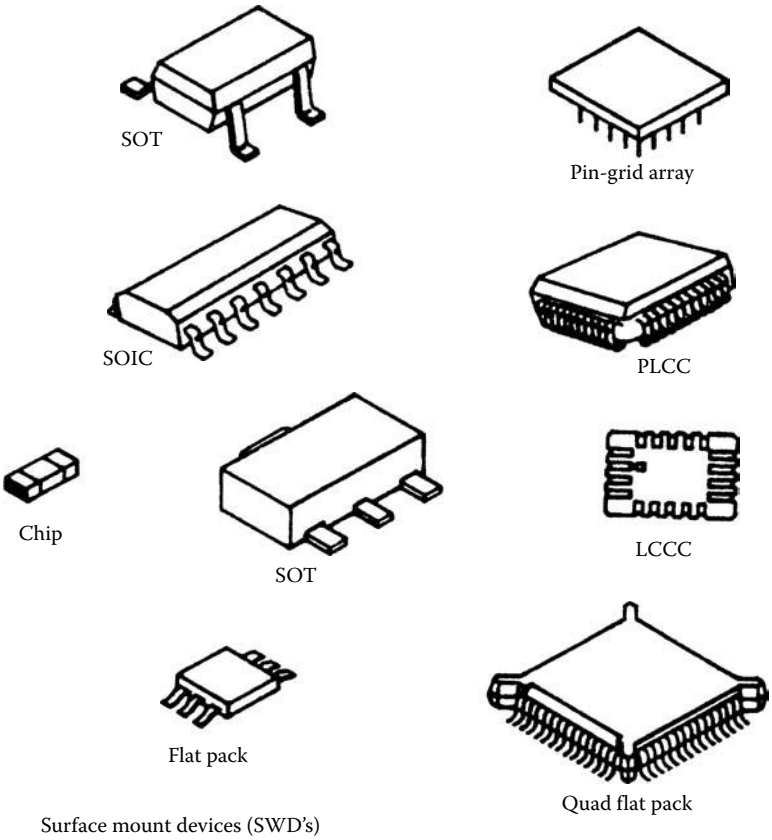


FIGURE 6.2
Continued.

6.6.1.1 Automatic Dual Inline Package Insertion

This refers to the automatic insertion of dual in-line package components (DIPs) and includes all integrated-circuit chips and chip sockets. The term "dual in-line package" refers to the two parallel rows of leads projecting from the sides of the package (Figure 6.2). Typically, DIPs have between 4 and 40 leads; DIPs with more than 40 leads are infrequently used. The lead span, which is the distance between the two rows of leads, is standardized at 0.3, 0.4, or 0.6 in.

Components are inserted with an automatic DIP inserter (Figure 6.3). Automatic insertion is carried out at high rates—approximately 2800 to 4500 per h or one component every 0.80–1.29 s. The DIP leads are inserted through predrilled holes in the board and are cut and clinched below the board (Figure 6.4). The automatic insertion head moves only in the vertical direction, while the board is positioned below it on an x–y table that can also rotate. High-performance DIP insertion machines can insert DIPs having any of the three standard lead spans with no tooling change, but base models can only handle 0.3 in. lead spans and 6 to 20 lead DIPs. To accommodate 2 and 4 lead DIPs, a special insertion head must be employed at additional cost. To check for electrical faults a component verifier may be employed that stops the machine if certain preprogrammed electrical characteristics are not met.

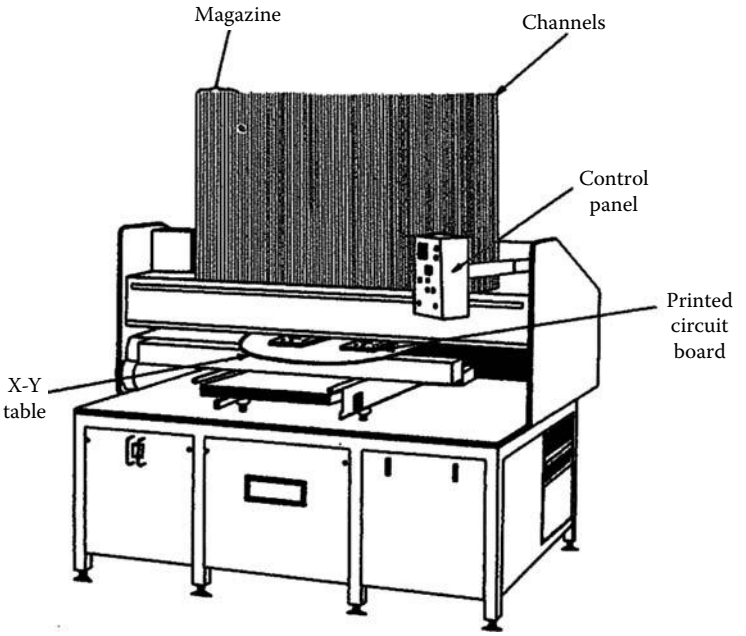


FIGURE 6.3
Automatic dual in-line package (DIP) insertion machine.

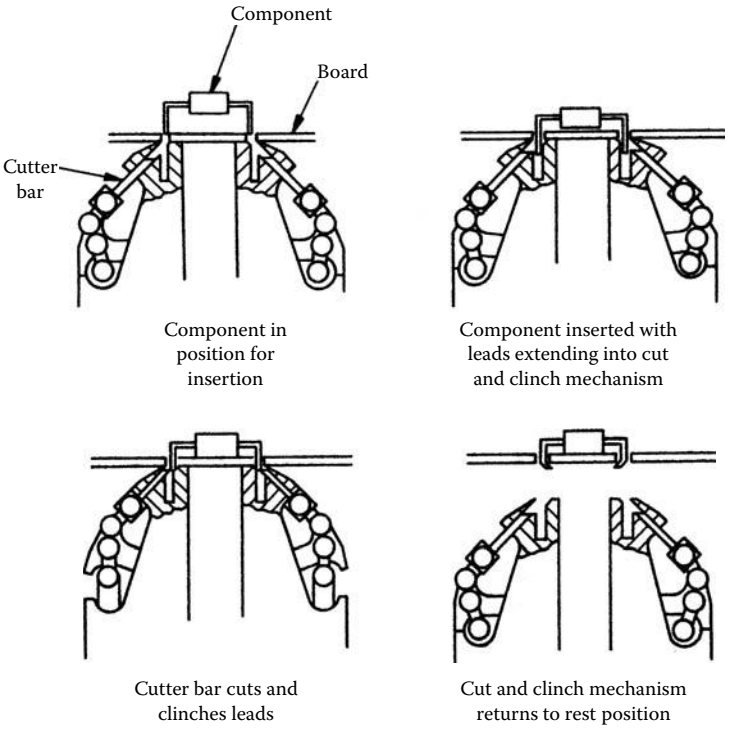


FIGURE 6.4
Cut and clinch sequence.

Dual in-line package components are purchased from component manufacturers in long tubes called channels, in which they are preoriented and stacked end-to-end. The channels are loaded onto the DIP inserting machine. Usually, one channel is used for each DIP type on the board, but if large numbers of one type are used then more channels can be assigned to the same component. A magazine refers to a group of channels, usually about 15. If a high component mix is required, then additional magazines can be added to the machine. The machine's size and speed restrict the number of magazines. The insertion cycle time is longer when the channel is farther from the insertion head. Channels can be changed by an operator as the machine runs, which eliminates down-time caused by empty channels.

6.6.1.2 Automatic Axial (VCD) Insertion

This refers to the automatic insertion of axial-lead components (Figure 6.2), also called VCDs (variable center distance components). These include resistors, capacitors, and diodes within the size limitations of the insertion head. Axial-lead components must usually have their leads bent at right angles prior to insertion, and the final lead span (called center distance) is variable.

Axial-lead components are inserted with an automatic axial-lead inserter (Figure 6.5). Components are inserted at rates of approximately 9500 to 32,000 components per hour or one component every 0.11–0.38 s. Rates of 32,000 per hour can only be achieved with a dual-head insertion machine—a machine that inserts components into two identical boards simultaneously. Obviously single-head axial-lead insertion machines work at half

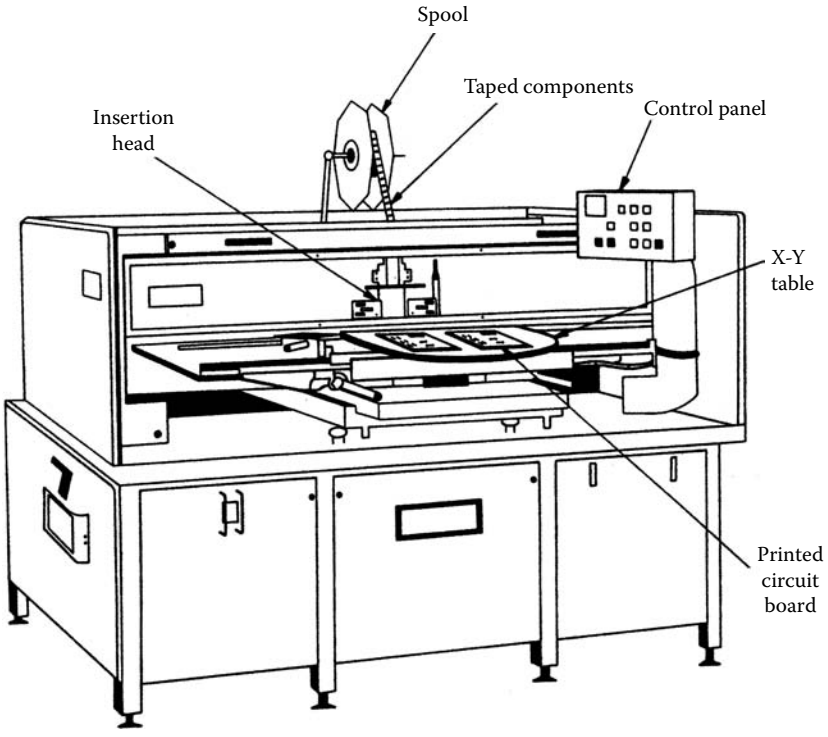


FIGURE 6.5
Automatic axial-lead insertion machine.

the rate of dual-head machines. The rates are higher than those for automatic DIP insertion, because components are fed on a spool in the correct sequence for insertion (Figure 6.6). Movements of the insertion head are much less. Spools can hold large numbers of components and only have to be changed infrequently.

Automatic axial-lead insertion proceeds as follows: (1) components are stored on a spool in the correct order for insertion (this is accomplished by the automatic component sequencer described below); (2) the spool is loaded manually onto the axial-lead inserter; (3) during the automatic insertion cycle the leads are automatically cut to remove the component from the tape, then they are bent at right angles to the correct center distance and the component is positioned with the leads passing through the board; (4) finally, the leads are cut and clinched below the board (Figure 6.4).

The axial-lead components are first mounted on a spool using a component sequencer. This machine (Figure 6.7) arranges the components on a tape spool in the correct sequence for insertion. Axial-lead components are purchased on spools with one component type on each spool. Spools are loaded manually onto the sequencer for every type of component on the board and from these a master spool is created.

A component sequencer can handle components at a rate of approximately 10,000 to 25,000 per hour or one component every 0.14–0.36 s. Component leads are automatically cut to remove the components from their individual tapes in the correct order for insertion. Components are then retaped and rolled onto the master spool. Master spools are made off-line and in advance of the component insertion process.

A module for a sequencer is a group of dispensing spools, usually about 20 in number. If a larger component mix is needed, then additional modules can be added to the sequencer up to a maximum of about 240 dispensing spools, with the limit being imposed by the

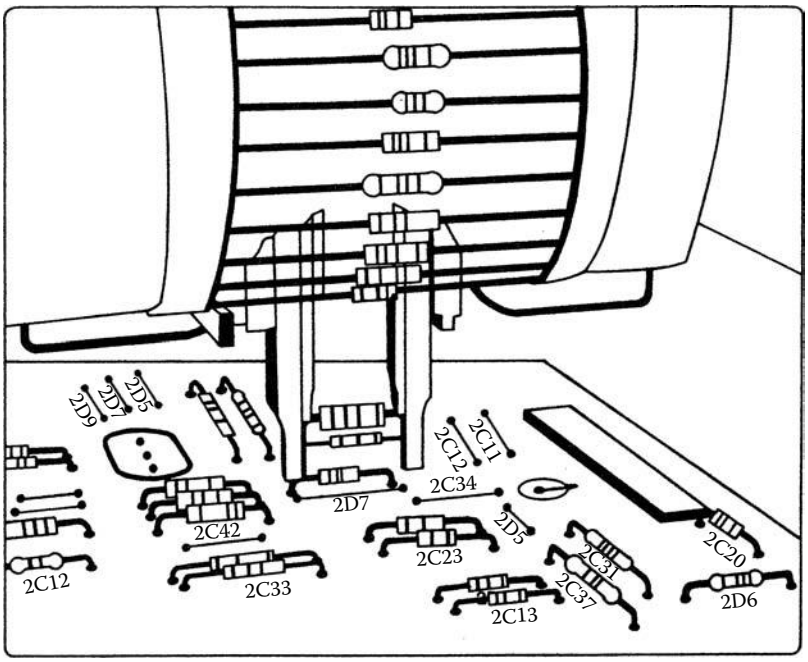


FIGURE 6.6
Axial-lead components on tape at the insertion head.

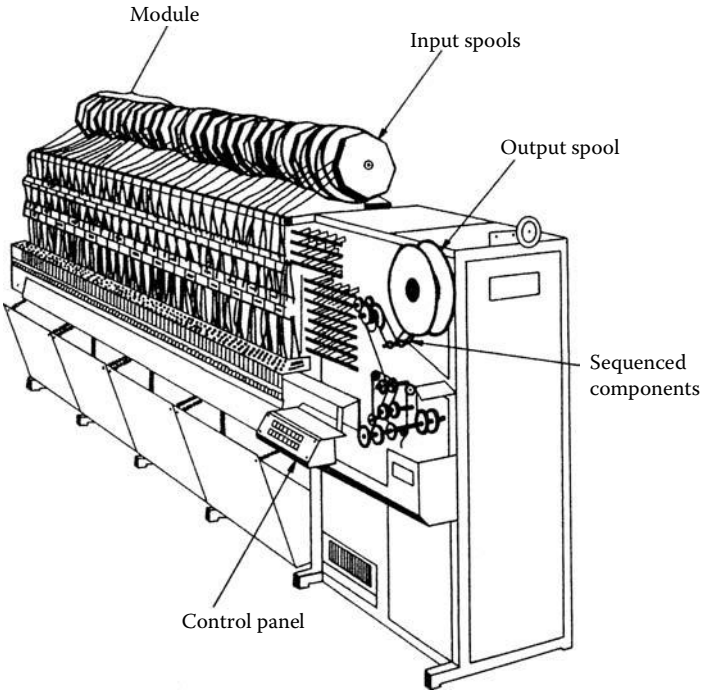


FIGURE 6.7
Automatic axial-lead sequencing machine.

physical size of the machine. To check for faulty components or a component out of order, a component verifier can be added to the sequencer.

These two processes, automatic axial-lead component insertion and sequencing, may be combined and carried out on one machine. Such a machine, about twice as large as a conventional automatic insertion machine, provides the advantage of eliminating the need for kitting and reduces the setup time by bringing inventory to the assembly line. Since components are stored at the assembly line, different batches can be run—both large and small—by simply writing a new program for each batch.

6.6.1.3 Automatic Single Inline Package Insertion

Single inline packages (SIP) have a single line of leads projecting from the base of the component (Figure 6.2). This package style is often used for resistor networks and similar devices. Automatic SIP inserters are similar to automatic DIP inserters. Some DIP insertion machines have, as an option, the ability to insert SIP components using an additional insertion head.

6.6.1.4 Automatic Radial Component Insertion

Radial through hole components have a small number of leads from the base of the component (Figure 6.2) and components with a metal-covered body are often referred to as cans. Various transistors, capacitors, and similar devices are available as radial components. Automatic insertion machines for radial-lead components are similar to automatic axial-lead component insertion machines.

6.6.1.5 Semiautomatic Insertion

This refers to semiautomatic component insertion, that is, machine-assisted manual insertion. Inserted at this station are all DIP and axial-lead components that cannot be machine inserted either because of their size or their location on the board. Also inserted are radial-lead components, SIPs, and some connectors. Wherever possible in high-volume assembly, semiautomatic insertion is used instead of manual insertion, since it can reduce the insertion time by 80%.

A semiautomatic insertion machine (Figure 6.8) automatically presents the correct component to the operator and indicates, by use of a light beam, the correct location and orientation for the component on the board. The component is then inserted by hand, with the leads sometimes being automatically cut and clinched. Components are inserted in this way at rates of approximately one component every 5 s. All components must have their leads preformed to the correct dimensions for insertion prior to presentation to the operator. Typically, components are stored in a rotating tray. After receiving a signal from the operator, the tray rotates so that only the section containing correct components is presented. The light beam (which can be located either above or below the board) illuminates the holes for the insertion and uses a symbol to indicate component polarity.

6.6.1.6 Manual Insertion

Manual insertion of through hole components may be included in the assembly sequence, before and/or after the soldering of the board. Two stations are sometimes needed, because some components cannot withstand the high temperatures of wave soldering. However, these manual insertion stations may involve the use of special hand tools to facilitate the

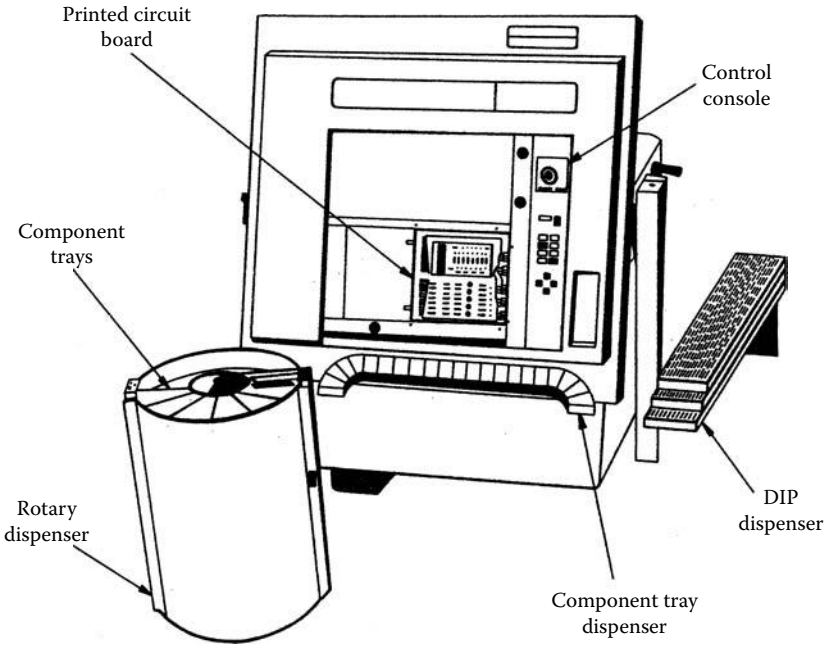


FIGURE 6.8
Semiautomatic insertion machine.

handling and insertion of certain components. Typically, manual assembly accounts for a high proportion of total assembly time, even when a relatively small number of manually assembled components are involved.

At the first manual assembly station, large nonstandard components are inserted. They are inserted manually, because the part trays used in semiautomatic machines cannot accommodate many of these parts due to their large size. If a particular manufacturer does not use a semiautomatic machine, then all the components that would have been inserted using this machine are inserted manually. Also, components assembled mechanically (i.e., secured with screws or bolts) that are to be wave soldered are assembled here.

At the second manual assembly station (often referred to as final assembly), all the remaining components are inserted. These include components that cannot be wave soldered because of their sensitivity to heat. Also, components that are secured mechanically are installed here. These include handles, some large electrolytic capacitors, connectors, and power transistors which are secured with screws or bolts and nuts. Lastly, some components, such as diodes and resistors, usually with axial leads, are soldered on the top of the board to the leads of other components. It is important to note that any through-hole components on the underside of the board must be manually inserted and manually soldered with consequent increases in manufacturing costs.

6.6.1.7 Robot Insertion

An assembly station for robotic insertion may be included in the assembly process. At this station, robotic insertion of nonstandard components using a one-arm robot may be performed. Robot insertion is used mainly to reduce the amount of manual labor involved in PCB assembly.

6.6.1.8 Inspection and Rework

After insertion, inspection and repair may occur. In this inspection of the partially assembled board, the inspector looks for faults that can be detected visually such as broken or bent leads or components inserted into the wrong holes. Components are either repaired and reinserted or discarded and replaced. Workers have available at each repair station all of the components inserted at the previous insertion station so that any component can be replaced. Inspect and repair stations can follow each insertion station. However, workers can never detect all the faults, and these will inevitably have to be detected and corrected later in the manufacturing process.

6.6.2 Assembly of Surface-Mounted Devices

The preceding discussion has dealt only with PCBs having through-hole components where the component leads pass through the board. However, surface-mounted devices (SMDs) are increasingly being employed. These components have pads or leads that are soldered to corresponding areas on the surface of the board. Surface-mounted devices include simple resistors in the form of a small rectangular prism (chip) and a variety of larger components such as flat packs, SOTs, PLCCs, SOICs, and LCCCs (Figure 6.2; see glossary for acronyms). Some surface-mounted devices are the direct equivalent of through-hole devices, but several specific SMD packages have been developed. These devices can be mounted on either side of the board and are sometimes interspersed with through-hole components.

Assembly of an SMD involves positioning the component on the board, which has previously had solder paste applied, usually by screen printing. Although SMDs can be

placed manually, accuracy requirements make it necessary to use auto-placement machines. Placement of SMDs is done by specifically designed pick-and-place machines (e.g., Figure 6.9). Placement machines have been designed with a variety of configurations and selection of the appropriate equipment is dependent on the types of parts to be placed, together with the production volumes. With modern machines, the placement speeds as low as 0.1 s or less per part, with larger components taking longer. High-speed machines for small components are often referred to as "chip shooters." Components can be fed to the placement machines in a variety of ways. The most common method is embossed (pocketed) tape, but paper tape, stick in-feeding and trays are also used.

Different types of placement machines are available as follows:

1. *In-line machines*

   These machines use a series of fixed position placement stations and each station places its respective component as the board moves down the line. Productivity rates can be very high by ganging several machines in sequence.

2. *Simultaneous machines*

   Simultaneous placement equipment places an entire array of components on the board at the same time.

3. *Sequential placement machines*

   Sequential placement machines are the most common high speed machines used in industry. These pick and place machines utilize numerically controlled *X–Y* moving tables and components are individually placed on the board in succession (Figure 6.9).

4. *Sequential/simultaneous machines*

   These placement machines also utilize an *X–Y* moving table and components are individually placed from multiple heads in succession. Simultaneous placement with several heads is also possible.

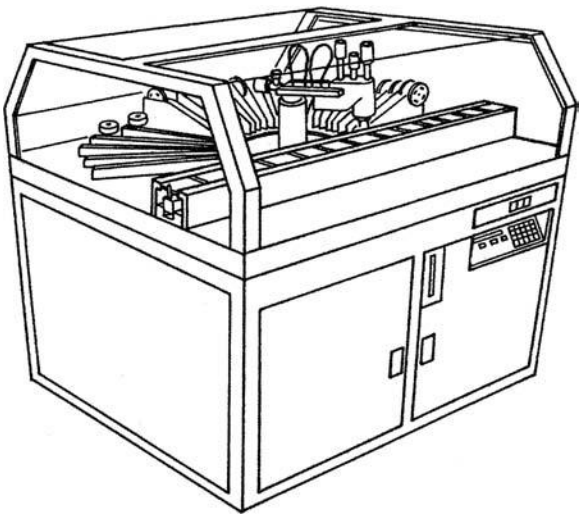


FIGURE 6.9
Pick-and-place machine for surface-mounted devices.

Selection of specific equipment is dependent on a number of factors, including the requirement for special features such as vision capability, adhesive application, component testing capability, and so on.

6.6.3 Soldering Processes

For high productivity, most electronic components are soldered to the board using an automatic large-scale soldering process such as wave and reflow soldering. Some components are soldered by hand, but this is time consuming and considerably adds to the assembly costs.

6.6.3.1 Wave Soldering

Wave soldering is a large-scale soldering process. The name is derived from the use of standing waves of molten solder to attach component leads to the board. After insertion of the electronic components, the panels of boards are loaded onto a conveyor and passed over a bath of molten solder such that the underside of the board passes across the top of a pumped wave of solder, which wets the exposed metallic areas of the board (those not protected with solder mask). A reliable mechanical and electrical connection results when the solder solidifies.

Wave soldering is mainly used for through-hole devices, but can be used for SMDs attached to the underside of the board. In this case, the components must be glued by the placement equipment onto the board surface before being passed through the solder wave. The components must also be capable of being passed through the wave without damage, which generally restricts this process to passive SMD components. The time taken for wave soldering and cleaning one board, or in the case of small boards, one panel or fixture, depends on the conveyor speed, with conveyor speed adjustment up to 20 fpm. Typically, conveyor speeds are near 10 fpm, which yields a time of approximately 2 min for a board, panel, or fixture to pass through the wave solder and cleaning station. However, conveyor speeds are selected to yield specific solder contact times, which are usually about 3 s.

As through-hole components have been largely replaced by surface-mounted components, wave soldering has been supplanted by reflow soldering methods. However, there is still significant wave soldering where SMT is not suitable (e.g., large power devices and high pin count connectors or where through-hole technology is still the most economic (e.g., in certain major appliances and consumer products)).

6.6.3.2 Reflow Soldering

Reflow soldering is a process in which a solder paste (a sticky mixture of powdered solder and flux) is used to hold the components in place on their attachment pads, after which the boards are carefully heated to melt the solder to form the joints. In most cases, solder paste is applied to the solder pads by stenciling. The stencils are etched stainless steel or brass sheets. Stenciling machines can be fully automatic or manually operated. A rubber or metal squeegee blade forces the paste through the stencil openings onto the pads on the board. The types of solder paste fall into three main categories [2]: Rosin Mildly Activated (RMA), water-soluble Organic Acid (OA) and no-clean. Each of these has advantages and disadvantages (Table 6.3) and the choice depends on the application and product type.

After component placement, the boards must be heated to melt the solder paste to form the joint between the component leads and the attachment pads. The assembly may be

TABLE 6.3

Comparison of Solder Paste Types

Type	Advantages	Disadvantages
RMA	• Stable properties • Good properties	• Needs chemical solvent or saponification for cleaning
OA	• Cleaned using pure water • Very good clean ability	• Humidity sensitive—short shelf and working life, solder ball tendency • Water leaches lead into waste steam
No clean	• No cleaning process, equipment or chemicals • Eliminates effluent issues	• May leave some visible residue behind

Source: Adapted from Intel Corporation Leaded Surface Mount Technology (SMT), 2000 Packaging Databook, Section 7–1.

heated by infrared lamps or (more commonly) by passing through a carefully-controlled oven or soldering with a hot air pencil. In the conventional reflow soldering process, there are usually four stages or zones, each having a distinct thermal profile: preheat, soak, reflow, and cooling. The setup of the machine for processing of a new board must be established by trials in a process called profiling.

Reflow soldering is the most common method for attaching SMDs to the board. Reflow soldering can be used for PTH components and is particularly useful for boards that have mainly SMDs with a few PTH parts. If this is done, the solder paste application screens must be adapted to deposit solder paste into the holes in the board.

6.6.4 Other Assembly Processes

Other processes included in the assembly sequence are cleaning, rework, and testing.

6.6.4.1 Cleaning

Cleaning of the board assembly is necessary to remove soldering residues and this is generally done with a liquid cleaner that may simply be water. In general, the cleaning of SMT assemblies is more difficult than PTH assemblies because of the smaller gaps between the components and the board surface. The required cleaning process depends on the type of solder paste used. Chemical solvents are used for RMA pastes and the waste effluents need to be dealt with. Water can be used for OA pastes, which must also be treated carefully as the effluent may contain lead. No-clean solder pastes are becoming increasingly popular as the cleaning process may then be eliminated.

6.6.4.2 Rework

Repair and rework for some boards is necessary to replace faulty components and parts that have been faultily inserted. Rework involves removal of the faulty components, followed by the placement and soldering of the replacement part. In general, rework is largely carried out manually, with aid of devices that ease the removal of parts from the assembly. Repair and rework of SMD assemblies may be easier than conventional PTH components, due to the availability of tools for removing components including hot-air machines.

pjwstk|402064|1435559649

However, if the parts are attached to the underside of the board using adhesives removal may be more difficult.

Manual reworking of faulty boards is expensive and consequently may be omitted for inexpensive boards. In this case, the faulty boards are simply scrapped, but this approach is generally not economic for PCB assemblies with expensive components.

6.6.4.3 Board Testing

Two types of testing of the PCB assembly are usually necessary and these are in-circuit testing and functional testing. During in-circuit testing, the board is checked for continuity or short circuits that may occur due to solder bridges or open circuits (e.g., bent or broken leads). Wrong components and incorrect orientations are also determined, together with components damaged by electrostatic discharge. In-circuit testing is usually carried out using a special bed-of nails test fixture to give access to the test points on the circuit board. The fixture consists of a number of spring-loaded contacts which serve as probes interfacing with board components and contact points. Special-purpose preprogrammed test routines are utilized to test the board. Functional testing uses the PWB edge connector as the testing interface. Functional testing generally checks for failures such as invalid system inputs or outputs, bad timing, and interface problems. The automatic test equipment basically simulates the electrical interface that the PCB assembly experiences during operation. The tests may be static or dynamic, which tests for timing errors in addition to logic levels.

6.6.5 Assembly Sequences for Printed Circuit Boards

The required basic sequence of assembly processes for a printed circuit board depends largely on the type of board and the mix of electronic components used. The assembly sequences are simpler if the electronic components are restricted to a single technology with only through hole or only surface-mounted components. Printed circuit board assemblies can be divided into three basic categories [1–3]. Type-1 boards are single technology boards and have either only PTH components or only SMD components (Figure 6.10). There are subcategories of type-1 boards dependent on whether components are mounted on both sides of the board or only one side. Type-2 boards are mixed technology boards with PTH components on the upper side of the board and surface mount components on the bottom side (Figure 6.11). Type-3 boards are also mixed technology but have PTH components on the top side and SMD components on both the top and bottom sides (Figure 6.12).

a. Type-1 Boards

   Figure 6.10a shows the sequence of operations for the assembly of a board with only PTH components on the top side of the board. Whether the assembly processes used are carried out automatically or manually is dependent on a number of factors including the quantity of boards to be produced. If there are only a small number of boards, the processes may all be carried out manually. The electronic components are inserted onto the top side of the board and then attached by wave soldering. Components can be mounted on the bottom side of the board also, but if this is done the items must be inserted manually and soldered by hand, which adds considerably to the costs of board assembly.

   Figure 6.10b shows the assembly sequence for a type-1 board with surface-mounted devices on the topside only. The assembly processes begin with the screen printing

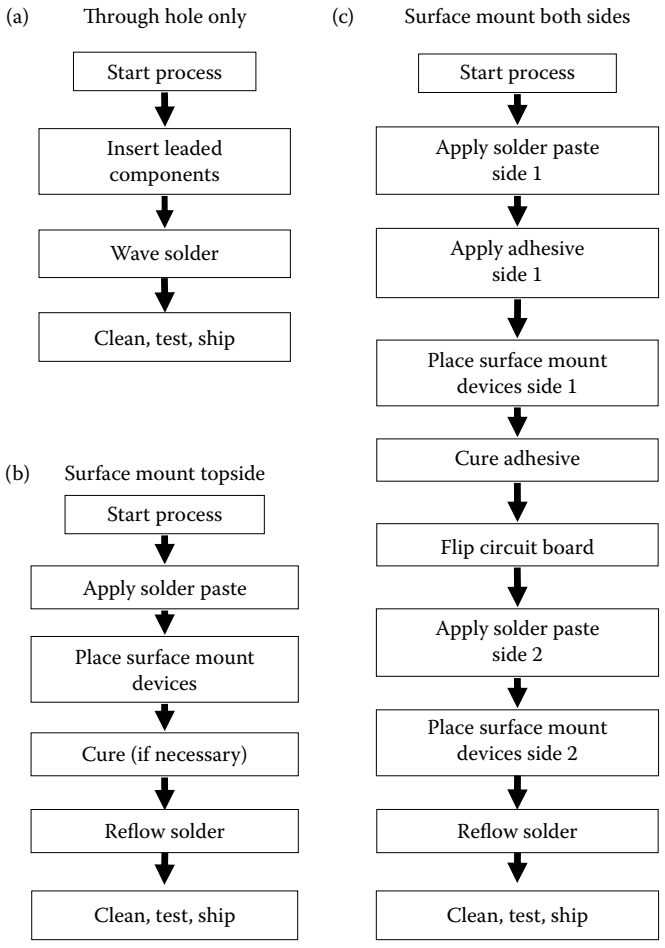
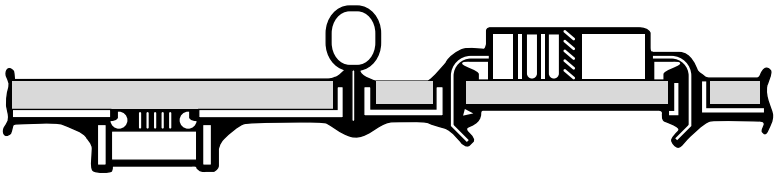


FIGURE 6.10
Assembly sequences for single technology boards (type 1).

of solder paste onto the mounting pads on the board surface. The SMDs are then placed in their appropriate positions and then affixed by reflow soldering. When surface-mounted components are also attached to the bottom side of the board, (Figure 6.10c) the sequence begins with solder paste application to the bottom side of the board, followed by placement of the underside components that are attached with an adhesive. The board is then inverted. Solder paste and components are then added to the upper side of the board. The board is then reflow soldered to affix all components to the board.

b. Type-2 Boards

Many boards are now being manufactured with a mixture of through-hole and surface-mounted devices. This combination of components complicates the insertion and assembly sequence. The through-hole components can be mounted on the upper side of the board and the surface-mounted devices on the bottom (known as a type-2 board); then the assembly sequence is as shown in Figure 6.11.



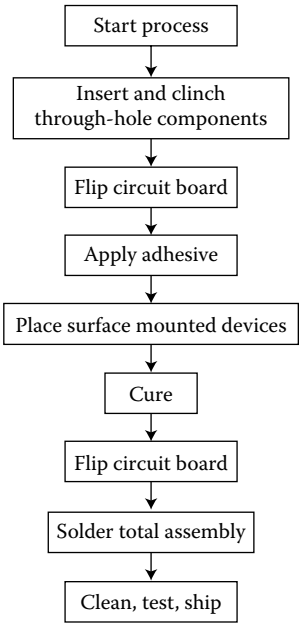


FIGURE 6.11
Assembly sequence for type-2 board—through-hole devices topside and surface-mounted devices bottom side.

For this to be possible, the surface-mounted devices must be restricted to those able to pass through the solder wave.

c. Type-3 Boards

When surface-mounted devices are placed on both sides of the board (type-3 board), a more complex assembly sequence is required. Firstly, the topside SMDs must be placed (Figure 6.12) and reflow soldered. The through-hole devices are then inserted and the board inverted for the underside SMDs to be placed. Wave soldering is then used to attach these components.

6.7 Estimation of PCB Assembly Costs

Printed circuit board assembly costs can be estimated using data on the insertion time and costs for the different electronics package styles, by considering all components added to the board in sequence. The materials necessary for the estimation of PCB assembly costs are presented at the end of this section. Databases giving the time for manual insertion and the costs for automatic and robot insertion are included. A worksheet is provided to

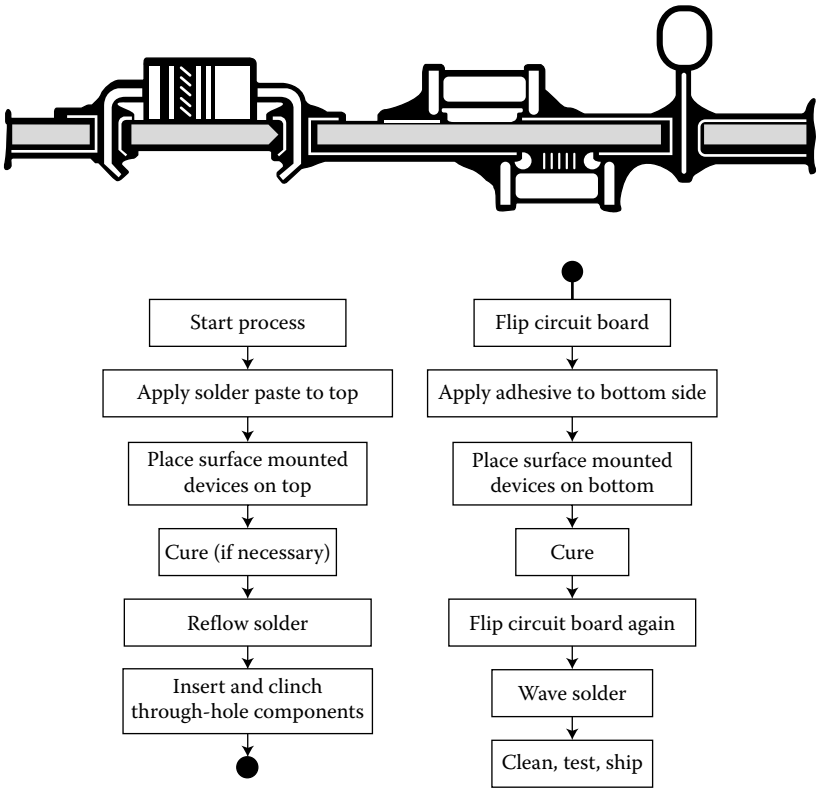


FIGURE 6.12
Assembly sequence for type-3 boards—through hole and surface-mounted topside and surface-mounted devices bottom side.

assist in tabulating the results. Components and operations are entered on the worksheet in assembly order, one line for each basic type of component or operation.

The time for manual insertion, obtained from the database, is entered on the worksheet and then multiplied by the operator rate to give the insertion cost. After per component allowances for rework costs are added, the total operation cost is entered. For automatic or robot insertion, the cost is obtained directly from the database, and then adjusted for programming, the setup, and rework.

For mechanical parts, the manual assembly times and costs can be obtained using the *Product Design for Assembly* handbook [3]. When all the operations have been entered, the total cost is obtained by summing the figures in the cost column.

6.7.1 Component Insertion Costs

The operation cost for the insertion of electronic components is made up of four parts.

- Insertion or placement cost
- Setup cost
- Rework cost
- Programming cost

TABLE 6.4

Insertion Times and Costs for Through-Hole Components

Type		Insertion Time (s), T_i		Insertion Cost ($), C_i	
		Manual	Semiautomatic	Automatic	Robot
Axial		19	7	0.012[a]	0.05
Post		8	5.0	0.012[a]	0.05
Radial		$10 + 1.8n_l$	8	0.012[a]	0.05
Can		$10 + 1.8n_l$	8	0.012[a]	0.05
SIP	$n_l \leq 40$	8	7	0.008	0.05
	$n_l > 40$	10	9	0.008	0.05
SIP socket	$n_l \leq 40$	8	7	0.008	0.05
	$n_l > 40$	10	9	0.008	0.05
DIP		$6.0 + 0.5n_l$	8	0.008	0.05
DIP socket		$6.0 + 0.5n_l$	8	0.008	0.05
Connector		$6.0 + 0.5n_l$	8	0.008	0.05
Pin grid array		$6.0 + 0.5n_l$	12	0.01	0.06

[a] Includes the cost of sequencing.

Data collected from a number of sources [8–10] for the insertion of electronic components is summarized in Tables 6.4 through 6.9.

6.7.1.1 Insertion Cost

Components can be inserted or placed on the board manually or automatically either using special purpose equipment or robots. If SMDs are placed on the underside of a board, an adhesive to hold the items in place prior to soldering may be required and this affects the placement times and costs. The insertion cost, C_{it} is given by

$$C_{it} = R_p C_i \tag{6.11}$$

where R_p is the number of parts of the same style inserted and C_i is the insertion cost per component. For automatic and robot insertion the insertion cost per component is obtained directly from Tables 6.4 and 6.5. For manual and semiautomatic insertion, the insertion cost per component is given by

$$C_i = \frac{T_i W_a}{3600} \tag{6.12}$$

where

T_i = the insertion time per component
W_a = the manual operator rate in \$/h.

The insertion times, T_i, for manual and semiautomatic insertion are given in Tables 6.4 and 6.5.

TABLE 6.5

Insertion Times and Costs for Surface-Mounted Components

Type		Insertion Time (s), T_i		Insertion Cost ($), C_i			
		Manual	Manual Adhesive	Automatic	Automatic Adhesive	Robot	Robot Adhesive
Chip		10	15	0.002	0.006	0.05	0.06
MELF		10	15	0.002	0.006	0.05	0.06
SOT		10	15	0.002	0.006	0.05	0.06
LCCC	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
LDCC	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
PLCC	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
SOIC	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
SSOP	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
SOJ		10	15	0.002	0.006	0.05	0.06
Flat pack	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
Quad flat pack	$n_l < 48$	15	20	0.002	0.006	0.05	0.06
	$n_l \geq 48$	20	30	0.005	0.008	0.05	0.06
Connector	$n_l < 24$	10	15	0.002	0.006	0.05	0.06
	$n_l \geq 24$	15	20	0.005	0.008	0.05	0.06
Ball grid array	$n_l < 48$	15	20	0.002	0.006	0.05	0.06
	$n_l \geq 48$	30	40	0.005	0.008	0.05	0.06

TABLE 6.6

Average Insertion Fault Rates for Through-Hole Components

Type	Insertion Fault Rate, A_f			
	Manual	Semiautomatic	Automatic	Robot
Axial	0.005	0.003	0.002	0.002
Post	0.002	0.001	0.001	0.001
Radial	0.005	0.003	0.002	0.002
Can	0.005	0.003	0.002	0.002
SIP	0.005	0.003	0.002	0.002
SIP socket	0.005	0.003	0.002	0.002
DIP	0.005	0.003	0.002	0.002
DIP socket	0.005	0.003	0.002	0.002
Connector	0.005	0.003	0.002	0.002
Pin grid array	0.005	0.003	0.002	0.002

TABLE 6.7

Average Insertion Fault Rates for Surface-Mounted Components

Type	Insertion Fault Rate, A_f					
	Manual	Manual Adhesive	Automatic	Automatic Adhesive	Robot	Robot Adhesive
Chip	0.002	0.002	0.001	0.001	0.002	0.002
MELF	0.002	0.002	0.001	0.001	0.002	0.002
SOT	0.002	0.002	0.001	0.001	0.002	0.002
LDCC	0.002	0.002	0.002	0.002	0.002	0.002
PLCC	0.002	0.002	0.002	0.002	0.002	0.002
SOIC	0.002	0.002	0.002	0.002	0.002	0.002
SSOP	0.002	0.002	0.002	0.002	0.002	0.002
SOJ	0.002	0.002	0.001	0.001	0.002	0.002
Flat pack	0.003	0.003	0.002	0.002	0.002	0.002
Quad flat pack	0.003	0.003	0.002	0.002	0.002	0.002
Connector	0.002	0.002	0.002	0.002	0.002	0.002
Ball grid array	0.003	0.003	0.002	0.002	0.002	0.002

6.7.1.2 Setup Cost

For each batch of boards produced the insertion machines must be setup with the required component feeding devices, feed tubes, tapes, and so on. The cost for components of the same package style is determined by the number of different parts to be inserted.

$$C_{st} = \frac{C_s N_{tp}}{B_s} \tag{6.13}$$

where C_{st} is the setup cost for a set of parts of the same package style, C_s is the setup cost per part type, N_{tp} is the number of different components of the package style and B_s is the batch size of boards to be produced.

TABLE 6.8

Rework Times for Through-Hole Components

Type		Removal Time (s) T_{rm}	Insertion Time (s) T_i	Soldering Time (s) T_{rs}
Axial		10	19	9
Post		8	8	6
Radial		$6 + 2n_l$	$10 + 1.8n_l$	$2.9 + 3n_l$
Can		$6 + 2n_l$	$10 + 1.8n_l$	$2.9 + 3n_l$
SIP	$n_l \le 40$	10	8	$2.9 + 3n_l$
	$n_l > 40$	15	10	$2.9 + 3n_l$
SIP socket	$n_l \le 40$	10	8	$2.9 + 3n_l$
	$n_l > 40$	15	10	$2.9 + 3n_l$
DIP		15	$6.0 + 0.5n_l$	$2.9 + 3n_l$
DIP socket		15	$6.0 + 0.5n_l$	$2.9 + 3n_l$
Connector		15	$6.0 + 0.5n_l$	$2.9 + 3n_l$
Pin grid array		30	$6.0 + 0.5n_l$	$2.9 + 3n_l$

TABLE 6.9

Rework Times for Surface-Mounted Components

Type	Unsoldering Time (s) T_{rm}		Insertion Time (s) T_i	Soldering Time (s) T_{rs}
	w/o Adhesive	with Adhesive		
Chip	10	15	10	9
MELF	10	15	10	9
SOT	10	15	10	$2.9 + 3n_l$
LDCC	15	25	10	$2.9 + 3n_l$
PLCC	15	25	10	$2.9 + 3n_l$
SOIC	15	25	10	$2.9 + 3n_l$
SSOP	15	25	10	$2.9 + 3n_l$
SOJ	12	15	10	$2.9 + 3n_l$
Flat pack	15	25	10	$2.9 + 3n_l$
Quad flat pack	15	25	20	$2.9 + 3n_l$
Connector	15	25	10	$2.9 + 3n_l$
Ball grid array	20	30	30	$2.9 + 3n_l$

6.7.1.3 Rework Cost

All insertion operations result in a small number of faulty insertions and these must usually be repaired at the rework stations. Reworking involves the removal of the faulty component (unsoldering), insertion of a replacement component and then soldering of the new component to the board. These three operations are carried out manually, but with the aid of tools that facilitate removal of the faulty components.

The cost to rework a faulty component is given by

$$C_{rwc} = \frac{(T_{rm} + T_i + T_{rs})W_a}{3600} + C_c \tag{6.14}$$

where

T_{rm} = the unsoldering or removal time
T_i = the manual insertion time for the component
T_{rs} = the time to solder the replacement component
C_c = the cost of the replacement component (if needed).

The total rework cost for each package type is given by

$$C_{rw} = R_p A_f C_{rwc} \tag{6.15}$$

where A_f = the average fault rate for insertions of the package style.

Tables 6.6 and 6.7 give the average insertion fault rates for the insertion of through-hole and surface-mounted components by different insertion methods. The times for component removal, manual insertion, and hand soldering are given in Tables 6.8 and 6.9.

6.7.1.4 Programming Cost

The automatic insertion equipment must be programmed for the PCB processed. This is done at the start of the production of the board design.

The programming cost per component style is given by

$$C_{pr} = \frac{R_p C_{ap}}{LV} \tag{6.16}$$

6.7.2 Worksheet for Printed Circuit Board Assembly Costs

The data given in Tables 6.3 through 6.9 can be used to estimate PCB assembly costs with the aid of the basic data in Table 6.10 and the worksheet in Table 6.11. Each line in the worksheet is used for components of the same package style with the same number of leads that are inserted by the same method.

6.7.3 Example

In order to illustrate the use of the worksheet to estimate assembly costs, consider the assembly of a logic board. This particular board contains the following list of components.

Electronic components			
Name	**Number**	**Number of Leads**	**Number of Different Types**
DIP	11	20	3
DIP	56	14	4
DIP socket	1	24	1
DIP	1	40	1
DIP	1	24	1
Connector	1	3	1
Connector	1	9	1

Mechanical Parts	
Name	**Number**
Screw	3
Washer	3
End plate	1
Hex nut	3
Nut	2

TABLE 6.10

Basic Data for PCB Assembly Worksheet

Setup cost per part type, C_s, cents	1.6
Assembly operator rate, W_a, $/hour	36
Programming cost per part, C_{ap}, cents	1.8
Batch size, B_s	2000
Life volume, LV	10,000

TABLE 6.11

Worksheet for Printed Circuit Board Assembly

					Insertion			Rework								
Name of the operation	**No. of Leads**	**No. of parts**	**No. of Part Types**	**Ave. Component Cost, $**	**Insertion Time, s**	**Cost per part, $**	**Total Insertion, $**	**Ave. no. of Faults**	**Removal Time, s**	**Insertion Time, s**	**Soldering Time, s**	**Total Rework, $**	**Setup Cost, $**	**Programming Cost, $**	**Total Cost, $**	**Description**
	n_l	R_p	N_t	C_c	T_i	C_i	C_{ti}	A_f	T_{rm}	T_i	T_{rs}	C_{rw}	C_{st}	C_{pr}	C_{in}	
	Total															

It is assumed that the smaller DIPs, radials, and axials are inserted automatically and the remaining components or parts manually inserted or assembled, except for one DIP, which is assembled into the corresponding DIP socket after wave solder of the assembled board.

Table 6.12 shows the completed worksheet for this assembly. A separate line on the worksheet is used for each component type (package style and the number of leads). The first line is for the automatic insertion of 11 DIPs with 20 leads, with 3 different DIP packages included. This information is included in columns 2 to 4 of the worksheet. These DIPs are inserted automatically and the insertion cost per insertion is obtained from Table 6.4 and entered into column 7 of the worksheet. The total cost for the insertion of these 11 DIPs is calculated using Equation 6.11 and entered into column 8. The costs for rework of faulty insertions is calculated in columns 8 to 13 using the data in Tables 6.6 and 6.8, with the cost determined by Equation 6.14 and entered into column 13 of the worksheet. The setup cost is determined by Equation 6.13 and entered into column 14. The programming cost is calculated using Equation 6.15 and entered into column 15. Finally, the total cost for the insertion of the 11 DIPs is obtained by adding the results in columns 8, 13, 14, 15.

The costs for the other electronic components are entered into the other rows of the worksheet and calculated in a similar manner. At the bottom of the worksheet, the calculations for the mechanical components, mainly screws, nuts, and washers, are entered. The times for these components are obtained from the DFA handbook [9] (or the charts in Chapter 3).

The completed worksheet for this example board gives a total estimated assembly cost of $2.77. The consideration of avoidable costs indicates that an elimination of the 10 fasteners would save 63 cents—a surprisingly high figure for a board with only one nonelectrical component, namely, the end plate. The operation costs for the automatic insertion processes include the cost of rework, which amounts to a total of 13.6 cents—clearly a significant item.

Finally, it was assumed in this analysis that the manufacturer would have an automatic machine available for the insertion of the 32 radial components. It is interesting that if these components were to be inserted manually, an additional expense of $4.35 would be incurred.

6.8 Case Studies in PCB Assembly

The analyses of two case studies are now presented.

6.8.1 Measuring Instrument Connector Board

Figure 6.13 shows the layout of components on the upper and lower sides of a small PCB.

Labor rate	$36/h
Production quantity	1000
Number of batches	2
Boards per panel	4

It is assumed that all DIP sockets, axials, and radials are autoinserted and that all posts and connectors on the upper side of the board are semiautoinserted before wave soldering.

TABLE 6.12

Completed Worksheet

Name of the Operation	No. of Leads	No. of Parts	No. of Part Types	Ave. Component Cost, $	Insertion			Rework					Setup Cost, $	Programming Cost, $	Total Cost, $	Description
					Insertion Time, s	Cost per Part, $	Total Insertion, $	Ave. no. of Faults	Removal Time, s	Insertion Time, s	Soldering Time, s	Total Rework, $				
	n_l	R_p	N_t	C_c	T_i	C_i	C_{ti}	A_f	T_{rm}	T_i	T_{rs}	C_{rw}	C_{st}	C_{pr}	C_{in}	
DIP	20	11	3			0.008	0.09	0.002	15	16	62.9	0.021	0.002	0.002	0.113	Auto insert
DIP	14	56	4			0.008	0.45	0.002	15	13	44.8	0.082	0.003	0.01	0.543	Auto insert
Axial	2	16	4			0.012	0.19	0.002	10	19	9	0.012	0.003	0.003	0.210	Auto insert
Radial	2	32	6			0.012	0.38	0.002	10	13.6	8.9	0.021	0.005	0.006	0.415	Auto insert
DIP socket	24	1	1		18	0.18	0.18	0.005	15	18	74.9	0.005	0	0	0.185	Manual insert
DIP	40	1	1		26	0.26	0.26	0.005	15	26	123	0.008	0	0	0.268	Manual insert
Connector	3	1	1		7.5	0.075	0.075	0.005	15	7.5	11.9	0.002	0	0	0.077	Manual insert
Connector	9	1	1		10.5	0.105	0.105	0.005	15	10.5	29.9	0.003	0	0	0.108	Manual insert
Screw		3	1		9.8	0.098	0.294								0.294	Manual assemble
Nut		3	1		4.4	0.044	0.132								0.132	Manual assemble
End plate		1	1		4.5	0.045	0.045								0.045	Manual assemble
Washer		3	2		4.7	0.047	0.141								0.141	Manual assemble
DIP	24	1	1		4	0.04	0.04								0.04	DIP into socket
														Total	2.770	

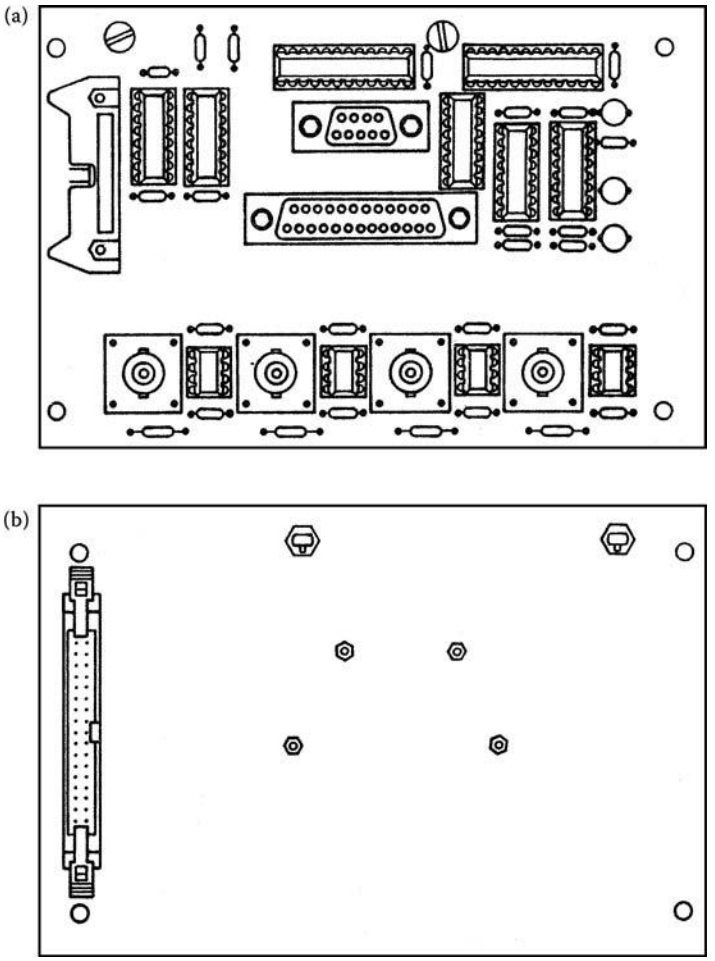


FIGURE 6.13
Layout of components for a small PCB. (a) Upper side; (b) lower side.

The single connector on the underside of the board must be hand inserted and hand soldered after wave soldering has occurred. The total cost of the assembly of this board is $5.10, and of this total, $1.97 is associated with the single hand-inserted and hand-soldered connector on the underside of the board. This highlights the importance of avoiding manually inserted and soldered parts as much as possible. The cost of this particular board could be reduced considerably by a simple redesign to place this single connector on the upper side of the board.

It is interesting to compare the assembly cost with the cost of complete manual assembly of the board. For a labor cost of $36/h, the cost of complete manual assembly is $10.69. Figure 6.14 shows the effect of varying the quantity of boards required on the assembly cost per board. For the autoinserted board, it is necessary to reduce the quantity to only six boards before the cost is more than for manual assembly with a $36/h labor rate. This illustrates why, if automatic insertion equipment is available, it is usually economical to use this even for small board quantities or for a few autoinsertable components. In addition, for manual assembly in this case, it is necessary to reduce the labor cost to around $15

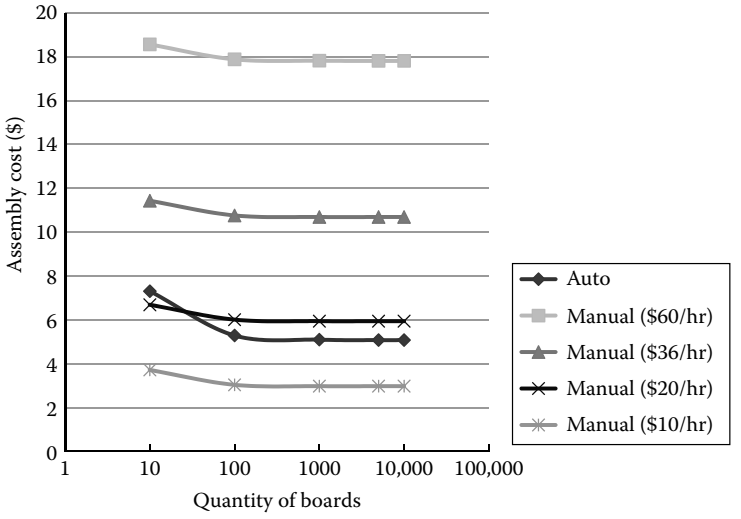


FIGURE 6.14
Effect of production volume on costs for PCB in Figure 6.13.

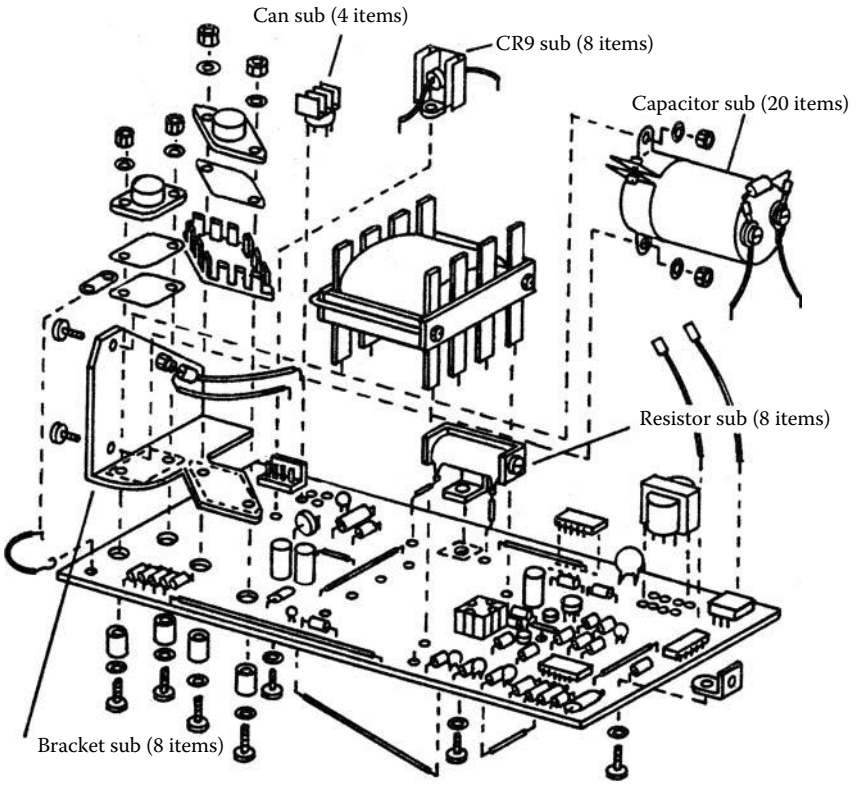


FIGURE 6.15
Components in a small power-supply board. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1987. With permission.)

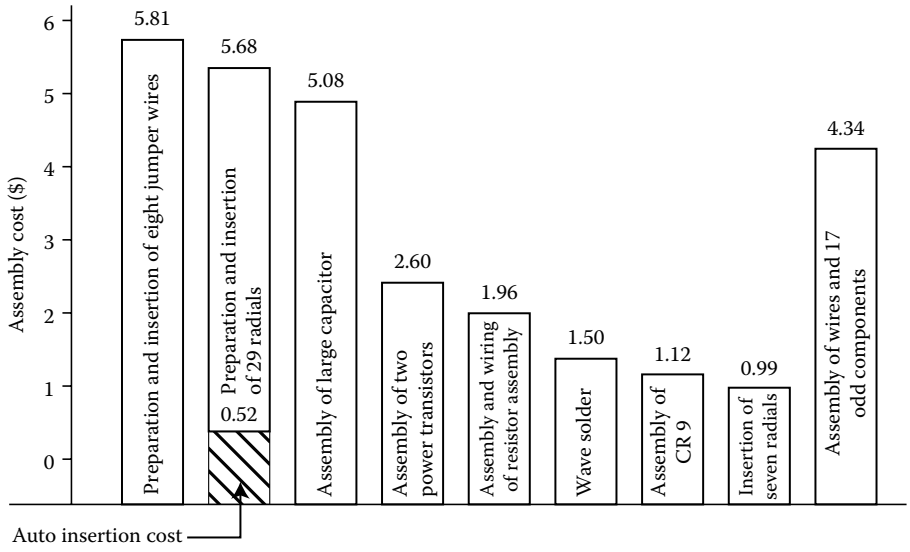


FIGURE 6.16
Breakdown of assembly costs for small power supply.

per hour before the assembly cost is less than that for the autoinserted board. It is obvious why the assembly of PCBs is often carried out in countries where manual labor costs are considerably lower than those in the United States.

6.8.2 Power Supply

Many electronic products, in particular power supplies, contain a number of large, odd-shaped components, and many mechanical parts (screws, washers, heat sinks, brackets, etc.) are needed to secure them. As a result, power supplies present particular assembly difficulties. Part of this can be attributed to a lack of consideration by components suppliers to features that facilitate the ease of assembly. Figure 6.15 [3] shows an exploded view of a typical small power supply. The large can capacitor at the top right requires around 20 items, mainly mechanical, to mount it onto the board. Similarly, a large number of mechanical parts are required for the two power transistors on the left-hand side. Figure 6.16 shows

TABLE 6.13
Video Board Design Parameters

Board length	6.25 in.
Board width	2.5 in.
Board thickness	0.062 in.
Copper weight	0.5 oz
Number of holes	502
Minimum trace width	0.015 in.
Minimum conductor spacing	0.006 in.

TABLE 6.14

Parts List for the Video Board

Package Style	Repeat Count	No. of Leads	No. of Different Types	Insertion Method	Average Part Cost, $
DIP	3	20	2	Auto	0.1
DIP	7	14	4	Auto	0.1
SIP	4	8	3	Auto	0.05
SIP	1	6	1	Auto	0.05
SIP	1	5	1	Auto	0.05
Radial	3	2	1	Auto	0.05
Can	1	2	1	Manual	0.1
PTH connector	3	10	1	Auto	0.05
PTH connector	1	3	1	Auto	0.05
PTH connector	1	2	1	Auto	0.05
PTH connector	1	24	1	Robot	0.1
PTH connector	1	40	1	Robot	0.15
PTH connector	1	34	1	Robot	0.1
PTH connector	1	25	1	Robot	0.1
Chip	25	2	7	Auto	0.01
Quad flat pack	1	100	1	Robot	2.00

TABLE 6.15

Parts List for Small PC Board

Package Style	Repeat Count	No. of Leads	No. of Different Types	Insertion Method	Average Part Cost, $
SOIC	1	40	1	Auto	1.0
SOIC	1	50	1	Auto	1.0
Flat pack	1	8	1	Auto	0.5
SOT	3	4	3	Auto	0.1
Quad flat pack	1	156	1	Robot	3.00
Quad flat pack	1	80	1	Robot	2.00
Quad flat pack	1	44	1	Robot	1.50
Chip	122	2	80	Auto	0.01
PTH connector	1	4	1	Auto	0.1
PTH connector	1	53	1	Robot	0.5

a breakdown of the costs for assembly of this power supply determined by the method described in Section 6.6. The total manual assembly cost is $29.08. Considerable savings could be made by eliminating the jumper wires (saving $5.81), inserting the radial components automatically (saving $5.16), and simplifying the assembly of the large can capacitor ($5.08). Obviously, the availability of this type of cost information early in the design process guides designers in directions that have the greatest influence on assembly cost reduction.

6.9 Glossary of Terms

The following is a brief description of some of the terminology used in this chapter. The physical configurations of some electrical components, the manual assembly operations, and some terms pertaining to automatic insertion equipment are given.

Axial-lead component: Electrical component of cylindrical shape with two leads exiting from opposite ends of the component in line with its axis (Figure 6.2). The component is sometimes called a VCD (variable center distance). The most common axial-lead components are resistors, capacitors, and diodes.

Ball Grid Array (BGA): The surface-mounted equivalent of pin grid arrays. The underside of the package has terminal projections (balls) arranged in a pattern of concentric squares, for connection to pads on the circuit board by reflow soldering. BGA chips are particularly good for devices that have many terminations, such as modern microprocessors.

Can-type IC: A cylindrical integrated circuit, packaged so that the leads form a circular pattern (Figure 6.2). This multileaded radial component can have from 3 to 12 leads.

Cement: Due to the requirements for ruggedness placed on some PCBs, components can be cemented to the board to reduce the effects of vibrations. This sometimes requires that the component leads be bent prior to cementing.

Center distance: Distance between leads when formed for insertion. This term applies to two-leaded components and DIPs; also termed *lead span*.

Channel: Plastic container in the form of a long tube, in which a number of DIPs are placed in single file and oriented for dispensing to an insertion machine; also called *stick*.

Chip resistor, chip capacitor: Chips are small passive SMD packages rectangular in shape with pads at both ends for mounting to the board. Most commonly these are chip resistor and chip capacitor packages

CLCC: See LCCC

Clinch: The bending of a component lead end after insertion through the PCB. This temporarily secures the component prior to soldering. In a full clinch, the lead is bent to contact the terminal area. In a modified clinch, the lead is partially bent to a predetermined intermediate angle.

Component: Any electrical device to be attached to the PCB.

DIP (dual in-line package (Figure 6.2)): A rectangular integrated circuit, packaged so as to terminate in two straight rows of pins or leads.

DIP Socket: A dual in-line (DIP) package into which a standard DIP component can be inserted without soldering. The number of leads is the same as those on the DIP component to be inserted. These sockets are used so that the DIP component can be changed without having to be unsoldered from the board. Subsequent insertion of the DIP package into the corresponding socket is usually done manually.

ECO (engineering change order): A component or insulated jumper wire, installed manually, which is needed when the electrical circuit cannot be etched onto the board without crossing paths at some point. Often, the leads are not inserted into the board but are manually soldered to the leads of components already assembled on the board. ECO wires are also referred to as jumper wires. (See Retrofit.)

Fault: Any error that causes the assembled PCB to fail testing or inspection procedures and requires rework.

Flat Pack: A flat pack is an integrated circuit package with fine pitch gull-wing shaped leads along two sides of the package. Typically, the number of leads can be as high as 200.

Hybrid: PCB populated by both surface-mounted and through-hole components also referred to as *mixed-mounting technology.*

Insertion: Process whereby the component is grasped, prepared if necessary, and placed on the board, temporarily secured if necessary.

LCCC (leadless ceramic chip carrier): A leadless ceramic chip carrier (LCCC) is a SMD package made of a ceramic material that can withstand high temperatures and can be hermetically sealed. It does not have leads, but has pads around all four sides of its perimeter. Note that the acronym CLCC is also used for this package.

LDCC (leaded ceramic chip carrier): An SMD package made of a ceramic material that can withstand high temperatures and can be hermetically sealed. It has leads around all sides of its perimeter that are rolled under to form mounting pads.

Kitting: Preparing a package of parts, usually with instructions for assembly, to facilitate manual assembly.

Magazine: A unit containing a group of dispensing channels, usually about 15, used for an automatic DIP insertion machine.

MELF: MELF is an acronym for the metal electrode face and this is cylindrical surface-mounted package with metal caps at each end for soldering to the board. This package is basically a standard axial leaded component with metal caps instead of leads at each end. As these packages are round, they have a tendency to roll out of position prior to soldering.

Module: A unit containing a group of dispensing spools, usually 20 or less, used with an automatic axial-lead component sequencer.

Nonstandard component: Any component that cannot be inserted by dedicated, automatic machinery because of its physical characteristics (i.e., size, shape, lead span, etc.) These are also called "odd-form" components.

Pallet: A tray where components are arranged in a known position and orientation.

PCB (printed circuit board): An insulating board onto which an electrical circuit has been printed in the form of conductive paths. Contains drilled holes into which the leads of components are inserted. It is also known as a *printed wiring board* (PWB).

Pin Grid Array (PGA): A type of chip package in which the connecting pins are located on the bottom in grid of concentric squares. PGA chips are particularly good for devices that have many pins, such as modern microprocessors.

PLCC (plastic-leaded chip carrier): A package in which an integrated circuit chip is mounted to form an SMD. It is made of a plastic material that can withstand high temperatures and has rolled-under leads around all the four sides of its perimeter.

Post: Posts are pins soldered into holes in the board to act as terminals or test points.

Preform: Forming the leads of a component to the correct dimensions prior to insertion. Axial-lead components usually have their leads bent at right angles for insertion, and DIPs sometimes require lead or pin straightening. Radial-lead components, may have their leads notched or a stand-off or spacer installed, which maintains the required clearance between the component and the board. Can-type ICs and transistors often need a type of lead forming called "form a," which refers to the profile of the leads after forming.

Quad Flat Pack: A quad flat pack is an integrated circuit package with fine pitch gull-wing shaped leads along all four sides of the package. The dimensions of the package body are usually fixed, but the number and pitch of the leads can vary.

Radial-lead component: Electrical components with leads at right angles to the body (Figure 6.2). Examples are disc capacitors, "kidney" or "jellybean" capacitors, cermet resistors, and so on.

Reflow solder: Process by which surface-mounted devices become secured to the PCB. Components are placed onto solder paste that has been added to pads on the board, often by screen printing. Heat is applied to the board and the solder paste melts to attach the devices to the board.

Retrofit: A type of ECO that involves only the assembly of wires (jumper wires) to the PCB. Can refer to an assembly station in the PCB assembly process where only wires are assembled.

Rework: Repair a fault. This usually means severing the leads of the component and removing it, removing the individual leads from the PCB holes, cleaning the holes, inserting a new component, and soldering its leads. The operations are performed manually and are time-consuming and expensive.

SIP (single inline package): An integrated circuit—usually a resistor network or a connector packaged so as to terminate in one straight row of pins or leads (Figure 6.2).

SIP Socket: A single in-line (SIP) package into which a standard SIP component can be inserted without soldering. The number of leads is the same as those on the SIP component to be inserted. These sockets are used so that the SIP component can be changed without having to be unsoldered from the board. Subsequent insertion of the SIP package into the corresponding socket is usually done manually.

Sleeve: An insulating plastic tube slid manually onto the lead of a component to insertion to guard against electrical short circuits (Figure 6.2).

SMD (surface-mounted device): A component (often leadless) that is secured to the surface of the board.

SOIC (small-outline integrated circuit): An SMP package made of a plastic material that can sustain high temperatures and has leads in a gull-wing shape along its two longer sides (Figure 6.2).

SOJ: A small outline J-leaded (SOJ) package is an integrated circuit package with J-shaped leads on two sides of the package and can be mounted flat.

SOT (small-outline transistor): An SMD package for discrete components with about four leads in a gull-wing shape along two sides (Figure 6.2).

Spacer: This can be a small plastic ring (Figure 6.2) used to keep a minimum clearance between the component and the board. It is usually cemented to the board before the component is inserted. Some components use temporary spacers that are removed after the component is secured. Some spacers are provided with holes corresponding to each lead (Figure 6.2).

Spool: The package for holding taped axial-lead components.

SSOP: A shrink small outline L-leaded package (SSOP) is an integrated circuit package with gull-wing type leads on two sides of the body and can be mounted flat. The lead pitch is usually less than 1.27 mm.

Standard component: Any component that can be inserted by an automatic insertion machine.

Stick: A plastic container in which a number of DIPs are aligned in single file and are oriented for dispensing to an automatic insertion machine.

Tin: Providing a layer of solder on the surface of leads prior to insertion.

Touch-up: Cleaning the underside or solderside of a PCB after wave soldering to remove any excess solder, which can cause short circuits.

Transistor: A small component whose body has a cylindrical envelope except for one flat face, with three leads at right angles to the body (Figure 6.2).

VCD (variable center distance): The capability of an axial-lead component insertion head to vary the distance between leads when forming and inserting an axial-lead component (Figure 6.2). The term is also used to refer to an axial-lead component. The terms *adjustable span* and *variable span* can also be used.

Wave solder: To automatically solder all the leads on an assembled PCB by conveying it, at a slight incline, over a wave of solder.

PROBLEMS

1. Consideration is given to the purchase of an automatic DIP insertion machine that would be fully occupied inserting 26 identical 14-pin DIPs into a PCB. At present, the DIPs are inserted manually. Estimate the breakeven total batch size for the boards if one setup is used for the batch. Include the costs of rework and the cost (150 cents) for a replacement component when rework is carried out. The assembly worker rate is \$36/h, including overheads.
2. A PCB has 25 axial leaded components of 15 types, 32 radial components (2 leads) of 4 types, 2 radial components (3 leads) of 1 type, 14 DIPs (16 pins) of 10 types, and 1 connector (SIP) with 20 pins.
   All the components are inserted manually, but the company is interested in the probable savings if a radial inserter for two lead radials and a DIP inserter are available.
   Estimate the total cost of manual insertion and the savings to be obtained through the use of autoinserters. Assume a total life volume (total batch size) of 50 and an assembly worker rate of \$45/h. Neglect the cost of replacement components.
3. A PCB has 28 14-pin DIPs of 6 types and 32 axial components of 10 types inserted automatically. Manual insertion of 6 can-type components with three leads each. Estimate the assembly cost per board if the batch size is 200. Include the cost of rework. Assume an assembly worker rate of \$30/h and an average component replacement cost of \$1.00.
4. A small video board is double-sided and has the following main parameters.
   The board is made from FR-4 material and has gold plated edge connectors. It requires solder masking and legend printing on both sides.
   a. The cost of a simple double-sided board in FR-4 costs \$0.04/in^2. Estimate the manufacturing cost of the bare board, excluding hole drilling, legend printing, solder masking, and final testing.
   b. During manufacture of the boards the dimensions of the standard panel size used are length 24 in. and width 18 in. The separation of the boards in the panel is 0.1 in. and a clearance of 0.2 in. at the edge of the board must be used. Determine the number of boards per panel.
   c. The maximum stack height of panels for hole drilling is 0.5 in. The entry and exit films have the same thickness as the boards. Assuming that it takes 2 s to load and unload each panel and film and that each hole has a drilling time of 2 s, estimate the cost per board for hole drilling. The operating cost of the drilling machine including labor is \$60/h.
   d. The operating cost rate for solder masking is \$50/h and the masking operation time is 60 s per side. If the panel loading and unloading time is 2 s, estimate the cost per board for solder masking.
   e. The operating cost rate for legend printing is \$60/h and the masking operation time is 30 s per side. If the panel loading and unloading time is 2 s, estimate the cost per board for legend printing.

5. The video board in Problem 4 has a mixture of through hole and surface-mounted components on the upper side only. The parts list for the board is given in the following table.
   a. What will be the probable assembly sequence for this board?
   b. Using the data in Section 6.7, estimate the cost of assembling this board excluding soldering operations. Assume that all components that are reworked are replaced with new components. A copy of the worksheet in Table 6.11 can be used for this problem.
   c. The can component on line 7 of the table requires the component to be bent over and the can case soldered to the board by hand. What would be the savings if this component could be replaced by a similar component that could be automatically inserted?
6. A small control board for a PC has mainly surface-mounted components and two through-hole (PTH) connectors mounted on the upper side of the board. The parts list for this board is given in the table below.
   a. What will be the probable assembly sequence for this board?
   b. Using the data in Section 6.7, estimate the cost of assembling this board excluding soldering operations. Assume that all components that are reworked are replaced with new components. A copy of the worksheet in Table 6.11 can be used for this problem.
   c. A variant of this board has three 20 pin SOICs on the underside of the board, with an average cost of $0.5 each. What is the probable assembly sequence for this variant of the board and the additional cost of assembly?

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7

Design for Machining

7.1 Introduction

In machining, material is removed from the workpiece until the desired shape is achieved. Clearly, this is a wasteful process, and many engineers feel that a main objective should be to design components that do not require machining. Since most manufacturing machines are designed to remove metal by machining, the view that machining should be avoided must be considered impracticable for the immediate future. However, the trend toward the use of "near net shape" processes that conserve material is clearly increasing, and when large-volume production is involved, this approach should be foremost in the designer's mind.

In this chapter, the common machining processes are first introduced. Then the ways in which the work material can be readily changed to the desired form by machining are considered, together with the ways in which the surfaces of the component are finished. Finally, an introduction to early cost estimating for designers is presented.

All machine tools provide a means of (1) holding a cutting tool or abrasive wheel, (2) holding a workpiece, and (3) providing relative motion between them in order to generate the required surfaces.

7.2 Machining Using Single-Point Cutting Tools

Lathes are designed to rotate the workpiece and feed the cutting tool in the direction necessary to generate the required machined surface.

The workpiece is gripped in a chuck or collet or is mounted on a faceplate mounted on the end of the main spindle of the machine. The rotation of the workpiece is provided by an electric motor driving the main spindle through a series of gears. Cutting tools can be driven or fed parallel to or normal to the axis of rotation of the workpiece.

Modern lathes are provided with computer control of all workpiece and tool motions. These are known as computer numerical control (CNC) lathes, and the tools can be fed in any direction in the horizontal plane to generate a required contour on the workpiece. Figure 7.1 shows a cylindrical surface being generated in cylindrical turning.

The feed motion setting on the lathe is the distance moved by the tool during each revolution of the workpiece. The feed f is defined as the displacement of the tool relative to the workpiece, in the direction of feed motion, per stroke or per revolution of the

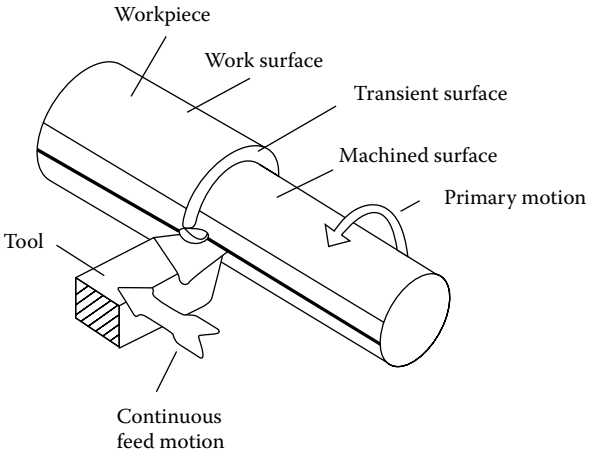


FIGURE 7.1
Cylindrical turning.

workpiece or tool. Thus, to turn a cylindrical surface of length l_w, the number of revolutions of the workpiece is l_w/f, and the machining time t_m is given by

$$t_m = \frac{l_w}{(fn_w)} \tag{7.1}$$

where n_w is the rotational speed of the workpiece.

It should be emphasized that t_m is the time for one pass of the tool (one cut) along the workpiece. This single pass does not necessarily mean, however, that the machining operation is completed. If the first cut is designed to remove a large amount of material at high feed (roughing cut), the forces generated during the operation will probably have caused significant deflections in the machine structure. The resulting loss of accuracy may necessitate a further machining operation at low feed (finish cut) to bring the workpiece diameter within the limits specified and to provide a smooth machined surface. For these reasons, the workpiece is often machined oversize during the roughing cut, leaving a small amount of material that is subsequently removed during the finishing cut. For very large depths, it may be necessary to provide several rough cuts or passes.

Figure 7.2 illustrates five typical lathe operations: cylindrical turning, facing, boring, external threading, and cut-off. In each case, the primary motion and the feed motion, together with certain other terms and dimensions, are indicated. In any machining operation the workpiece has three important surfaces:

1. The work surface, the surface on the workpiece to be removed by machining.
2. The machined surface, the desired surface produced by the action of the cutting tool.
3. The transient surface, the part of the surface formed on the workpiece by the cutting edge and removed during the following cutting stroke, during the following revolution of the tool or workpiece, or, in other cases (e.g., a thread-turning operation), (Figure 7.2d) during the following pass of the tool.

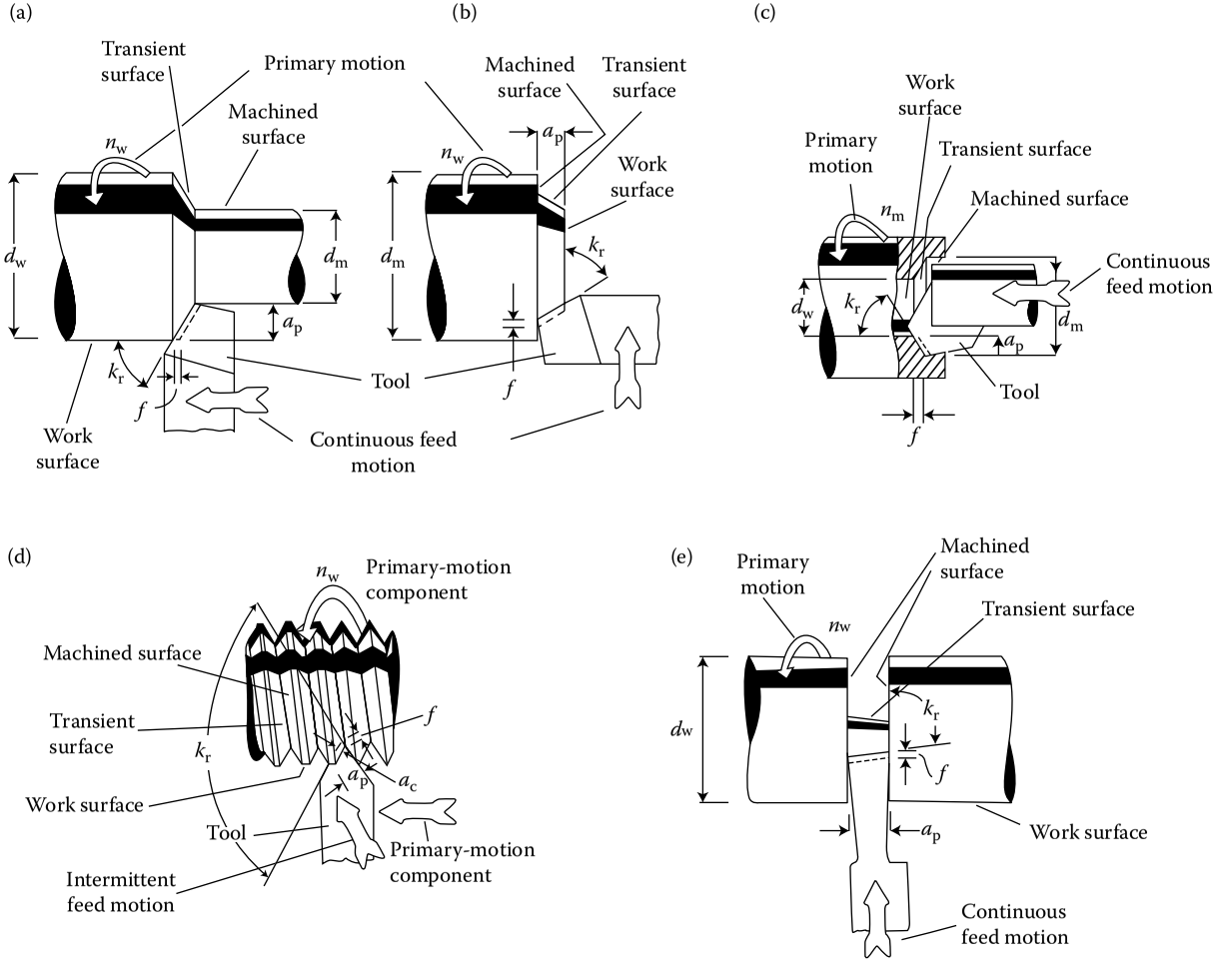


FIGURE 7.2
Lathe operations: (a) Cylindrical turning, (b) facing, (c) boring, (d) external threading, (e) parting or cut-off. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

In Figure 7.2a, which shows the geometry of a cylindrical-turning operation, the cutting speed at the tool corner is given by $\pi d_m n_w$, where n_w is the rotational speed of the workpiece, and d_m is the diameter of the machined surface. The maximum value of the cutting speed is given by $\pi d_w n_w$, where d_w is the diameter of the work surface. Thus, the average, or mean, cutting speed υ_{av} is given by

$$\upsilon_{av} = \pi n_w \frac{(d_w + d_m)}{2} \tag{7.2}$$

The metal removal rate Z_w is the product of the mean cutting speed and the cross-sectional area of the material being removed A_c. Thus

$$\begin{aligned} Z_w &= A_c \upsilon_{av} \\ &= \pi f a_p n_w (d_w + d_m)/2 \\ &= \pi f a_p n_w (d_m + a_p) \end{aligned} \tag{7.3}$$

This same result could have been obtained by dividing the total volume of metal removed by the machining time t_m.

For a given work material machined under given conditions, the unit power or energy required to remove a unit volume of material, p_s, can be measured. This factor is mainly dependent on the work material, and if its value is known, the power P_m required to perform any machining operation can be obtained from

$$P_m = p_s Z_w \tag{7.4}$$

Finally, if the overall efficiency of the machine tool motor and drive systems is denoted by E_m, the electrical power P_e consumed by the machine tool is given by

$$P_e = \frac{P_m}{E_m} \tag{7.5}$$

Approximate values of the unit power p_s for various work materials are presented at the end of this chapter.

An operation in which a flat surface is generated by a lathe is shown in Figure 7.2b and can be performed by feeding the tool in a direction at right angles to the axis of workpiece rotation. This operation is known as facing, and when the rotational speed of the workpiece is constant, the cutting speed at the tool corner varies from a maximum at the beginning of the cut to zero when the tool reaches the center of the workpiece.

The machining time t_m is given by

$$t_m = \frac{d_m}{(2 f n_w)} \tag{7.6}$$

The maximum cutting speed υ_{max} and maximum metal removal rate $Z_{w,max}$ are given by

$$\upsilon_{max} = \pi n_w d_n \tag{7.7}$$

$$Z_{w,max} = \pi f a_p n_w d_m \tag{7.8}$$

With modern CNC lathes, the rotational speed of the workpiece can be gradually increased during a facing operation as the tool moves toward the center of the workpiece. In this case, the machining time is reduced. However, as the tool approaches the center of the workpiece, the maximum rotational speed of the spindle is encountered, and machining then proceeds at this maximum speed and, consequently, with diminishing cutting speed.

Figure 7.2c shows an internal cylindrical surface being generated. This operation is termed as boring and can only be used to enlarge an existing hole in the workpiece. If the diameter of the work surface is d_w and the diameter of the machined surface is d_m, the mean cutting speed is given by Equation 7.2 and the metal removal rate by

$$Z_w = \pi f a_p n_w (d_m - a_p) \tag{7.9}$$

Finally, the machining time t_m is given by Equation 7.1 if l_w is taken as the length of the hole to be bored.

The lathe operation illustrated in Figure 7.2d is known as external threading, or single-point screw cutting. The combined motions of the tool and workpiece generate a helix on the workpiece and are obtained by setting the relationship between rotational speed and tool feed to give the required pitch of the machined threads. The machining of a thread necessitates several passes of the tool along the workpiece, each pass removing a thin layer of metal from one side of the thread. The feed is applied in increments, after each pass of the tool, in a direction parallel to the machined surface. In calculating the production time, allowance must be included for the time taken to return the tool to the beginning of the cut, to increment the feed, and to engage the feed drive.

The last lathe operation to be illustrated (Figure 7.2e) is used when the finished workpiece is to be separated from the bar of material. It is known as a cut-off operation and produces two machined surfaces simultaneously. As with a facing operation at constant rotational speed, the cutting speed and hence the metal removal rate varies from a maximum at the beginning of the cut to zero at the center of the workpiece. The machining time is given by Equation 7.6 and the maximum metal removal rate by Equation 7.8. Again, with modern CNC lathes, the rotational speed of the workpiece can be controlled to give constant cutting speed until the limiting rotational speed is reached.

Multispindle automatic lathes are used for high volume or mass production of small components machined from work material in bar form. The various motions of these lathes are controlled by specially machined cams, and the operations are completely automatic, including feeding of the workpiece through the hollow spindles.

The vertical-boring machine operates on the same principle as a lathe, but has a vertical axis and is used for large components. Like the lathe, this machine rotates the workpiece and applies continuous, linear feed motion to the tool.

Another machine that uses single-point tools and has a rotary primary motion is a horizontal-boring machine. This machine is needed mostly for heavy, noncylindrical workpieces in which an internal cylindrical surface is to be machined. In general, the words "horizontal" or "vertical" used when describing a machine tool refer to the orientation of the machine spindle that provides primary motion (main spindle). Thus, in the horizontal borer, the main spindle is horizontal.

The principal feature of the horizontal-boring machine is that the workpiece remains stationary during machining, and all the generating motions are applied to the tool. The most common machining process is boring and is shown in Figure 7.3. Boring is achieved

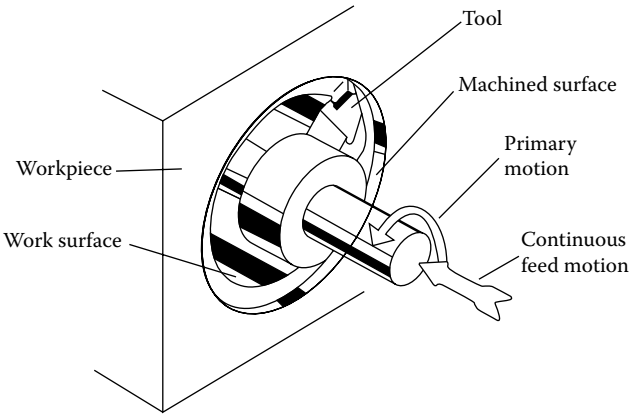


FIGURE 7.3
Boring on a horizontal-boring machine. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

by rotating the tool, which is mounted on a boring bar connected to the spindle, and then feeding the spindle, boring bar, and tool along the axis of rotation. A facing operation can be carried out by using a special toolholder (Figure 7.4) that feeds the tool radially as it rotates. The equations developed earlier for the machining time, and the metal removal rate in boring and facing also apply to this machine.

The planer is suitable for generating flat surfaces on very large parts. With this machine, a linear primary motion is applied to the workpiece and the tool is fed at right angles to this motion (Figure 7.5). The primary motion is normally accomplished by a rack-and-pinion drive using a variable-speed motor, and the feed motion is intermittent. The machining time t_m and metal removal rate Z_w can be estimated as follows:

$$t_m = \frac{b_w}{(fn_r)} \tag{7.10}$$

where b_w is the width of the surface to be machined, n_r is the frequency of cutting strokes, and f is the feed. The metal removal rate Z_w during cutting is given by

$$Z_w = fa_p\upsilon \tag{7.11}$$

where υ is the cutting speed and a_p is the depth of cut (the depth of the layer of material to be removed).

7.3 Machining Using Multipoint Tools

A drilling machine (or drill press) can perform only those operations in which the tool is rotated and fed along its axis of rotation (Figure 7.6). The workpiece always remains stationary during the machining process. On small drill presses, the tool is fed by the manual operation of a lever (known as sensitive drilling). The most common operation performed

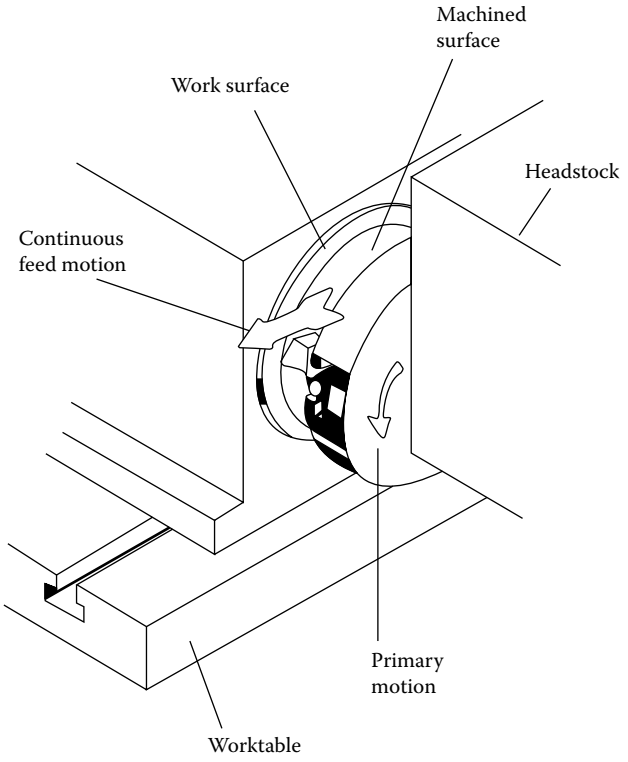


FIGURE 7.4
Facing on a horizontal-boring machine. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

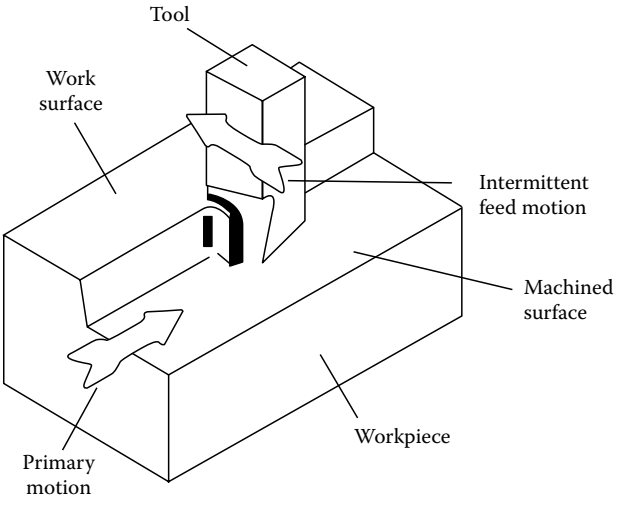


FIGURE 7.5
Production of a flat surface on a planer. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

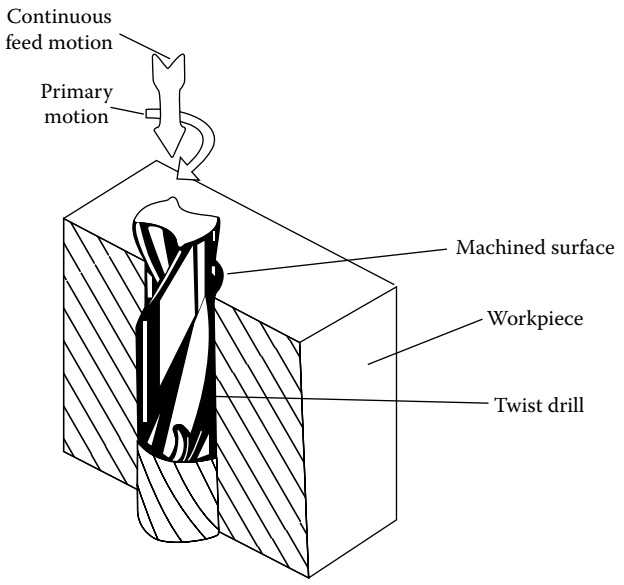


FIGURE 7.6
Drilling on a drill press. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

on this machine is drilling with a twist drill to generate an internal cylindrical surface. A twist drill has two cutting edges, each of which removes its share of the work material.

The machining time t_m is given by

$$t_m = \frac{l_w}{(fn_t)} \tag{7.12}$$

where l_w is the length of the hole produced, f is the feed (per revolution), and n_t is the rotational speed of the tool.

The metal removal rate Z_w may be obtained by dividing the volume of material removed during one revolution of the drill by the time for one revolution. Thus

$$Z_w = \left(\frac{\pi}{4}\right) f d_m^2 n_t \tag{7.13}$$

where d_m is the diameter of the machined hole. If an existing hole of diameter d_w is enlarged, then

$$Z_w = \left(\frac{\pi}{4}\right) f (d_m^2 - d_w^2) n_t \tag{7.14}$$

Twist drills are usually considered suitable for machining holes having a length of no more than five times their diameter. Special drills requiring special drilling machines are available for drilling deeper holes.

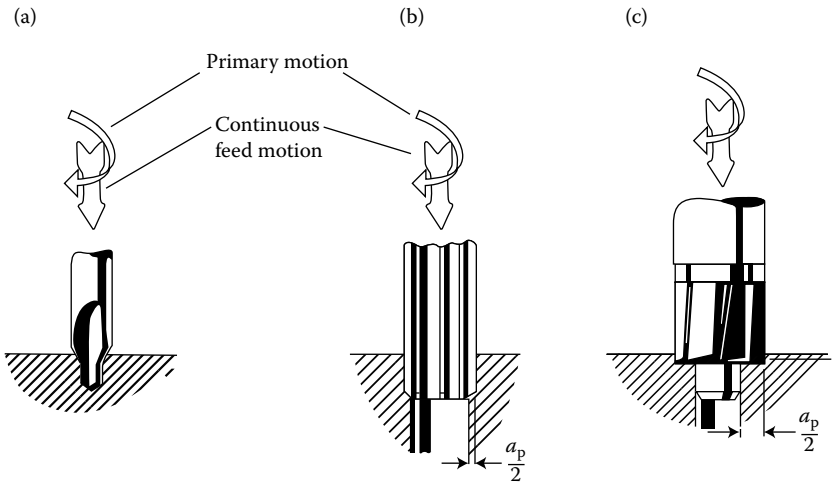


FIGURE 7.7
Some drill-press operations, (a) center drilling, (b) reaming, (c) spot-facing. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The workpiece is often held in a vise bolted to the machine worktable. The drilling of a concentric hole in a cylindrical workpiece, however, is often carried out on a lathe.

Several other machining operations can be performed on a drill press, and some of the more common ones are illustrated in Figure 7.7. The center-drilling operation produces a shallow, conical hole with clearance at the bottom. This center hole can provide a guide for a subsequent drilling operation to prevent the drill point from "wandering" as the hole is started. The reaming operation is intended for finishing a previously drilled hole. The reamer is similar to a drill, but has several cutting edges and straight flutes. It is intended to remove a small amount of work material only, but it considerably improves the accuracy and surface finish of a hole. The spot-facing (or counterboring) operation is designed to provide a flat surface around the entrance to a hole; this flat surface can provide a suitable seating for a washer and nut, for example.

There are two main types of milling machines: horizontal and vertical. In the horizontal-milling machine, the milling cutter is mounted on a horizontal arbor (or shaft) driven by the main spindle.

The simplest operation, slab milling, is used to generate a horizontal surface on the workpiece, as shown in Figure 7.8.

When estimating the machine time t_m in a milling operation, it should be remembered that the distance traveled by the cutter is larger than the length of the workpiece. This extended distance is illustrated in Figure 7.9 in which it can be seen that the cutter travel distance is given by $l_w + \sqrt{a_e(d_t - a_e)}$, where l_w is the length of the workpiece, a_e the depth of cut, and d_t the diameter of the cutter. Thus the machining time is given by

$$t_m = \left[l_w + \sqrt{a_e(d_t - a_e)} \right] \upsilon_f \tag{7.15}$$

where υ_f is the feed speed of the workpiece.

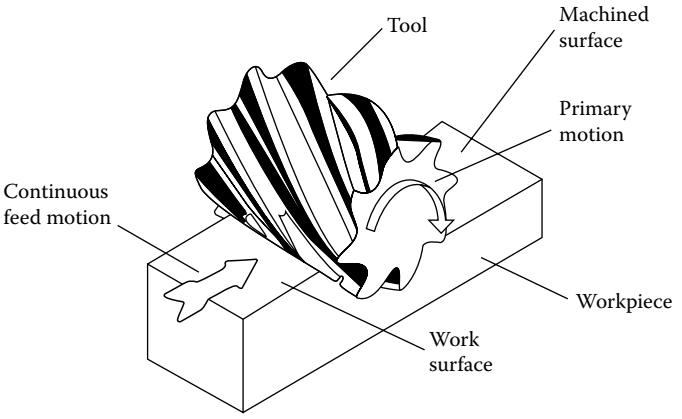


FIGURE 7.8
Slab milling on a knee-type horizontal milling machine. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The metal removal rate Z_w is equal to the product of the feed speed and the cross-sectional area of the metal removed, measured in the direction of feed motion. Thus, if a_p is equal to the workpiece width,

$$Z_w = a_e a_p \upsilon_f \tag{7.16}$$

Figure 7.10 shows some further horizontal-milling operations. In form cutting, the special cutter has cutting edges shaped to form the cross-section required on the workpiece. These cutters are generally expensive to manufacture, and form milling is used only when the quantity to be produced is sufficiently large. In slotting, a standard cutter is used to produce a rectangular slot in a workpiece. Similarly, in angular milling, a standard cutter machines a triangular slot. The straddle-milling operation shown in the figure is only one of an infinite variety of operations that can be carried out by mounting more than one cutter on the machine arbor. In this way, combinations of cutters can machine a wide variety of cross-sectional shapes. When cutters are used in combination, the operation is often called gang milling.

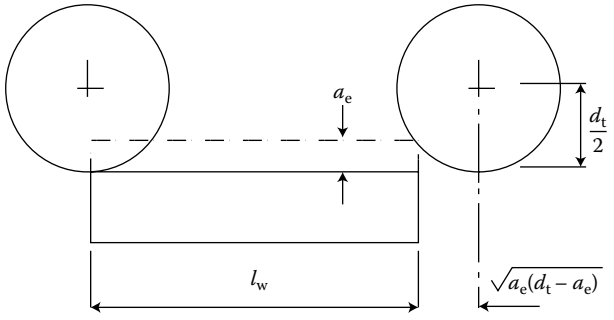


FIGURE 7.9
Relative motion between a slab-milling cutter and the workpiece during machining time. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

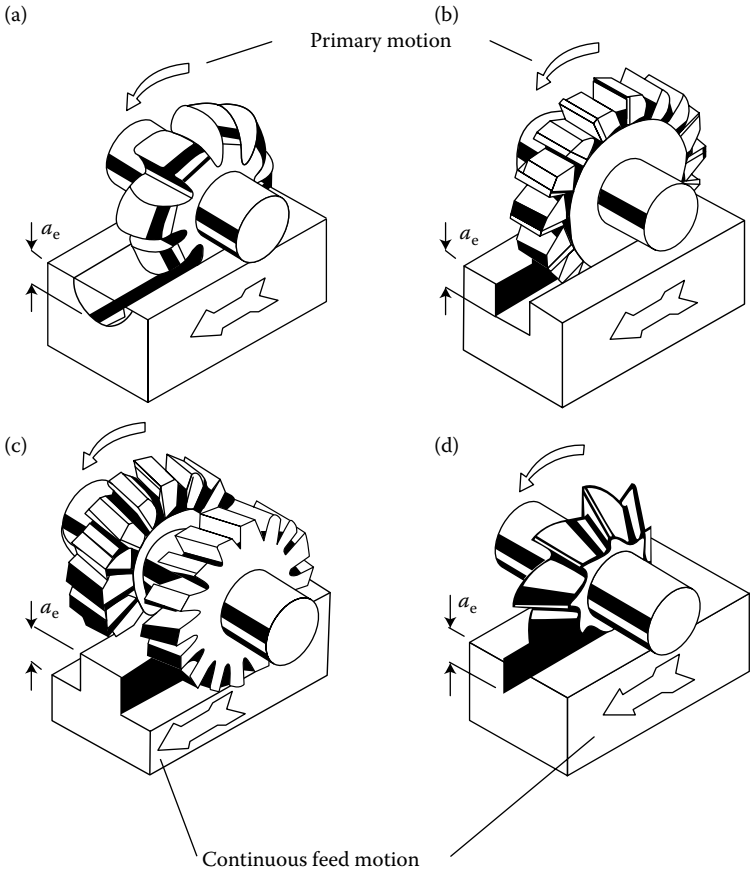


FIGURE 7.10
Some horizontal-milling operations, (a) Form cutting, (b) slotting, (c) straddle milling, (d) angular milling. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

A wide variety of operations involving the machining of horizontal, vertical, and inclined surfaces can be performed on a vertical-milling machine. As the name of the machine implies, the spindle is vertical.

A typical face-milling operation, where a horizontal flat surface is machined, is shown in Figure 7.11. The cutter employed is known as a face-milling cutter.

In estimating the machine time t_m, allowance should again be made for the additional relative motion between the cutting tool and workpiece. As can be seen in Figure 7.12, the total motion when the path of the tool axis passes over the workpiece is given by $(l_w + d_t)$, and, therefore, the machining time is given by

$$t_m = \frac{(l_w + d_t)}{\upsilon_f} \tag{7.17}$$

where l_w is the length of the workpiece, d_t is the diameter of the cutter, and υ_f is the feed speed of the workpiece.

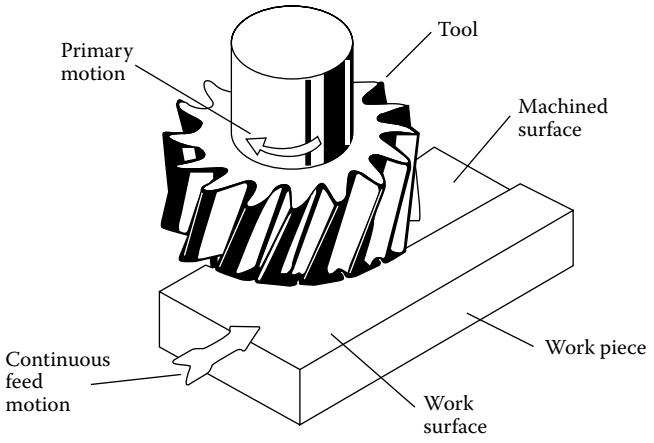


FIGURE 7.11
Face milling on a vertical-milling machine. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

When the path of the tool axis does not pass over the workpiece

$$t_m = \left[l_w + 2\sqrt{a_e\left(d_t - a_e\right)} \right] \upsilon_f \tag{7.18}$$

where a_e is the width of the cut in vertical milling.

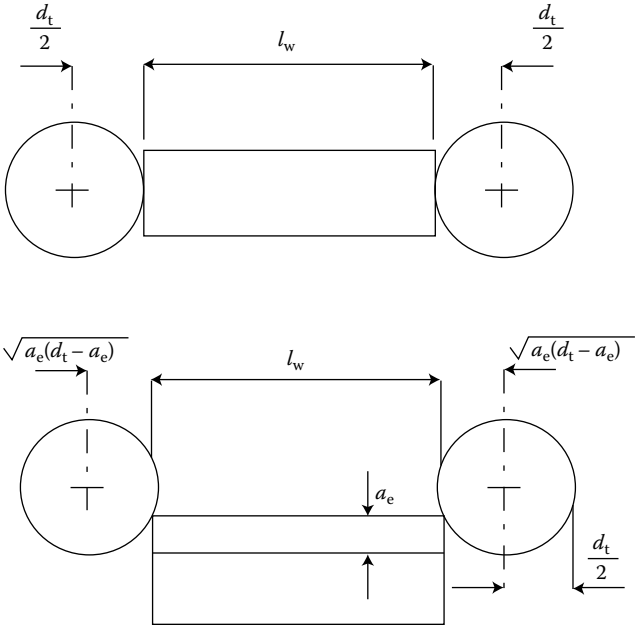


FIGURE 7.12
Relative motion between the face-milling cutter and the workpiece during machining time. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

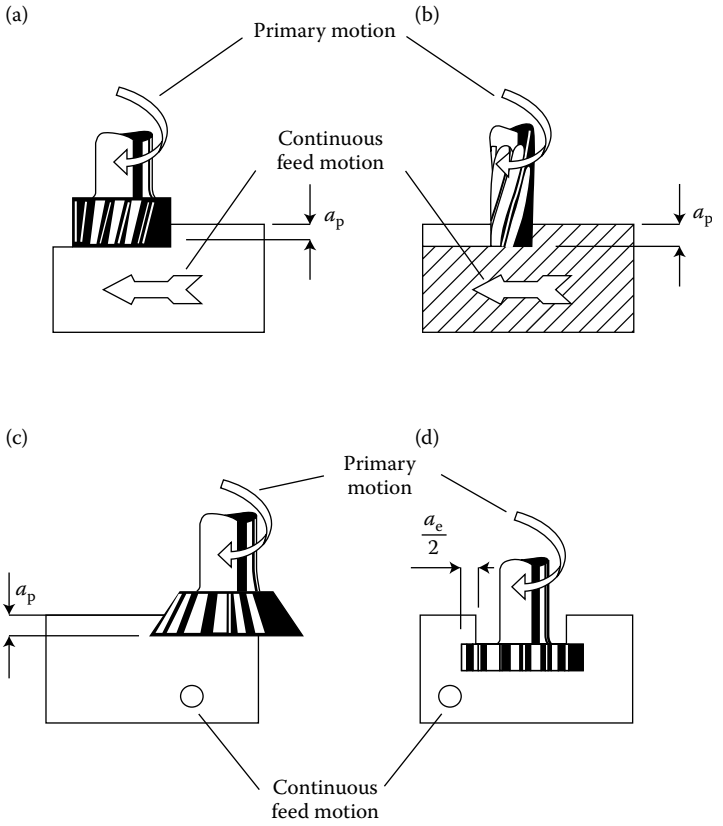


FIGURE 7.13
Some vertical-milling machine operations, (a) horizontal surface, (b) slot, (c) dovetail, (d) T slot. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The metal removal rate Z_w in both cases is given by Equation 7.16.

Various vertical-milling machine operations are illustrated in Figure 7.13.

Another machine using multipoint tools is the broaching machine. In broaching, the machine provides the primary motion (usually hydraulically powered) between the tool and workpiece, and the feed is provided by the staggering of the teeth on the broach, each tooth removing a thin layer of material (Figure 7.14). Since the machined surface is usually produced during one pass of the tool, the machining time t_m is given by

$$t_m = \frac{l_t}{\upsilon} \tag{7.19}$$

where l_t is the length of the broach and υ is the cutting speed. The average metal removal rate Z_w can be estimated by dividing the total volume of metal removed by the machining time.

Broaching is widely used to produce noncircular holes. In these cases, the broach can be either pulled or pushed through a circular hole to enlarge the hole to the shape required or to machine a key way, for example (Figure 7.15). Broaches must be designed individually

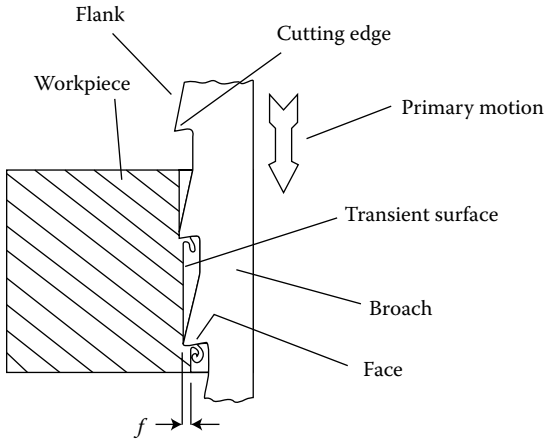


FIGURE 7.14
Broaching on a vertical-broaching machine. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

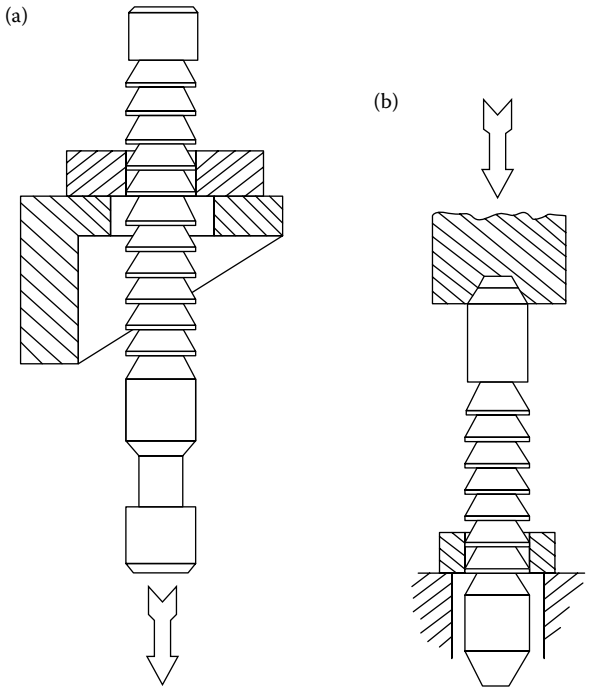


FIGURE 7.15
Methods of broaching a hole, (a) Pull broach; (b) Push broach. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

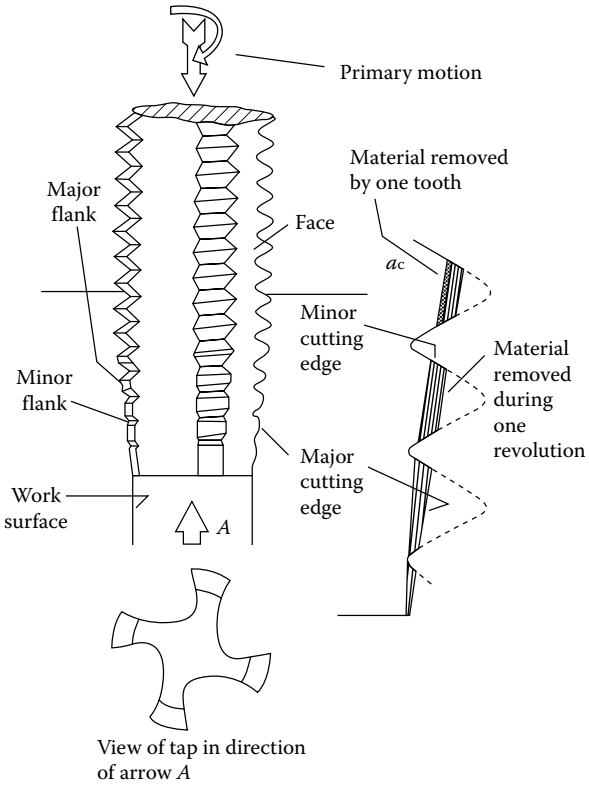


FIGURE 7.16
Tapping. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

for the particular job and are expensive to manufacture. This high cost must be taken into account when comparing broaching to slower, alternative machining methods.

The production of internal and external screw threads can be accomplished by the use of taps and dies. These multipoint tools can be thought of as helical broaches.

In Figure 7.16, a tap is fed into a prepared hole and rotated at a low speed. The relative motion between a selected point on a cutting edge and the workpiece is, therefore, helical; this motion is the primary motion. All machining is done by the lower end of the tap, where each cutting edge removes a small layer of metal (Figure 7.16) to form the thread shape; the fully shaped thread on the tap serves to clear away fragments of chips that may collect. A die has the same cutting action as a tap, but is designed to produce an external thread.

Internal threading using taps can be carried out on turret lathes and drill presses. External threading using dies can be carried out on turret lathes and special screw-cutting machines.

7.4 Machining Using Abrasive Wheels

Abrasive wheels (or grinding wheels) are generally cylindrical, disc-shaped, or cup-shaped (Figure 7.17). The machines on which they are used are called grinding machines, or

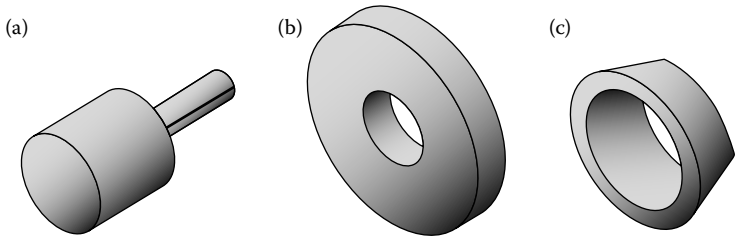


FIGURE 7.17
Common shapes of abrasive wheels, (a) Cylindrical, (b) disc, (c) cup. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

grinders; they all have a spindle that can be rotated at a high speed and on which the grinding wheel is mounted. The spindle is supported by bearings and mounted on a housing; this assembly is called the wheel head. A belt drive from an electric motor provides power for the spindle. The abrasive wheel consists of individual grains of very hard material (usually silicon carbide or aluminum oxide) bonded in the form required.

Abrasive wheels are sometimes used in rough grinding, where material removal is the important factor; more commonly, abrasive wheels are used in finishing operations, where the resulting smooth surface finish is the objective.

In the metal-cutting machine tools described earlier, generation of a surface is usually obtained by applying a primary motion to either the tool or workpiece and a feed motion to either the tool or the workpiece. In grinding machines, however, the primary motion is always the rotation of the abrasive wheels, but often two or more generating (feed) motions are applied to the workpiece to produce the desired surface shape.

In horizontal-spindle surface grinding (Figure 7.18), the principal feed motion is the reciprocation of the worktable on which the work is mounted; this motion is known as the traverse. Further feed motions may be applied either to the wheel head, by moving it down (known as infeed), or to the table, by moving it parallel to the machine spindle (known as cross-feed). In Figure 7.18 a horizontal surface is generated on a workpiece by a cross-feed

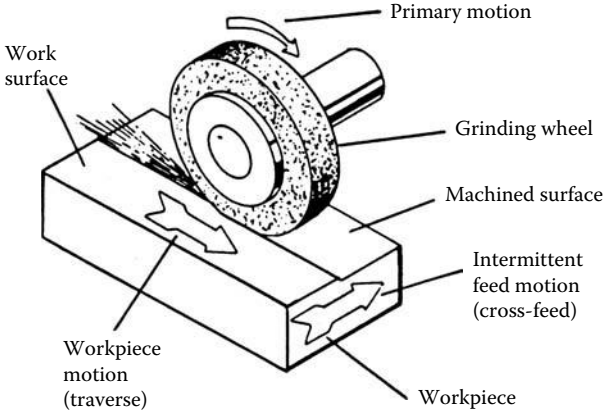


FIGURE 7.18
Surface grinding on a horizontal-spindle surface grinder. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

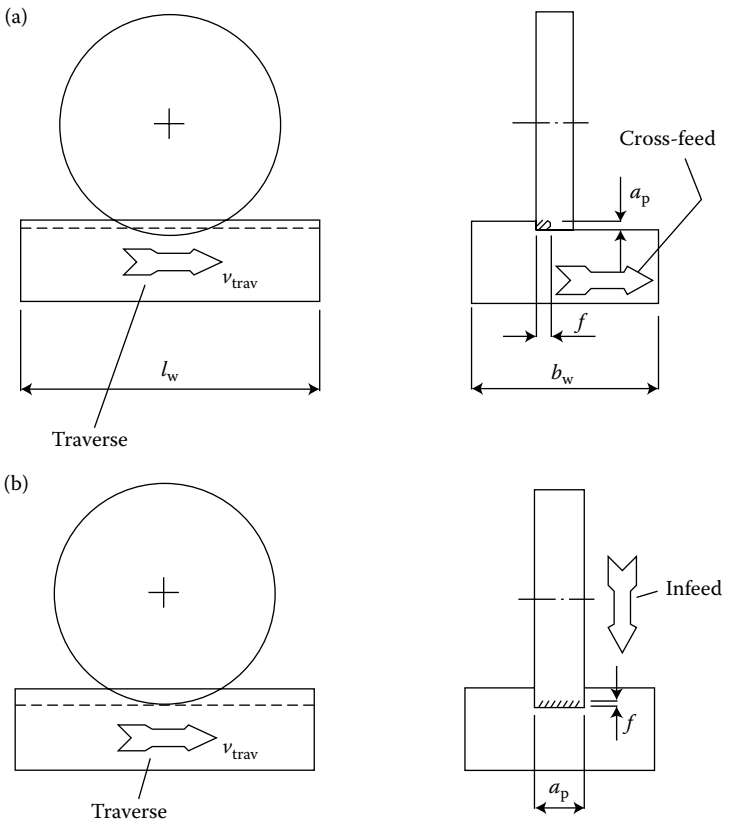


FIGURE 7.19
Horizontal-spindle surface-grinding operations, (a) Traverse grinding; (b) plunge grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

motion. This feed motion, which is intermittent, is usually applied after each stroke or pass of the table. The amount of cross-feed f may, therefore, be defined as the distance the tool advances across the workpiece between each cutting stroke. The operation is known as traverse grinding.

Figure 7.19 shows the geometries of both traverse grinding and plunge grinding on a horizontal-surface grinder. From Figure 7.19a, the metal removal rate in traverse grinding is given by

$$Z_w = f a_p \upsilon_{trav} \tag{7.20}$$

where f is the cross-feed per cutting stroke, a_p is the depth of cut, and υ_{trav} is the traverse speed.

The machining time t_m is given by

$$t_m = \frac{b_w}{(2 f n_r)} \tag{7.21}$$

where n_r is the frequency of reciprocation and b_w is the width of the workpiece.

In a similar way, for the plunge-grinding operation (Figure 7.19b), the metal removal rate is given by Equation 7.20.

Before estimating the machining time in the plunge-grinding operation, it is necessary to describe a phenomenon known as "sparking-out." In any grinding operation where the wheel is fed in a direction normal to the work surface (infeed), the feed f, which is the depth of the layer of material removed during one cutting stroke, is initially less than the nominal feed setting on the machine. This feed differential results from the deflection of the machine tool elements and workpiece under the forces generated during the operation. Thus, on completion of the theoretical number of cutting strokes required, some work material still has to be removed. The operation of removing this material called sparking-out is achieved by continuing the cutting strokes with no further application of feed until metal removal becomes insignificant (no further sparks appear). If the time for sparking-out is denoted by t_s, the machining time in plunge grinding is given by

$$t_m = \left(\frac{a_t}{2fn_r} \right) + t_s \tag{7.22}$$

where a_t is the total depth of work material to be removed.

In vertical-spindle surface grinding (Figure 7.20) a cup-shaped abrasive wheel performs an operation similar to face milling. The worktable is reciprocated and the tool fed intermittently downward; these motions are known as traverse and infeed, respectively. A horizontal surface is generated on the workpiece, and because of the deflection of the machine structure, the feed f is initially less than the feed setting on the machine tool. This means that sparking-out is necessary, as in plunge grinding on a horizontal-spindle machine.

The metal removal rate is given by

$$Z_w = f a_p \upsilon_{trav} \tag{7.23}$$

where a_p is equal to the width of the workpiece and υ_{trav} is the traverse speed.

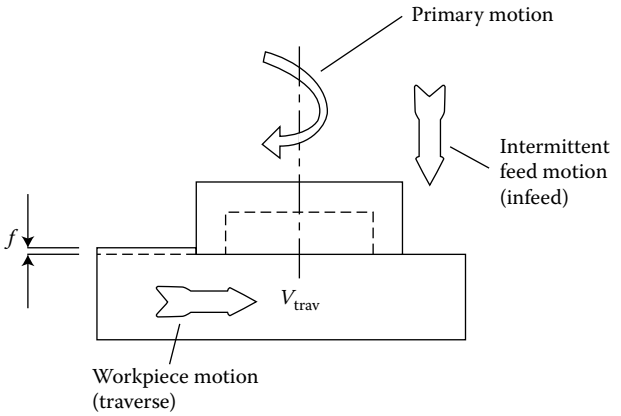


FIGURE 7.20
Surface grinding on a vertical-spindle surface grinder. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The machining time is given, as in plunge grinding on a horizontal-spindle machine, by Equation 7.22.

Larger vertical-spindle surface grinders are available with rotary worktables on which several workpieces can be mounted. The machining time per part for this type of grinder is given by

$$t_m = \left(\frac{a_t}{f n_w} + t_s \right) / n \tag{7.24}$$

where n_w is the rotational speed of the worktable and n is the number of workpieces mounted on the machine.

In cylindrical grinding (Figure 7.21), the workpiece is supported and rotated between centers. The headstock provides the low-speed rotational drive to the workpiece and is mounted, together with the tailstock, on a worktable that is reciprocated horizontally using a hydraulic drive. The grinding-wheel spindle is horizontal and parallel to the axis of workpiece rotation, and horizontal, hydraulic feed can be applied to the wheel head in a direction normal to the axis of workpiece rotation; this motion is known as infeed.

Figure 7.21 shows a cylindrical surface being generated using the traverse motion—an operation that can be likened to cylindrical turning, where the single-point cutting tool is replaced by a grinding wheel. In fact, grinding attachments are available that allow this operation to be performed on a lathe.

The geometries of traverse and plunge grinding on a cylindrical grinder are shown in Figure 7.22. In traverse grinding, the maximum metal removal rate is closely given by

$$Z_{w,max} = \pi f d_w \upsilon_{trav} \tag{7.25}$$

where d_w is the diameter of work surface, υ_{trav} is the traverse speed, and f is the feed per stroke of the machine table (usually extremely small compared to d_w). The machining time is given by Equation 7.22.

In the plunge-grinding operation shown in Figure 7.22b, the wheel is fed into the workpiece, without traverse motion applied, to form a groove. If υ_f is the feed speed of the

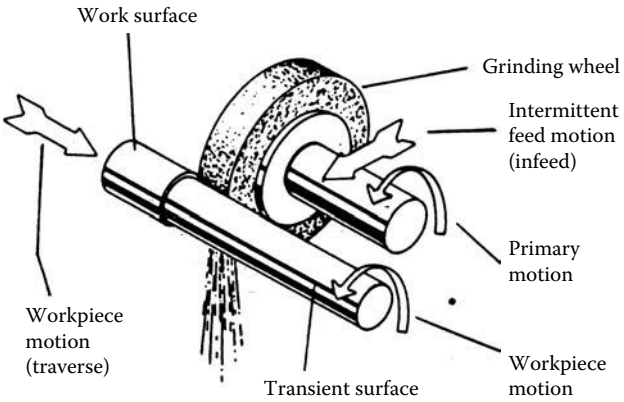


FIGURE 7.21
Cylindrical grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

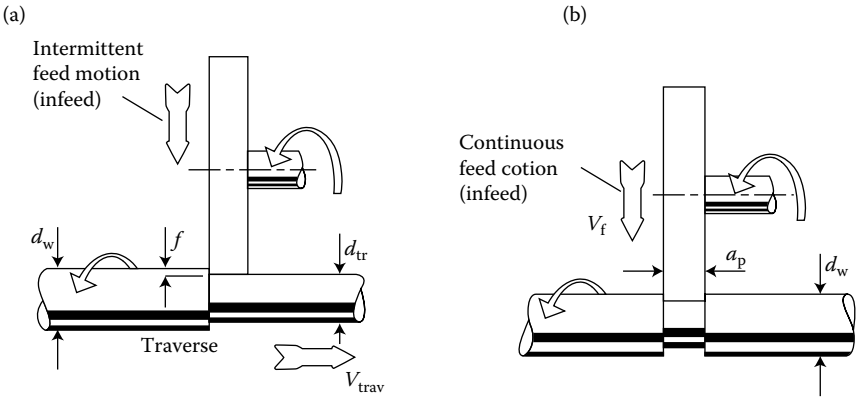


FIGURE 7.22
Cylindrical-grinding operations, (a) Traverse grinding; (b) plunge grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

grinding wheel, d_w the diameter of the work surface, and a_p the width of the grinding wheel, the maximum metal removal rate is given by

$$Z_{w,max} = \pi a_p d_w \upsilon_f \tag{7.26}$$

and the machining time is

$$t_m = \left(\frac{a_t}{\upsilon_f}\right) + t_s \tag{7.27}$$

where a_t is the total depth of material to be removed and t_s is the sparking-out time.

In internal grinding (Figure 7.23), the wheel head supports a horizontal spindle and can be reciprocated (traversed) in a direction parallel to the spindle axis. A small cylindrical

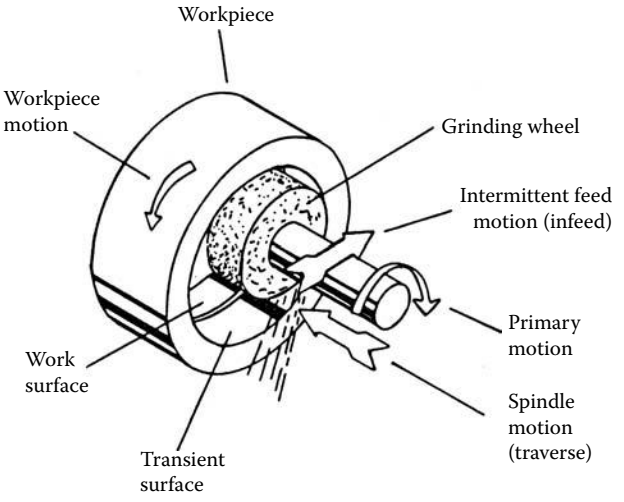


FIGURE 7.23
Internal grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

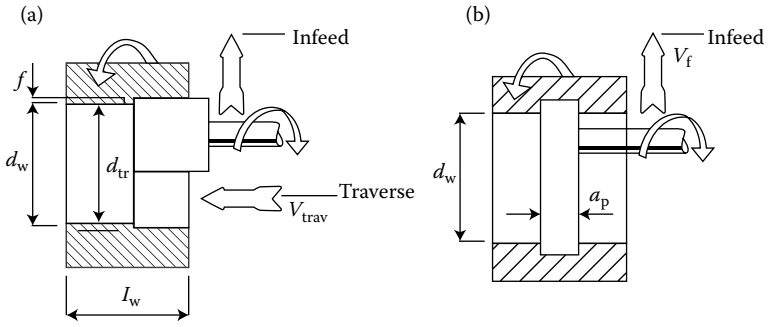


FIGURE 7.24
Internal-grinding operations, (a) Traverse grinding; (b) plunge grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

grinding wheel is used and is rotated at a very high speed. The workpiece is mounted in a chuck or on a magnetic faceplate and rotated. Horizontal feed is applied to the wheel head in a direction normal to the wheel spindle; this motion is known as infeed. Again, traverse and plunge grinding can be performed, the geometries of which are shown in Figure 7.24.

Traverse grinding is shown in Figure 7.24a, and the maximum removal rate, which occurs at the end of the operation, is given by

$$Z_{w,max} = \pi f d_m \upsilon_{trav} \tag{7.28}$$

where f is the feed, υ_{trav} is the traverse speed, and d_m is the diameter of the machined surface. The machining time is again given by Equation 7.22.

Finally, in plunge grinding (Figure 7.24b) the maximum removal rate is given by

$$Z_{w,max} = \pi a_p d_m \upsilon_f \tag{7.29}$$

and the machining time by Equation 7.27.

Now that the various machine tools, machining operations, and basic Equations for metal removal rate and machining time have been introduced, we can turn our attention to those design factors that affect the cost of machining and cost estimating for designers.

7.5 Standardization

Perhaps the first rule in designing for machining is to design using standard components as much as possible. Many small components, such as nuts, washers, bolts, screws, seals, bearings, gears, and sprockets, are manufactured in large quantities and should be employed wherever possible. The cost of these components is much less than the cost of similar, nonstandard components. Clearly, the designer needs catalogues of the standard items available; these can be obtained from suppliers. Supplier information is provided in standard trade indexes, where companies are listed under products. However, there is a

danger in overemphasizing standardization. Many of the impressive successes brought about by the application of DFMA procedures were only made possible by breaking away from standardization. For example, the IBM "proprinter" was successful, mainly because the designers departed from the customary approach to the design of dot-matrix printers. They included a novel new mechanism for driving the print head; they also introduced new plastic materials for the base and departed from the use of standard components for securing important items such as the power transformer and drive motors. Taken to extremes, a slavish adherence to company "standards" prevents innovation in design.

A second rule is, if possible, minimize the amount of machining by preshaping the workpiece. Workpieces can sometimes be preshaped by using castings or welded assemblies or by metal deformation processes, such as extrusion, deep drawing, blanking, or forging. Obviously, the justification for preforming of workpieces depends on the required production quantity. Again standardization can play an important part when workpieces are to be preformed. The designer may be able to use preformed workpieces designed for a previous similar job; because the necessary patterns for castings or the tools and dies for metal-forming processes are already available.

Finally, even if standard components or standard preformed workpieces are not available, the designer should attempt to standardize on the machined features to be incorporated in the design. Standardizing on machined features means that the appropriate tools, jigs, and fixtures are available, thus reducing manufacturing costs considerably. Examples of standardized machined features might include drilled holes, screw threads, keyways, seatings for bearings, splines, and so on. Information on standard features can be found in various reference books.

7.6 Choice of Work Material

When choosing the material for a component, the designer must consider applicability, cost, availability, machinability, and the amount of machining required. Each of these factors influences the others, and the final optimum choice is generally a compromise between conflicting requirements. The applicability of various materials depends on the component's eventual function and is decided by such factors as strength, resistance to wear, appearance, corrosion resistance, and so on. These features of the design process are outside the scope of this chapter, but once the choice of material for a component has been narrowed, the designer must then consider factors that help to minimize the final cost of the component. It should not be assumed, for example, that the least expensive work material automatically results in minimum cost for the component. For example, it might be more economical to choose a material that is less expensive to machine (more machinable) but has a higher purchase cost. In a constant cutting-speed, rough-machining operation, the production cost C_{pr} per component is given by

$$C_{pr} = Mt_l + Mt_m + \left(Mt_{ct} + C_t\right)t_m/t \tag{7.30}$$

where M is the total machine and operator rate, t_l is the nonproductive time, t_m is the machining time (time the machine tool is operating), t is the tool life (machining time between tool changes), t_{ct} is the tool changing time, C_t is the cost of providing a sharp tool,

including the cost of regrinding and/or the depreciation of the insert holder and insert where applicable.

The machining time is given by

$$t_m = \frac{K}{\upsilon} \tag{7.31}$$

where K is a constant for the particular operation and υ is the cutting speed.

Also, the tool life t is given by Taylor's tool life equation

$$\upsilon t^n = \upsilon_r t_r^n \tag{7.32}$$

where υ_r and t_r are the reference cutting speed and tool life, respectively, and n is the Taylor tool-life index, which is mainly dependent on the tool material. Usually, for high-speed steel tools n is assumed to be 0.125 and for carbide tools it is assumed to be 0.25.

If Equations 7.31 and 7.32 are substituted into Equation 7.30, and the resulting expression differentiated, it can be shown that the cutting speed υ_c for minimum cost is given by

$$\upsilon_c = \upsilon_r \left(\frac{t_r}{t_c} \right)^n \tag{7.33}$$

where t_c is the tool life for minimum cost and is given by

$$t_c = \left[\left(\frac{1}{n} \right) - 1 \right] \left(t_{ct} + \frac{C_t}{M} \right) \tag{7.34}$$

Thus, if Equations 7.30 through 7.34 are combined, the minimum cost of production C_{min} is given by

$$C_{min} = Mt_l + \frac{MK}{(1-n)\upsilon_r} \left(\frac{t_c}{t_r} \right)^n \tag{7.35}$$

The first term in this expression is the cost of the nonproductive time on the machine tool and is not affected by the work material chosen or by the amount of machining carried out on the workpiece. The second term is the cost of the actual machining operation, and for a given machine and tool design it depends on the values of n, υ_r, t_r, and K. The factor n mainly depends on the tool material; $\upsilon_r t_r^n$ is a measure of the machinability of the material; K is proportional to the amount of machining to be carried out on the workpiece and can be regarded as the distance traveled by the tool cutting edge corner relative to the workpiece during the machining operation. For a given operation on a given machine tool and with a given tool material it is shown in Equation 7.34 that the tool life for minimum cost would be constant and hence (from Equation 7.35) that the machining costs would be inversely proportional to the value of $\upsilon_r t_r^n$. Since υ_r is the cutting speed giving a tool life of t_r, more readily machined materials have a higher value of $\upsilon_r t_r^n$ and hence give a lower machining cost.

Taking, for example, a machining operation using high-speed steel tools ($n = 0.125$) and a low carbon steel workpiece and typical figures of $M = \$0.00833/s$, $t_l = 300$ s, $t_c = 3000$ s, $K = 183$ m (600 ft), and $\upsilon_r = 0.76$ m/s (150 ft/min) when $t_r = 60$ s, then from Equation 7.35 the

minimum production cost per component C_{min} is \$6.22. If, however, an aluminum workpiece for which a typical value of υ_r is 3.05 m/s (600 ft/mm) when t_r is 60 s could be used, the use of aluminum would reduce the production cost to \$3.43. In other words, an additional amount equal to the difference between these two costs could be spent for each workpiece in order to employ the more machinable material, that is, as much as \$2.79 additional per workpiece.

Clearly, the designer should try to select work materials that would result in minimum total component cost.

7.7 Shape of Work Material

With the exception of workpieces that are to be partially formed before machining, such as forgings, castings, and welded structures, the choice of the shape of the work material mainly depends on availability. Metals are generally sold in plate, sheet, bar, or tube form (Table 7.1) in a wide range of standard sizes.

The designer should check on the standard shapes and sizes from the supplier of raw material and then design components that require minimal machining.

Components manufactured from a circular or hexagonal bar or tube are generally machined on those machine tools that apply a rotary primary motion to the workpiece; these types of components are called rotational components (Figure 7.25a). The remaining components are manufactured from square or rectangular bar, plate, or sheet and are called nonrotational components (Figure 7.25b). Components partially formed before machining can also be classified as either rotational or nonrotational components.

Some of the machining techniques used to alter the initial workpiece shape will now be described and help to illustrate some further design rules for machined components.

7.8 Machining Basic Component Shapes

7.8.1 Disc-Shaped Rotational Components ($L/D \leq 0.5$)

Rotational components where the length-to-diameter ratio is less than or equal to 0.5 may be classified as discs. For diameters to approximately 300 mm (12 in.) the workpiece would

TABLE 7.1

Standard Material Shapes and Ranges of Sizes

Name	Size	Shape
Plate	6–75 mm (0.25–3 in.)	
Sheet	0.1–5 mm (0.004–0.2 in.)	
Round bar or rod	3–200 mm dia. (0.125–8 in. dia.)	
Hexagonal bar	6–75 mm (0.25–3 in.)	
Square bar	9–100 mm (0.375–4 in.)	
Rectangular bar	3×12–100×150 mm (0.125×0.5–4×6 in.)	
Tubing	5 mm dia., 1 mm wall–100 mm dia., 3 mm wall (0.1875 in. dia., 0.035 in. wall–4 in. dia., 0.125 in. wall)	

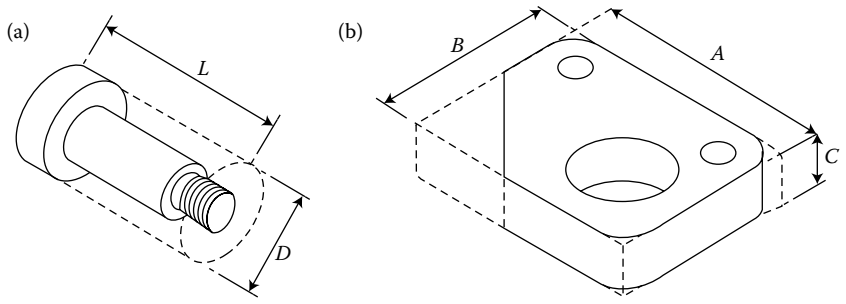


FIGURE 7.25
Basic component shapes, (a) Rotational; (b) nonrelational. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

generally be gripped in a lathe chuck; for larger diameters, it would be necessary to clamp the workpiece on the table of a vertical borer. The simplest operations that could be performed would be machining of the exposed face and drilling, boring, and threading a concentric hole. All these operations could be performed on one machine without regripping the workpiece (Figure 7.26). The realization that neither the unexposed face nor a portion of the outer cylindrical surface can be machined leads to some general guidelines for design: if possible, design the component so that machining is not necessary on the unexposed surfaces of the workpiece when it is gripped in the work-holding device. Also, the diameters of the external features should gradually increase, and the diameters of the internal features should gradually decrease from the exposed face.

Of course, with the examples shown in Figure 7.26, it would probably be necessary to reverse the workpiece in the chuck to machine the opposite face. However, if its diameter were less than about 50 mm (2 in.), the desired surfaces could probably be machined on the end of a piece of bar stock and the component then separated from the bar by a parting or cut-off operation (Figure 7.27). It should be remembered that when a workpiece must be reversed in the chuck, the concentricity of features are difficult to maintain (Figure 7.28).

When machined surfaces intersect to form an edge, the edge is square; when surfaces intersect to form an internal corner, however, the edge is rounded to the shape of the tool

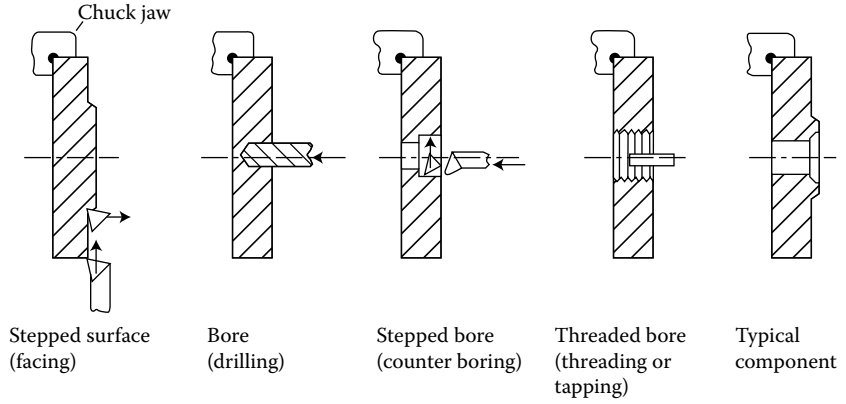


FIGURE 7.26
Some ways of machining a disc-shaped workpiece. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

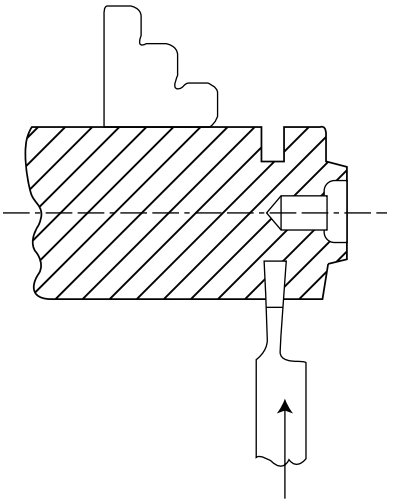


FIGURE 7.27
Parting finished components from bar stock. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

comer. Thus, the designer should always specify radii for internal corners. When the two intersecting faces are to form seatings for another component in the final assembly, the matching corner on the second component should be chamfered to provide clearance (Figure 7.29). Chamfering ensures proper seating of the two parts and presents little difficulty in the machining operations.

On rotational components, some features may be necessary that can only be produced by machine tools other than those that rotate the workpiece. Consequently, the batch of workpieces requiring these features have to be stacked temporarily and then transferred

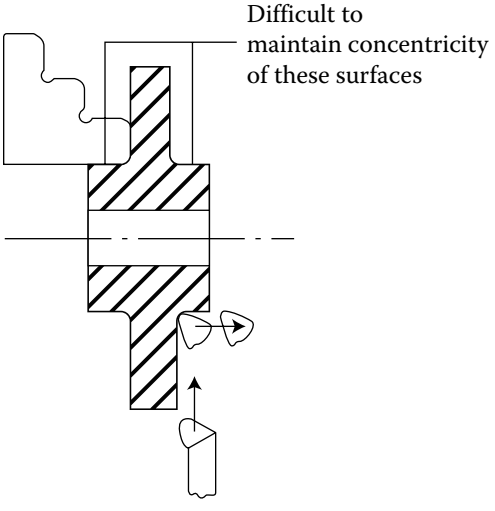


FIGURE 7.28
Machining of components stepped to both ends. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

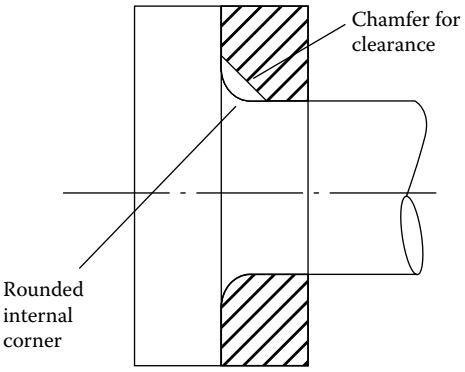


FIGURE 7.29
Rounded corners and chamfers. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

to another machine tool that may be in another part of the factory. This storage and transfer of workpieces around a factory presents a major organizational problem and considerably adds to the manufacturing costs. Thus, if possible, the components should be designed to be machined on one machine tool only.

Plane-machining operations may also be required on a rotational component. Such operations might be carried out on a milling machine. Finally, auxiliary holes (those not concentric with the component axis) and gear teeth may be required. Auxiliary holes would be machined on a drill press and would generally form a pattern as shown in Figure 7.30. Axial auxiliary holes are usually the easiest to machine, because one of the flat surfaces on the workpiece can be used to orient it on the work-holding surface. Thus, the designer should avoid auxiliary holes inclined to the workpiece axis. Gear teeth would be generated on a special gear-cutting machine, and this process is generally slow and expensive.

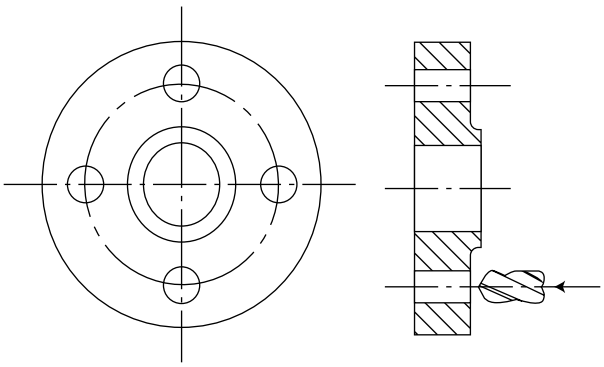


FIGURE 7.30
Drilling a pattern of auxiliary holes.

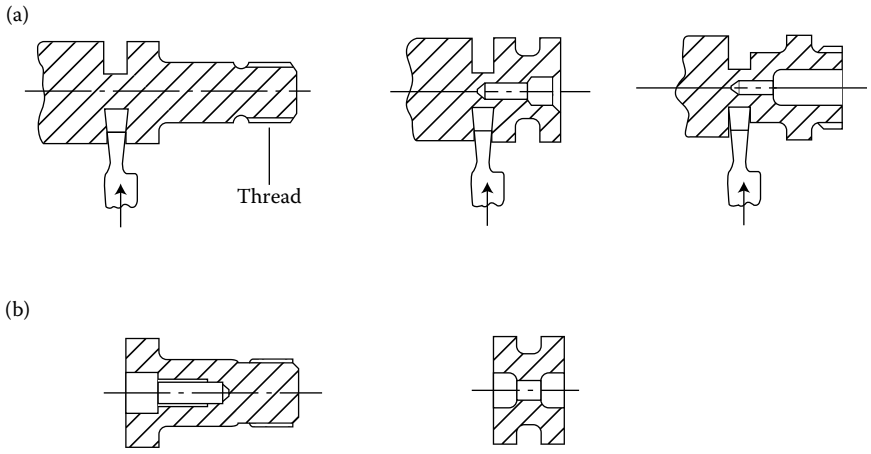


FIGURE 7.31
Machining components from bar stock, (a) Components that can be parted off complete; (b) components that cannot be parted off complete. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

7.8.2 Short, Cylindrical Components ($0.5 < L/D < 3$)

The workpieces from which short, cylindrical components are produced would often be in the form of bar stock, and the machined component would be separated from the workpiece by parting or cut-off as was shown in Figure 7.27. The whole of the outer surface of this type of component can be machined without interference from the jaws of the chuck. However, it is important for the designer to ensure (if possible) that the diameters of a stepped internal bore are gradually decreasing from the exposed end of the workpiece and that no recesses or grooves are required on the surface produced in the parting or cut-off operation (Figure 7.31).

7.8.3 Long, Cylindrical Rotational Components ($L/D \geq 3$)

Long, cylindrical rotational components would often be supported between centers or gripped at the headstock end by a chuck and supported by a center at the other end. If the L/D ratio is too large, the flexibility of the workpiece creates a problem because of the forces generated during machining. Thus, the designer should ensure that the workpiece, when supported by the work-holding devices, is sufficiently rigid to withstand the machining forces.

When a rotational component must be supported at both ends for machining of the external surfaces, internal surfaces of any kind cannot be machined at the same time. In any case, with slender components, concentric bores would necessarily have large length-to-diameter ratios and would be difficult to produce. Thus, the designer should try to avoid specifying internal surfaces for rotational components having large L/D ratios.

A common requirement on a long, cylindrical component is a keyway, or slot. A keyway is usually milled on a vertical-milling machine using an end-milling cutter (Figure 7.32a) or on a horizontal-milling machine using a side- and face-milling cutter (Figure 7.32b). The shape of the end of the keyway is determined by the shape of the milling cutter used, and the designer, in specifying this shape, is specifying the machining process.

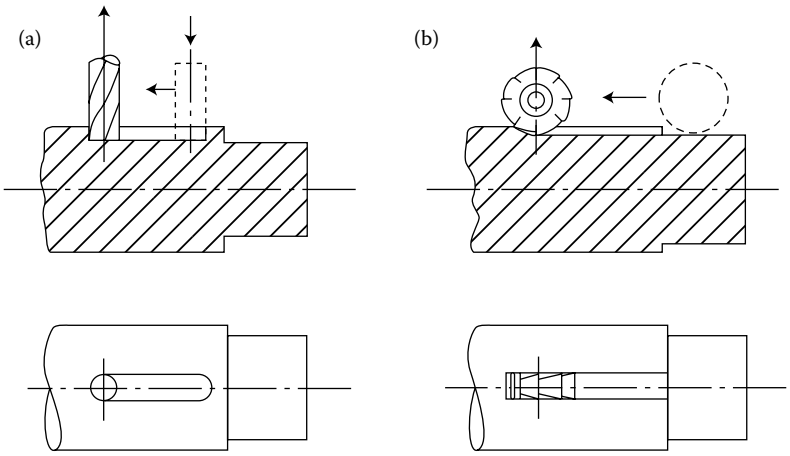


FIGURE 7.32
Machining of a keyway. (a) Vertical milling, (b) horizontal milling. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

Before the ways of changing basic nonrotational shapes by machining operations are discussed, some general points should be noted regarding undesirable features on rotational components. These undesirable design features can be categorized as follows:

1. Features impossible to machine.
2. Features extremely difficult to machine that require the use of special tools or fixtures.
3. Features expensive to machine even though standard tools can be used.

In considering the features of a particular design, it should be realized that

1. Surfaces to be machined must be accessible when the workpiece is gripped in the work-holding device.
2. When the surface of workpiece is being machined, the tool and tool-holding device must not interfere with the remaining surfaces on the workpiece.

Figure 7.33a shows an example of a component with external surfaces impossible to machine. This is because, during the machining of one of the cylindrical surfaces, the tool would interfere with the other cylindrical surface Figure 7.33b shows a component that would be extremely difficult to machine on a lathe, because when the hole is drilled, the workpiece would have to be supported in a special holding device. Even if the workpiece were transferred to a drill press for the purpose of drilling the hole (in itself an added expense), a milled preparation would be required (Figure 7.33c) to prevent the drill from deflecting sideways at the beginning of the drilling operation.

Figure 7.34 shows two examples where the tool or toolholder would interfere with other surfaces on the workpiece. The small radial hole shown in Figure 7.34a would be difficult to machine, because a special long drill would be required. The internal recess shown in the component in Figure 7.34b could not be machined, because it would be impossible to design a cutting tool that would reach through the opening of the bore.

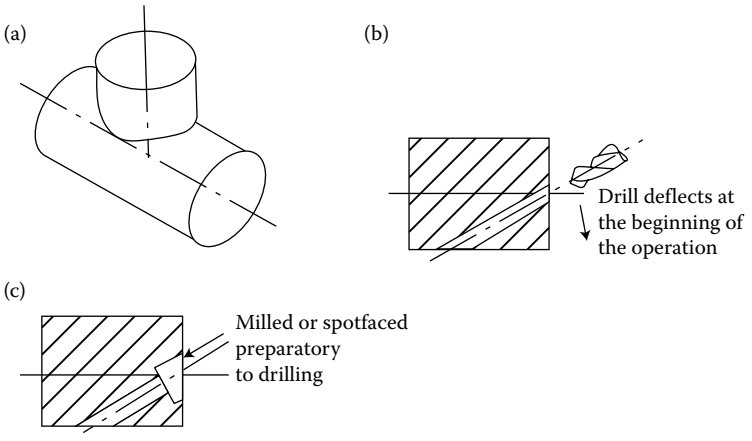


FIGURE 7.33
Difficulties arising when nonconcentric cylindrical surfaces are specified, (a) Impossible to machine, (b) difficult to machine, (c) can be machined on a drill press. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

Figure 7.35a shows a screw thread extending to a shoulder. Extending a screw thread to a shoulder would be impossible, because when the lathe carriage is disengaged from the lead screw at the end of each pass, the threading tool generates a circular groove in the workpiece. Thus, it is necessary to provide a run-out groove (Figure 7.35b) so that the threading tool has clearance and does not interfere with the remaining machined surfaces.

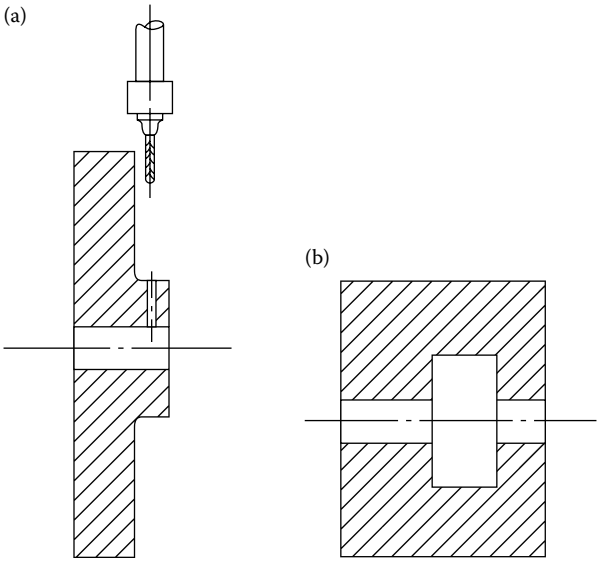


FIGURE 7.34
Design features to avoid in rotational parts, (a) Special drill required to machine radial hole, (b) impossible to machine internal recess. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

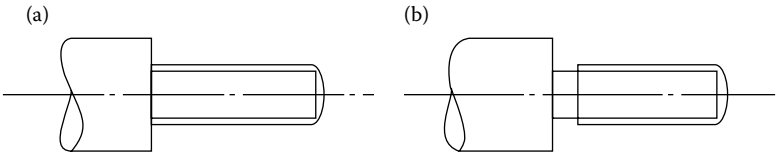


FIGURE 7.35
Machined screw threads on stepped components, (a) Impossible to machine, (b) good design with run-out groove. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

7.8.4 Nonrotational Components ($A/B \leq 3$, $A/C \geq 4$)

Extremely thin, flat components should be avoided because of the difficulty of work holding while machining external surfaces. Many flat components would be machined from plate or sheet stock and would initially require machining of the outer edges. Outer edges would generally be machined on either a vertical- or horizontal-milling machine. Figure 7.36 shows the simplest shapes that can be generated on the edge of a flat component. It can be seen that internal corners must have radii no smaller than the radius of the milling cutter used.

In general, the minimum diameter of cutters for horizontal milling (about 50 mm [2 in.] for an average machine) is much larger than the diameter of a cutter for vertical milling (about 12 mm [0.5 in.]). Thus, small internal radii would necessitate vertical milling. However, as can be seen from Figure 7.36, a flat workpiece that must be machined around the whole periphery is generally clamped to the machine worktable with a spacer beneath the workpiece smaller than the finished component. This means of work holding requires at least two bolt holes to be provided in the workpiece. In horizontal milling, the workpiece can be gripped in a vise.

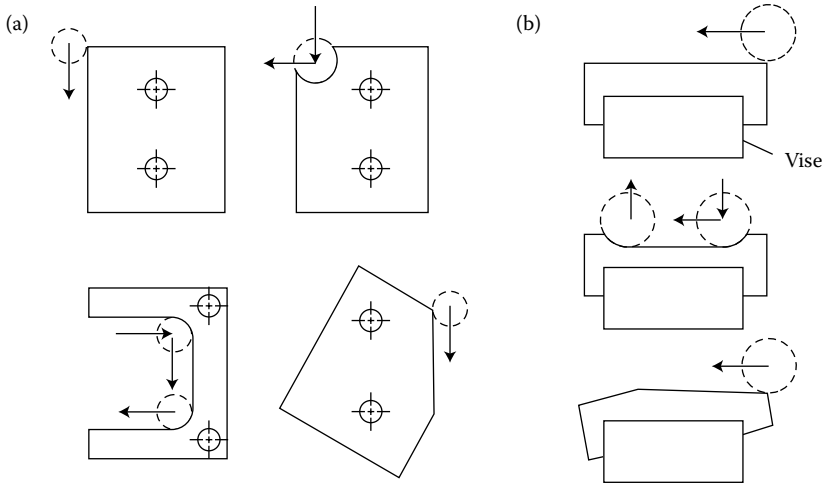


FIGURE 7.36
Milling external shape of flat components, (a) Vertical milling (plan view), (b) horizontal milling (front view). (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

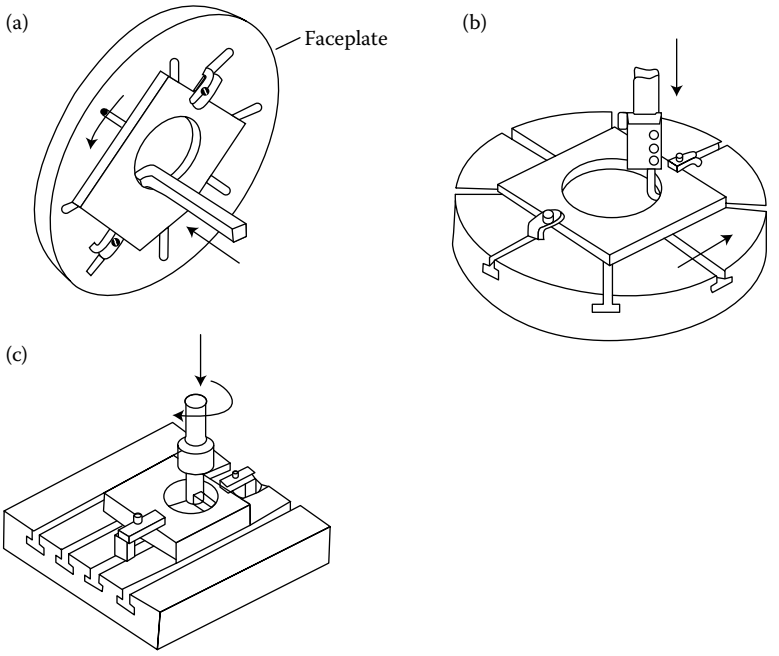


FIGURE 7.37
Machining of principal bores in nonrotational workpieces. (a) Lathe, (b) vertical borer, (c) jig borer. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

With flat components required in reasonably large batch sizes, manufacturing costs can often be considerably reduced by simultaneous machining of a stack of workpieces.

Sometimes large holes (principal bores) are required in nonrotational components. These principal bores are generally normal to the two large surfaces on the component and require machining by boring. This operation could be performed on a lathe (Figure 7.37a), where the workpiece would be bolted to a faceplate, or on a vertical borer (Figure 7.37b), where the workpiece would be bolted to the rotary worktable. For small parts, however, where high accuracy is required, the bores would be machined on a jig borer. A jig borer is similar to a vertical-milling machine, but the spindle is fed vertically and can hold a boring tool (Figure 7.37c). From these examples, it can be seen that where possible, principal bores should be cylindrical and normal to the base of the component. It can also be seen that a spacer is required between the workpiece and the work-holding surface.

The next type of secondary machining operation to be considered is the provision of a series of plane surfaces such as the machining of steps, slots, and so on, in one of the large surfaces on the workpiece. If possible, plane-surface machining should be restricted to one surface of the component only, thus avoiding the need for reclamping the workpiece. Plane surfaces might be machined on milling machines, or, in very large workpieces (such as machine beds), on planing machines. Figure 7.38 shows a variety of plane-surface machining operations, and it can be seen that plane-machined surfaces should, if possible, be either parallel or normal to the base of the component. Also, internal radii need not be specified for the milling operations, because the corners of the teeth on milling cutters are usually sharp.

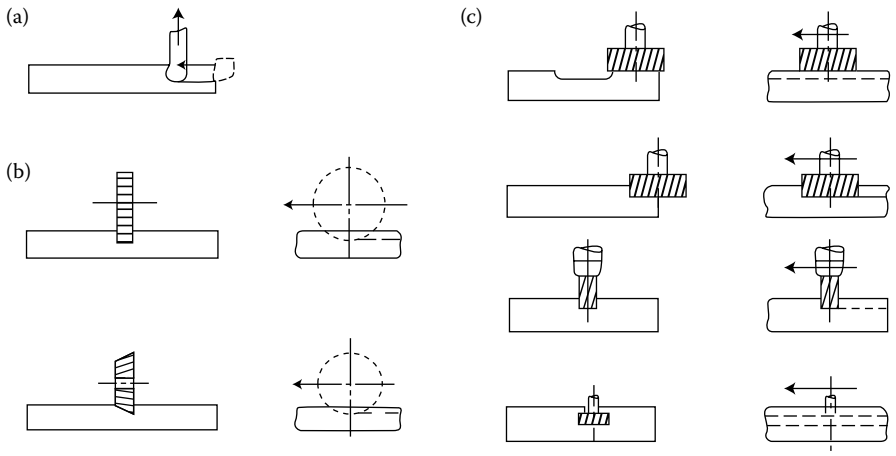


FIGURE 7.38
Plane-surface machining of flat components, (a) Shaping or planing, (b) horizontal milling, (c) vertical milling. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

Finally, auxiliary holes might be required in flat components; these would generally be machined on a drill press. Similar requirements to those discussed for the machining of auxiliary holes in disc-shaped rotational components apply. Thus, auxiliary holes should, if possible, be cylindrical and normal to the base of the component and preferably related by a pattern to simplify positioning of the workpiece for drilling.

7.8.5 Long, Nonrotational Components ($A/B > 3$)

Long, nonrotational components would often be machined from a rectangular- or square-section bar stock. Extremely long components should be avoided because of work-holding difficulties. The most common machining operations would be drilling and milling. Machined surfaces parallel to the principal axis of the component should be avoided because of the difficulties of holding down the entire length of the workpiece. Instead, the designer should, if possible, utilize work material preformed to the cross-section required.

7.8.6 Cubic, Nonrotational Components ($A/B < 3$, $A/C < 4$)

Cubic components should be provided with at least one plane surface that can initially be surface-ground or milled to provide a base for work-holding purposes and a datum for further machining operations.

If possible, the outer machined surfaces of the component should consist of a series of mutually perpendicular plane surfaces parallel to and normal to its base. In this way, after the base has been machined, further machining operations can be carried out on external surfaces with minimal reclamping of the workpiece. Figure 7.39, for example, shows a cubic workpiece where the external exposed surfaces can all be machined on a vertical-milling machine without reclamping. From this figure, it can be seen that sharp internal corners parallel to the base can be machined readily, but sharp internal corners normal to the base should be avoided.

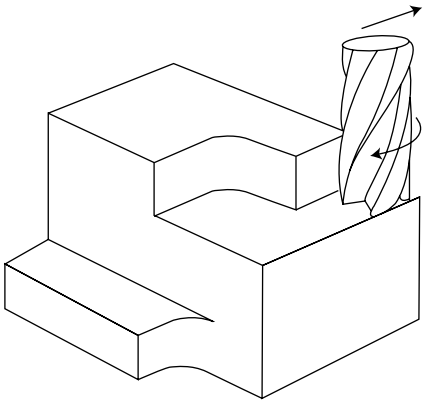


FIGURE 7.39
Milling outer surface of a cubic workpiece. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The workpiece shown in Figure 7.39 is blocklike, but others may be hollow or boxlike. Main bores in cubic components are often machined on a horizontal-boring machine. For ease of machining, internal cylindrical surfaces should be concentric and decrease in diameter from the exposed surface of the workpiece. Also where possible, blind bores should be avoided, because in horizontal boring the boring bar must usually be passed through the workpiece. Internal machined surfaces in a boxlike cubic component should be avoided unless the designer is certain that they would be accessible.

With small cubic components it is possible to machine pockets or internal surfaces using an end-milling cutter as shown in Figure 7.40. Again it can be seen that internal corners

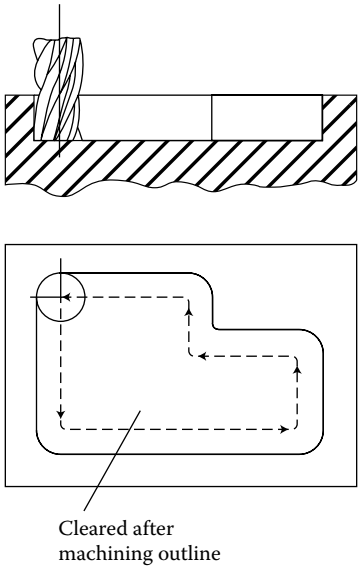


FIGURE 7.40
Milling a pocket in a blocklike cubic workpiece. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

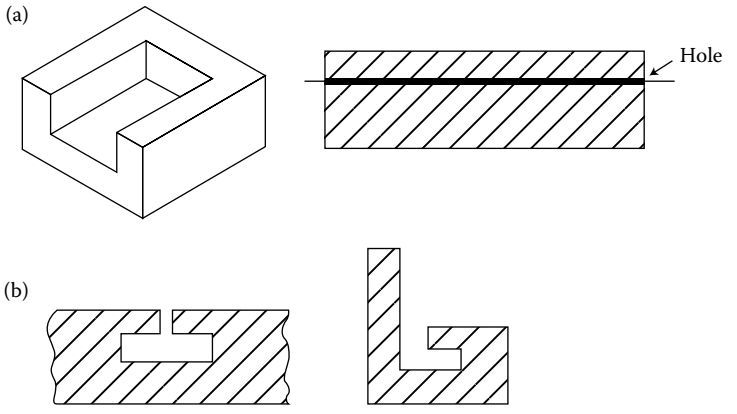


FIGURE 7.41
Design features to avoid in nonrotational components. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

normal to the workpiece base must have a radius no smaller than that of the cutter. Usually, the same cutter is used to clear out the pocket after machining the outer shape, and the smaller the cutter diameter the longer it takes to perform this operation. Consequently, the cost of the operation is related to the radii of the vertical internal corners. Thus, internal corners normal to the workpiece base should have as large a radius as possible.

Finally, cubic components often have a series of auxiliary holes. Auxiliary holes should be cylindrical and either normal to or parallel to the base of the component; they should also be in accessible positions and have *L/D* ratios that make it possible to machine them with standard drills. In general, standard drills can produce holes having *L/D* ratios as large as 5.

Figure 7.41a shows examples of features that would be difficult and expensive to produce in nonrotational components. In the first case, the internal vertical corners are shown sharp; these features cannot be produced with standard tools. In the second case, the

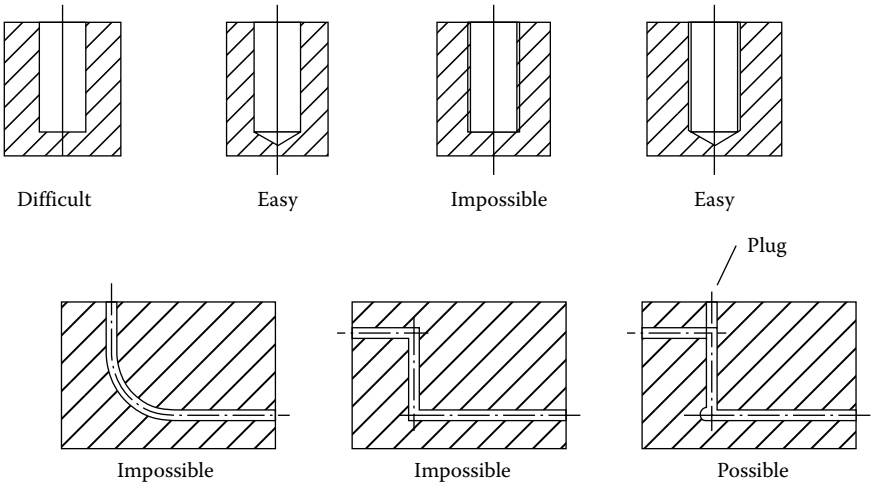


FIGURE 7.42
Design of blind holes. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

through hole has an extremely large *L/D* ratio and would be difficult to produce even with special deep-hole drilling techniques. Figure 7.41b shows examples of machined features virtually impossible to produce, because a suitable tool cannot be designed that would reach all the internal surfaces. Figure 7.42 shows the design of some blind holes. A standard drill produces a hole with a conical blind end, and therefore the machining of a hole with a square blind end requires a special tool. Thus, the end of a blind hole should be conical. If the blind hole is to be provided with a screw thread, the screw thread is tapped, and the designer should not specify a fully formed thread to the bottom of the blind hole since this type of screw thread is impossible to produce.

Holes that have a dogleg, or bend, should be avoided if possible. A curved hole (Figure 7.42) is clearly impossible to machine; however, drilling a series of through-holes and plugging unwanted outlets can often achieve the desired effect although this operation is expensive.

7.9 Assembly of Components

Most machined components must eventually be assembled, and the designer should consider the assembly process. Design for the ease of assembly is treated in Chapter 3; however, one or two aspects of this subject that affect machining are mentioned here. The first requirement is, of course, that it should be physically possible to assemble the components. Obviously, the screw thread on a bolt or screw should be the same as the mating thread on the screwed hole into which the bolt or screw is to be inserted. Some assembly problems, however, are not quite so obvious. Figure 7.43 shows some impossible assembly

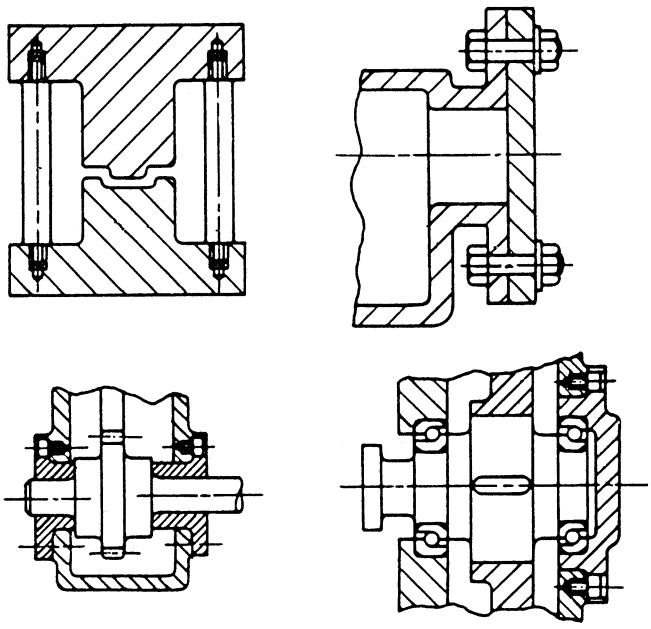


FIGURE 7.43
Components that cannot be assembled. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

situations, and it is left to the reader to decide why the components cannot be assembled properly.

A further requirement is that each operating machined surface on a component should have a corresponding machined surface on the mating component. For example, where flanges on castings are to be bolted together, the area around the bolt holes should be machined perpendicular to the hole (spot-faced, for example) to provide a proper seating for the bolt heads, nuts, or washers. Also, internal corners should not interfere with the external corner on the mating component. Figures 7.29 and 7.35 give examples of how this interference can be avoided. Finally, an incorrect specification of tolerances can make assembly difficult or even impossible.

7.10 Accuracy and Surface Finish

A designer would not generally want to specify an accurate surface with a rough finish or an inaccurate surface with a smooth finish. When determining the accuracy and finish of machined surfaces, it is necessary to take into account the function intended for the machined surface. The specification of too-close tolerances or too-smooth surfaces is one of the major ways a designer can add unnecessarily to manufacturing costs. Such specifications could, for example, necessitate a finishing process, such as cylindrical grinding after rough turning, where an adequate accuracy and finish might have been possible using the lathe that performed the rough-turning operation. Thus, the designer should specify the widest tolerances and roughest surface that would give acceptable performance for operating surfaces.

As a guide to the difficulty of machining to within required tolerances it can be stated that

1. Tolerances from 0.127 to 0.25 mm (0.005–0.01 in.) are readily obtained.
2. Tolerances from 0.025 to 0.05 mm (0.001–0.002 in.) are slightly more difficult to obtain and increase production costs.
3. Tolerances 0.0127 mm (0.0005 in.) or smaller require good equipment and skilled operators and significantly add to production costs.

Figure 7.44 illustrates the general range of surface finish that can be obtained in different operations. It can be seen that any surface with a specified surface finish of 1 μm (40 μin.) arithmetical mean or better generally requires separate finishing operations, which substantially increases costs. Even when the surface can be finished on one machine, a smoother surface requirement would mean increased costs.

To illustrate the cost increase as the surface finish is improved, a simple turning operation can be considered. If a tool having a rounded corner is used under ideal cutting conditions, the arithmetical mean surface roughness R_a is related to the feed by

$$R_a = \frac{0.0321 f^2}{r_\varepsilon} \tag{7.36}$$

where f is the feed and r_ε is the tool corner radius.

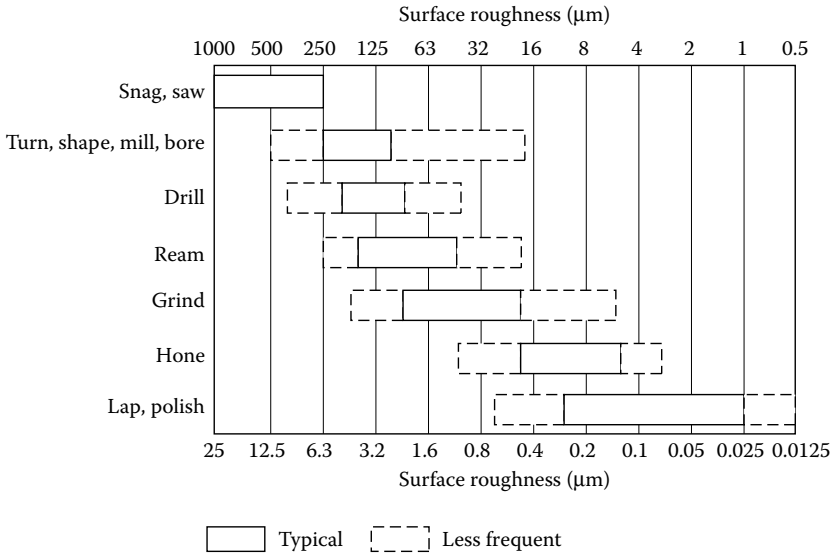


FIGURE 7.44
General range of surface roughness obtainable by various machining operations. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

The machining time t_m is inversely proportional to the feed f and related by the equation

$$t_m = \frac{l_w}{f n_w} \tag{7.37}$$

where l_w is the length of the workpiece and n_w is the rotational speed of the workpiece.

Substitution of f from Equation 7.36 in Equation 7.37 gives the machining time in terms of the specified surface finish:

$$t_m = \frac{0.18 l_w}{\left[n_w \left(R_a r_\varepsilon \right)^{0.5} \right]} \tag{7.38}$$

Thus, the machining time (and hence the machining cost) is inversely proportional to the square root of the surface finish. Figure 7.45 shows the relationship between production cost and surface finish for a typical turning operation. It can be seen that the costs rise rapidly when low values of surface finish are specified.

For many applications, a smooth, accurate surface is essential. This smooth, accurate surface can most frequently be provided by finish grinding. When specifying finish grinding, the designer should take into account the accessibility of the surfaces to be ground. In general, surfaces to be finish-ground should be raised and should never intersect to form internal corners. Figure 7.46 shows the types of surfaces that are most readily finish-ground using standard-shaped abrasive wheels.

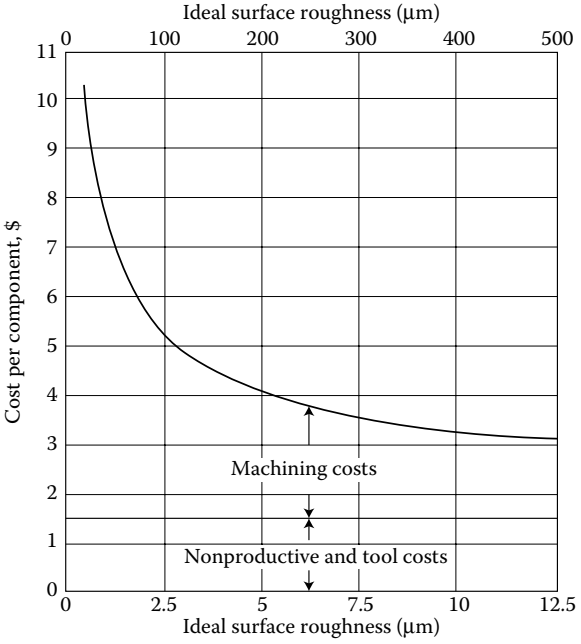


FIGURE 7.45
Effect of specified surface roughness on production costs in a turning operation, where the corner radius $r_\varepsilon = 0.03$ in. (0762 mm), the rotational frequency of the workpiece $n_w = 200$ rpm (3.33 s^{-1}), and the length of the workpiece $l_w = 34$ in. (864 mm). (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

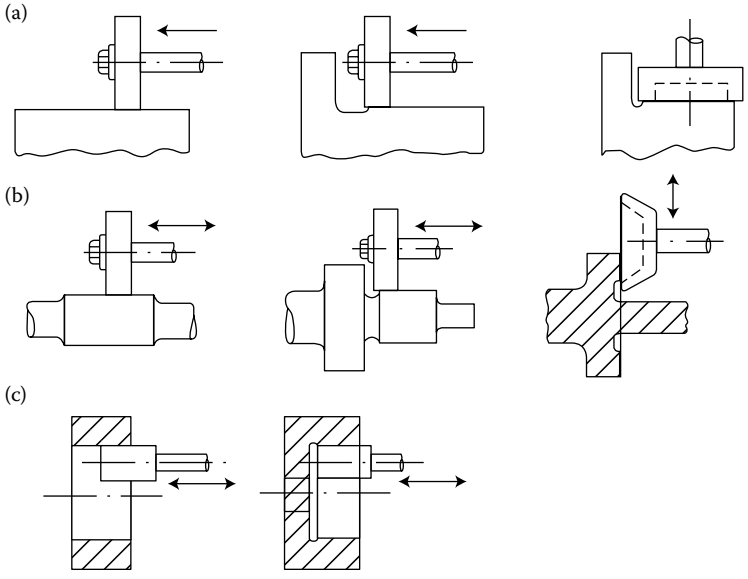


FIGURE 7.46
Surfaces that can readily be finish-ground, (a) Surface grinding, (b) cylindrical grinding, (c) internal grinding. (Adapted from Boothroyd, G. and Knight, W.A. *Fundamentals of Machining and Machine Tools*. 3rd ed. CRC Press, Boca Raton, FL, 2006.)

7.11 Summary of Design Guidelines

This section lists the various design guidelines that have been introduced, providing a summary of the main points a designer should keep in mind when considering the design of machined components.

Standardization

1. Utilize standard components as much as possible.
2. Preshape the workpiece, if appropriate, by casting, forging, welding, and so on.
3. Utilize standard pre-shaped workpieces, if possible.
4. Employ standard machined features wherever possible.

Raw Materials

5. Choose raw materials that would result in minimum component cost (including cost of production and cost of raw material).
6. Utilize raw materials in the standard forms supplied.

Component Design

a. General

7. Try to design the component so that it can be machined on one machine tool only.
8. Try to design the component so that machining is not needed on the unexposed surfaces of the workpiece when the component is gripped in the work-holding device.
9. Avoid machined features the company is not equipped to handle.
10. Design the component so that the workpiece, when gripped in the work-holding device, is sufficiently rigid to withstand the machining forces.
11. Verify that when features are to be machined, the tool, toolholder, work, and work-holding device would not interfere with one another.
12. Ensure that auxiliary holes or main bores are cylindrical and have L/D ratios that make it possible to machine them with standard drills or boring tools.
13. Ensure that auxiliary holes are parallel or normal to the workpiece axis or reference surface and related by a drilling pattern.
14. Ensure that the ends of blind holes are conical and that in a tapped blind hole the thread does not continue to the bottom of the hole.
15. Avoid bent holes or dogleg holes.

b. Rotational Components

16. Try to ensure that cylindrical surfaces are concentric, and plane surfaces are normal to the component axis.
17. Try to ensure that the diameters of external features increase from the exposed face of the workpiece.
18. Try to ensure that the diameters of internal features decrease from the exposed face of the workpiece.

19. For internal corners on the component, specify radii equal to the radius of a standard rounded tool corner.
20. Avoid internal features for long components.
21. Avoid components with very large or very small *L/D* ratios.

c. Nonrotational Components

22. Provide a base for work holding and reference.
23. If possible, ensure that the exposed surfaces of the component consist of a series of mutually perpendicular plane surfaces parallel to and normal to the base.
24. Ensure that internal corners normal to the base have a radius equal to a standard tool radius. Also ensure that for machined pockets, the internal corners normal to the base have as large a radius as possible.
25. If possible, restrict plane-surface machining (slots, grooves, etc.) to one surface of the component
26. Avoid cylindrical bores in long components.
27. Avoid machined surfaces on long components by using work material preformed to the cross-section required.
28. Avoid extremely long or extremely thin components.
29. Ensure that in flat or cubic components, main bores are normal to the base and consist of cylindrical surfaces decreasing in diameter from the exposed face of the workpiece.
30. Avoid blind bores in large cubic components.
31. Avoid internal machined features in cubic boxlike components.

Assembly

32. Ensure that assembly is possible.
33. Ensure that each operating machined surface on a component has a corresponding machined surface on the mating component.
34. Ensure that internal corners do not interfere with a corresponding external comer on the mating component.

Accuracy and Surface Finish

35. Specify the widest tolerances and roughest surface that would give the required performance for operating surfaces.
36. Ensure that surfaces to be finish-ground are raised and never intersect to form internal corners.

7.12 Cost Estimating for Machined Components

Designers normally have a reasonable knowledge of the factors to bear in mind when attempting to minimize manufacturing costs for machined components and the previous section listed some design rules that might be followed. Ultimately, however, the designer

needs to know the magnitude of the effects of design decisions on manufacturing costs. The need for a method of estimating these costs is highlighted when considering the design of a product for ease of assembly. Techniques have been available for some time for analyzing an assembly for handling and insertion costs incurred as each part is added, and they are described in Chapter 3. As a result of such analyses, many suggestions for design simplifications arise—often involving the elimination of individual parts or components. However, it is also necessary to have methods for quickly estimating the cost of these parts and the cost of tooling so that the total savings in products costs can be quantified.

Before embarking on a discussion of how an estimating method for designers of machined components might be developed, we should consider how the requirements for such a method differ from conventional cost-estimating procedures. These conventional procedures are meant to be applied after the component has been designed and its production planned. Thus, every step in production is known and can be estimated with a high degree of accuracy. During the early stages of design, however, the designer would not wish to specify, for example, all the work-holding devices, and tools that might be needed; most likely, detailed design would not yet have taken place. Indeed, a final decision on the specific work material might not have been made at this stage. Thus, what is wanted is an approximate method requiring minimum information from the designer and assuming that the ultimate design would avoid unnecessary manufacturing expense and the component would be manufactured under reasonably economic conditions.

Perhaps the simplest approach would be to have the designer specify the shape and size of the original workpiece and the quantity of material to be removed by machining. Then, with data on typical material costs per unit weight, an estimate can be made of the cost of the material needed to manufacture the component. If an approximate figure is available for the average cost of removal of each cubic inch of the material by machining, an estimate can also be made of the machining cost.

Unfortunately, this very simple approach does not take adequate account of the nonproductive costs involved in a series of machining operations. For example, if 1 $in.^3$ of material were to be removed in one pass by a simple turning operation, the nonproductive costs would be quite small—the component would only need to be loaded into the lathe and unloaded once and the cutting tool would only be set and the feed engaged once. Compare this with 1 $in.^3$ of the same material removed by a combination of turning, screw cutting, milling, and drilling. In this case, the nonproductive costs accumulate and become a highly significant factor in the ultimate cost of the machined component, especially when the machined component is relatively small.

What is needed is a method that forms a compromise between this oversimplified approach and the traditional detailed cost-estimating methods used by manufacturing and industrial engineers.

7.12.1 Material Cost

Often, the most important factor in the total cost of a machined component is the cost of the original workpiece. This material cost frequently forms more than 50% of the total cost and, therefore, should be estimated with reasonable care. Table 7.2 gives densities and approximate costs in dollars per pound for a variety of materials in the basic shapes normally available. Provided the designer can specify the volume of material required for the original workpiece, the material cost can easily be estimated. Although the figures in Table 7.2 can be used as a rough guide, the designer would be able to obtain more accurate figures from material suppliers. Material prices fluctuate considerably with market

TABLE 7.2

Approximate Costs in Dollars per Pound for Various Metals

	Density						
	lb/in.³	**mg/m³**	**Bar**	**Rod**	**Sheet <0.5 in.**	**Plate >0.5 in.**	**Tube**
Ferrous							
Carbon steel	0.283	7.83	0.51	0.51	0.36	0.42	0.92
Alloy steel	0.31	8.58	0.75	0.75	1.20	—	—
Stainless steel	0.283	7.83	1.50	1.50	2.50	2.50	—
Tool steel	0.283	7.83	6.44	6.44	—	6.44	—
Nonferrous							
Aluminum alloys	0.10	2.77	1.93	1.93	1.95	2.50	4.60
Brass	0.31	8.58	0.90	1.22	1.90	1.90	1.90
Nickel alloys	0.30	8.30	5.70	5.70	5.70	5.70	—
Magnesium alloys	0.066	1.83	3.35	3.35	6.06	6.06	3.35
Zinc alloys	0.23	6.37	1.50	1.50	1.50	1.50	—
Titanium alloys	0.163	4.51	15.40	15.40	25.00	25.00	—

Note: To convert to dollars per kilogram multiply by 2.2.

conditions so the values given in Table 7.2 are included for the purposes of calculations in this Chapter.

7.12.2 Machine Loading and Unloading

Nonproductive costs are incurred everytime the workpiece is loaded into (and subsequently unloaded from) a machine tool. An exhaustive study of loading and unloading times has been made by Fridriksson [1]; he found that these times can be estimated quite accurately for a particular machine tool and work-holding device if the weight of the workpiece is known. Some of Fridriksson's results are presented in Table 7.3, which can be used to estimate machine loading and unloading times. To these figures must be added the times for turning coolant on and off, cleaning the work-holding or clamping device, and so on.

7.12.3 Other Nonproductive Costs

For every pass, cut, or operation carried out on one machine tool, further nonproductive costs are incurred. In each case, the tool must be positioned, perhaps the feed and speed settings changed, the feed engaged, and then, when the operation is completed, the tool must be withdrawn. If different tools are employed, then the times for tool engagement or indexing must also be taken into account. Some time elements for these tasks for different types of machine tools are presented in Table 7.4.

Also included in Table 7.4 are estimates of the basic setup time and additional setup time per cutting tool. The total set-up time must be divided by the size of the batch in order to obtain the setup time per component.

7.12.4 Handling between Machines

One of the costs to be considered is that incurred in moving batches of partially machined workpieces between machines. Fridriksson [1] made a study of this by assuming that

TABLE 7.3

Loading and Unloading Times (s) versus Workpiece Weight

	Workpiece Weight				
	0–0.2	0.2–4.5	4.5–14	14–27 (kg)	
Holding Device	**0–0.4**	**0.4–10**	**10–30**	**30–60 (lb)**	**Crane**
Angle plate (2 U-clamps)	27.6	34.9	43.5	71.2	276.5
Between centers, no dog	13.5	18.6	24.1	35.3	73.1
Between centers, with dog	25.6	40.2	57.4	97.8	247.8
Chuck, universal	16.0	23.3	31.9	52.9	—
Chuck, independent (4 jaws)	34.0	41.3	49.9	70.9	—
Clamp on table (3 clamps)	28.8	33.9	39.4	58.7	264.6
Collet	10.3	15.4	20.9	—	—
Faceplate (3 clamps)	31.9	43.3	58.0	82.1	196.2
Fixture, horizontal (3 screws)	25.8	33.1	41.7	69.4	274.7
Fixture, vertical (3 screws)	27.2	38.6	53.3	—	—
Hand-held	1.4	6.5	12.0	—	—
Jig	25.8	33.1	41.7	—	—
Magnet table	2.6	5.2	8.4	—	—
Parallels	14.2	19.3	24.8	67.0	354.3
Rotary table or index plate (3 clamps)	28.8	36.1	44.7	72.4	277.7
"V" Blocks	25.0	30.1	35.6	77.8	365.1
Vise	13.5	18.6	24.1	39.6	174.2

Source: Adapted from Fridriksson, L. Nonproductive Time in Conventional Metal Cutting. Report No. 3, *Design for Manufacturability Program*, University of Massachusetts, Amherst, February 1979.

TABLE 7.4

Some Nonproductive Times for Common Machine Tools

Machine Tool	Time to Engage Tool; etc.[a] (s)	Basic Setup Time (h)	Additional Setup per Tool (h)
Horizontal band saw	—	0.17	—
Manual turret lathe	9	1.2	0.2
CNC turret lathe	1.5	0.5	0.15
Milling machine	30	1.5	—
Drilling machine	9	1.0	—
Horizontal-boring machine	30	1.3	—
Broaching machine	13	0.6	—
Gear hobbing machine	39	0.9	—
Grinding machine	19	0.6	—
Internal grinding machine	24	0.6	—
Machining center	8	0.7	0.05

[a] Average times to engage tool, engage and disengage feed, change speed or feed. (Includes change tool for machining center.)

stacks of pallets of workpieces were moved around the factory using forklift trucks. He developed the following expression for t_f, the transportation time for a round trip by a forklift truck

$$t_f = 25.53 + 0.29(l_p + l_{rd})\ s \tag{7.39}$$

where l_p is the length of the pathway between machines and l_{rd} is the distance the truck must travel to respond to a request—both lengths are measured in feet.

Assuming that $(l_p + l_{rd})$ is 450 ft (137 m) on average and that for every trip with a load of full pallets, a trip must be made with empty pallets, the total time is

$$t_f = 315\,\text{s} \tag{7.40}$$

If a full load of pallets and workpieces is 2000 lb, the number of workpieces of weight W transported would be $2000/W$ and the time per workpiece t_{tr} is given by

$$t_{tr} = \frac{315}{(2000/W)} = 0.156W\ \text{s} \tag{7.41}$$

Thus, for a workpiece weighing 10 lb, the effective transportation time is only 1.6 s, which is small compared to typical loading and unloading times for that size workpiece (Table 7.3). However, allowances for transportation time can be added to the loading and unloading times, and these become significant for large workpieces.

7.12.5 Material Type

The so-called machinability of a work material has been one of the most difficult factors to define and quantify. In fact, it is impossible to predict the difficulty of machining a material from knowledge of its composition or its mechanical properties, without performing a machining test. Nevertheless, it is necessary for the purposes of cost estimating to employ published data on machinability. Perhaps the best source of such data, presented in the form of recommended cutting conditions, is the *Machining Data Handbook* [2].

7.12.6 Machining Costs

The machining cost for each cut, pass, or operation is incurred during the period between when the feed is engaged and, finally, disengaged. It should be noted that the tool would not be cutting for the whole of this time, because allowances for tool engagement and disengagement must be made—particularly for milling operations. However, typical values for these allowances can be found and are presented for various operations in Table 7.5 as correction factors to be applied to the actual machining time.

For an accurate estimation of actual machining time, it is necessary to know the cutting conditions, namely, cutting speed, feed, and depth of cut in single-point tool operations, and the feed speed, depth of cut, and width of cut in multipoint tool operations. Tables giving recommended values for these parameters for different work materials can fill large volumes, such as the Metcut *Machining Data Handbook* [2].

Analysis of the selection of optimum machining conditions shows that the optimum feed (or feed per tooth) is the largest that the machine tool and cutting tool can withstand.

TABLE 7.5

Allowances for Tool Approach

Operations	Allowances
Turn, face, cut-off bore,	$t'_m = t_m + 5.4 \qquad d_m > 2$
groove, thread	$t'_m = t_m + \left(1.35\, d_m^2\right) \qquad d_m \le 2$
Drill (twist) (approach)	$t'_m = t_m \left(1 + 0.5 d_m / l_w\right)$
Drill (twist) (start)	$t'_m = t_m + \left(88.5/\upsilon f\right) d_m^{1.67}$
Helical, side, saw, and key slot milling	$l'_w = l_w + 2\left(a_e \left(d_t - a_c\right)^{0.5} + 0.066 + 0.011 d_t\right)$
Face and end milling	$l'_w = l_w + d_t + 0.066 + 0.011 d_t$
Surface grinding	$l'_w = l_w + d_t/4$
Cyl. and int. grinding	$l'_w = l_w + w_t$
All grinding operations	$a'_r = a_r + 0.004 \qquad a_r \le 0.01$
	$a'_r = a_r + 0.29\left(a_r - 0.01\right) \qquad \begin{cases} a_r > 0.01 \\ a_r \le 0.024 \end{cases}$
	$a'_r = a_r + 0.008 \qquad a_r > 0.024$
Spline broaching	$l_t = -5 + 15 d_m + 8 l_w$
Internal keyway broaching	$l_t = 20 + 40 w_k + 85 d_k$
Hole broaching	$l_t = 6 + 6 d_m + 6 l_w$

Source: Adapted from Ostwald, P.F. *AM Cost Estimator*, McGraw-Hill, New York, 1985/1986.

Note: t_m = machining time, s; d_m = diameter of the machined surface, in.; l_w = length of the machined surface in the direction of cutting, in.; υ_f = speed × feed, in.^{2}/min (Table 7.6); a_e = depth of cut or depth of the groove in milling, in.; d_t = diameter of the cutting tool, in.; w_t = width of the grinding wheel, in.; a_r = depth of the material removed in rough grinding, in.; l_t = length of the tool, in.; w_k = width of the machined keyway, in.; d_k = depth of the machine keyway, in.

Then, selection of the optimum cutting speed can be made by minimizing machining costs (see Equation 7.33). The product of cutting speed and feed in a single-point operation gives a rate for the generation of the machined surface that can be measured in in.^{2}/min, for example. The inverse of such rates is presented by Ostwald [3] for a variety of workpiece and tool materials and for different roughing and finishing operations. Problem arises, however, when applying the figures for roughing operations. For example, Ostwald recommends a cutting speed of 500 ft/mm (2.54 m/s) and a feed of 0.02 in. (0.51 mm) for the rough machining of low carbon steel (170 Bhn) with a carbide tool. For a depth of cut of 0.3 in. (7.6 mm) this would mean a metal removal rate of 36 in.^{3}/min (9.82 μm^3/s). The *Machining Data Handbook* [2] quotes a figure of 1.35 hp min/in.^{3} (3.69 GJ/m^3) (unit power) for this work material. Thus, the removal rate obtained in this example would require almost 50 hp (36 kW). Since a typical medium-sized machine tool would have a 5 to 10 hp motor (3.7 to 7.5 kW) and an efficiency of around 70%, it can be seen that the recommended conditions could not be achieved except for small depths of cut. Under normal rough-machining circumstances, therefore, a better estimate of machining time would be obtained from the unit horsepower (specific cutting energy) for the material, the volume of material to be removed, and the typical power available for machining, as described earlier in this chapter.

For multipoint tools such as milling cutters, the chip load (feed per tooth) and the cutting speed are usually recommended for given tool materials. However, in these cases the machining time is not directly affected by the cutting speed but by the feed speed, which is controlled independent of the cutter speed. Thus, assuming that the optimum cutting speed is employed, the feed speed that gives the recommended feed per tooth can be used to estimate the machining time. Again, a check must be made that the power requirements for the machine tool are not excessive.

7.12.7 Tool Replacement Costs

Everytime a tool needs replacement because of wear, two costs are incurred:

1. The cost of machine idle time while the operator replaces the worn tool, and
2. The cost of providing a new cutting edge or tool. The choice of the best cutting speed for particular conditions is usually made by minimizing the sum of the tool replacement costs and the machining costs, since both of these are affected by changes in the cutting speed.

The minimum cost of machining a feature in one component on one machine tool is given by Equation 7.35. If the expressions for machining time t_m (Equation 7.31) and cutting speed υ_c (Equation 7.33) are substituted, the minimum cost of production can be expressed by

$$C_{min} = Mt_l + \frac{Mt_{mc}}{(1-n)} \tag{7.42}$$

where t_{mc} is the machining time when the optimum cutting speed for minimum cost is used.

It can be seen that the factor $1/(1-n)$ applied to the machining time allows tool replacement costs provided that the cutting speed for minimum cost is always employed. The factor would be 1.14 for high-speed steel tooling and 1.33 for carbides.

Under those circumstances where the use of optimum cutting conditions would not be possible because of power limitations, it is usually recommended that the cutting speed be reduced. This is because greater savings in tool costs result than if the feed were reduced. When the cutting speed has been reduced, with a corresponding increase in the machining time, the correction factor given by Equation 7.42 overestimates tool costs. If t_{mp} is the machining time where the cutting speed υ_{po} giving maximum power is used, then the production cost C_{po} for maximum power is given by

$$C_{po} = Mt_l + Mt_{mp} + \frac{(Mt_{ct} + C_t)t_{mp}}{t_{po}} \tag{7.43}$$

where t_{po} is the tool life obtained under maximum power conditions, which, from Taylor's tool life equation, is

$$t_{po} = t_c\left(\frac{\upsilon_c}{\upsilon_{po}}\right)^{1/n} \tag{7.44}$$

The tool life t_c under minimum cost conditions is given by Equation 7.34, and substituting Equations 7.44 and 7.34 into Equation 7.43 and using the relation in Equation 7.31 gives

$$C_{po} = Mt_l + Mt_{mp}\left\{1 + \left[\frac{n}{(1-n)}\right]\left(\frac{t_{mc}}{t_{mp}}\right)^{1/n}\right\} \tag{7.45}$$

Thus, Equation 7.45 can be used instead of Equation 7.42 when the cutting speed is limited by the power available on the machine tool and, therefore, when $t_{mp} > t_{mc}$.

7.12.8 Machining Data

In order to employ the approach described above, it is necessary to be able to estimate, for each operation, the machining time t_{mc} for minimum cost conditions and the machining time t_{mp} where the cutting speed is limited by power availability. It was shown earlier that machining data for minimum cost for single-point tools, presented in handbooks, can be expressed as speed × feed (υf), or the rate at which the machined surface can be generated. Table 7.6 gives typical values of υf for several material classifications selected and for lathe operations using high-speed tools or brazed carbide tools. These values were adapted from the data in the *Machining Data Handbook* [2], Analysis of the handbook data shows that if disposable insert carbide tools are to be used, then the data for brazed carbide tools can be multiplied by an average factor of 1.17.

When turning a surface of diameter d_m for a length l_w, the figures for υf given in Table 7.6 would be divided into the surface area ($A_m = \pi/_w d_m$) to give the machining time t_{mc}.

Thus

$$t_{mc} = \frac{60A_m}{(\upsilon f)} \text{ s} \tag{7.46}$$

For an estimate of the machining time t_{mp} for maximum power it is necessary to know the power available for machining and the unit power p_s (specific cutting energy) for the work material. Table 7.6 gives average values of p_s for the selection of work materials employed here.

When estimating the power available for machining P_m, it should be realized that small components are generally machined on small machines with lower power available, whereas larger components are machined on large higher-powered machines. For example, a small lathe may have less than 2 hp available for machining, whereas an average-sized lathe may have 5–10 hp available. A larger vertical lathe perhaps has 10–30 hp available. Typical power values for a selection of machines are presented in Figure 7.47, where the horsepower available for machining P_m is plotted against the typical weight capacity of the machine.

The machining time for maximum power is given by

$$t_{mp} = 60\, V_m p_s / P_m \text{ s} \tag{7.47}$$

where V_m is the volume of material to be removed in the machining operation. If a_p is the depth of cut, then V_m is given approximately by $\pi d_m l_w a_p$. However, for a facing or cut-off

TABLE 7.6

Machining Data

		Turning, Facing and Boring			Drilling and Reaming (1 in.)	
		vf (in²/min)[a]				
Material	**Hardness**	**HSS**	**Brazed Carbide**	p_s **(hp/in.³/min)[b]**	***vf*(in.²/min)[a] HSS**	p_s **(hp/in.³/min)[b]**
Low carbon steel (free machining)	150–200	25.6	100	1.1	33.0	0.95
Low carbon steel	150–200	22.4	92	1.35	13.4	1.2
Medium and high carbon steel	200–250	18.2	78	1.45	15.1	1.4
Alloy steel (free machining)	150–200	23.7	96	1.3	16.4	1.15
Stainless, ferritic (annealed)	135–185	12.6	48	1.55	9.4	1.35
Tool steels	200–250	12.8	54	1.45	6.2	1.4
Nickel alloys	80–360	9	42	2.25	14.3	2.0
Titanium alloys	200–275	12.6	24	1.35	7.9	1.25
Copper alloys (soft) (free machining)	40–150	76.8	196	0.72	38.4	0.54
Zinc alloys (die cast)	80–100	58.5	113	0.3	51.1	0.2
Magnesium and alloys	49–90	162	360	0.18	75.2	0.18
Aluminum and alloys	30–80	176	352	0.28	79.8	0.18

Factor	**For**	**Turning, Facing Boring**	**Milling**
k_f	Finishing	0.60	0.89
k_i	Disposable Insert	1.17	1.13

Factor	**For**	**Tool Diameter (in.) (mm)**							
		1/16	1/8	1/4	1/2	3/4	1	1.5	2 in.
k_h		1.59	3.18	6.35	12.7	19.7	25.4	38.1	50.8 mm
	Drilling and reaming	0.08	0.19	0.35	0.60	0.83	1.00	1.23	1.47

Factor	**For**	**Length/Diameter Ratio**					
		< 2	3	4	5	6	8
k_d	Deep holes	1.00	0.81	0.72	0.56	0.52	0.48

Source: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

[a] To convert in.²/min to m²/min, multiply by 6.45×10^{-4}.

[b] To convert hp min/in.³ to GJ/m³ multiply by 2.73.

All data are for rough machining. For finish machining multiply by k_f.

For cut-off or form tool operations, multiply by 0.2.

The term *carbide* refers to tools with brazed carbide inserts. For tools with disposable carbide inserts, multiple by k_i.

Data for drilling are for 1.0 in. diameter tools with hole depth/diameter less than 2.

For sawing, multiply the data for turning with HSS tools by 0.33.

For tap or die threading, multiply data for turning with HSS tools by 10 and divide by TPI (threads per inch); for standard threads TPI = $2.66 + 4.28/d_m$.

For single-point threading, multiply result for die threading by number of passes, approximately 100/TPI, and add tool engagement time for each pass.

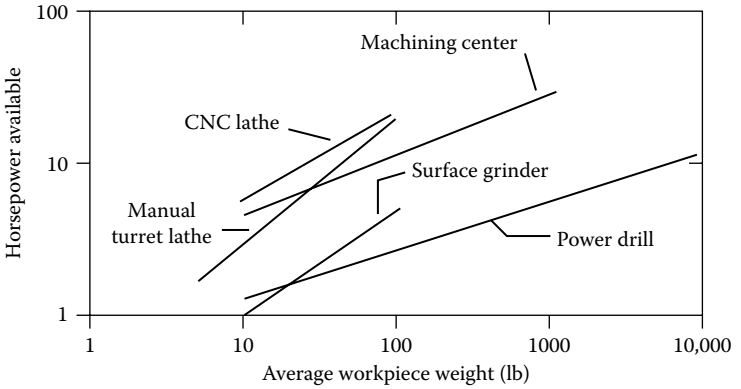


FIGURE 7.47
Relation between horsepower and workpiece weight for some machine tools.

operation carried out at constant rotational speed, the power limitations apply only at the beginning of the cut and the machining time is longer than that given by Equation 7.47.

It was pointed out earlier that for milling operations, it is convenient to estimate machining time from knowledge of the feed speed υ_f that gives the recommended feed per tooth. Data for milling selected materials are presented in Table 7.7.

The machining time t_m for recommended conditions is thus given by

$$t_{mc} = 60 l_w / \upsilon_f \text{ s} \tag{7.48}$$

where l_w is the length of the feature to be milled. However, it is important to note that this result must be corrected for the approach and overtravel distances, which are often as large as the cutter diameter.

The machining time for maximum power is given by Equation 7.47, but, again, corrections must be made for cutter approach and overtravel.

7.12.9 Rough Grinding

Limitations on the rate at which grinding operations can be carried out depend on many interrelated factors, including the work material, the wheel grain type and size, the wheel bond and hardness, the wheel and work speeds, downfeed, infeed, the type of operation, the rigidity of the machine tool, and power available. It appears that, assuming adequate power, these limitations can be summarized in terms of the maximum metal removal rate per unit width of the grinding wheel Z_w/w_t. For example, the *Machining Data Handbook* [2] gives the following recommendations for the rough grinding of annealed free-machining low carbon steel on a horizontal-spindle reciprocating surface grinder:

Wheel speed: 5500–6500 ft/min

Table speed: 50–150 ft/min

Downfeed: 0.003 in./pass

Crossfeed: 0.05–0.5 in./pass (1/4 wheel width maximum)

Wheel: A46JV (aluminum oxide grain, size 46, grade J, vitrified bond)

TABLE 7.7

Machining Data for Milling Operations

Material	Hardness (Bhn)	Milling v_f (in./min)[a] Side and Face HSS Brazed Carb.		End (1.5 in.) HSS Brazed Carb.		p_s (hp/in.^{3}/min)[b]
Low carbon steel (free machining)	150–200	19.2	52.9	4.5	15.7	1.1
Low carbon steel	150–200	13.5	43.3	2.2	9.9	1.4
Medium and high carbon steel	200–250	10.8	37.3	1.8	8.9	1.6
Alloy steel (free machining)	150–200	13.7	40.2	2.7	10.5	1.3
Stainless, ferretic (annealed)	135–185	14.0	41.0	2.4	6.0	1.7
Tool steels	200–250	6.7	23.7	0.9	4.5	1.5
Nickel alloys	80–360	4.1	7.7	1.0	—	2.15
Titanium alloys	200–275	3.9	13.2	1.5	7.1	1.25
Copper alloys (soft) (free machining)	40–150	50.5	108.3	9.9	20.7	0.72
Zinc alloys (die cast)	80–100	28.0	60.1	9.8	16.0	0.4
Magnesium and alloys	40–90	77.0	240.6	27.5	55.0	0.18
Aluminum and alloys	30–80	96.2	216.5	20.4	36.7	0.36

Source: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

[a] To convert in/min to mm/s multiple by 0.423.

[b] To convert hp/min/in3 to GJ/m3 multiply by 2.73.

If the wheel width w_t were 1 in. and an average table speed (work speed) of 75 ft/min were employed, then a downfeed of 0.003 in. and a maximum crossfeed of 0.25 in. would give a metal removal rate Z_w of 0.68 in.^{3}/min. In a plunge-grinding operation, the wheel width would be equal to the width of the groove to be machined and the rough grinding time t_{gc} for recommended conditions would be given by

$$t_{gc} = 60\, V_m/Z_w \tag{7.49}$$

where V_m is the volume of metal to be removed and Z_w is the metal removal rate (in.^{3}/min). If the groove depth a_d were 0.25 in. and the groove length l_w were 4 in., the grinding time would be

$$t_{gc} = 60 a_d w_t l_w/Z_w = 60(1)(0.25)(4)/0.68 = 88.2\ \text{s}$$

The *Machining Data Handbook* [2] also gives values of the unit power (specific cutting energy) for the surface grinding of various materials. The unit power p_s depends to a large extent on the downfeed, and for a downfeed of 0.003 in., 13 hp min/in. would be required for carbon steel. In our example, the removal rate for a 2 in. wide groove, would be

$$Z_w = 60(2)(0.25)4/88.2 = 1.36 \text{ in.}^3/\text{min}$$

and the power required P_m would then be given by

$$P_m = p_s Z_w = 13(1.36) = 17.7 \text{ hp}$$

Clearly, for a particular rough-grinding operation, it is necessary to check the grinding time t_{gp} when maximum power is used, and this is given by

$$t_{gp} = 60\, V_m p_s / P_m \tag{7.50}$$

The estimated rough-grinding time t_{gr} would be given by the grinding time t_{gc} for recommended conditions or the grinding time t_{gp} for maximum power, whichever is the largest. Table 7.8 gives recommendations for typical conditions for the horizontal-spindle surface grinding of selected materials. These recommendations are expressed in terms of Z_w/w_t, the metal removal rate per unit width of wheel in rough grinding, and the corresponding unit power p_s.

If the operation is one of plunge grinding, the width of the grinding wheel is known. In a traverse operation, the width of the wheel depends mainly on the grinding machine.

In a plunge-grinding operation, the depth of material to be removed is specified by the geometry of the finished workpiece. In a traverse-grinding operation, it is necessary to remove the rough-grinding stock left by the previous machining operation.

TABLE 7.8

Machining Data for Horizontal-Spindle Surface Grinding

Material	Hardness (Bhn)	Z_w/w_t (in.²/min)	p_s (hp/in.³/min)
Low carbon steel (free machining)	150–200	0.68	13
Low carbon steel	150–200	0.68	13
Medium and high carbon steel	200–250	0.68	13
Alloy steel (free machining)	150–200	0.68	14
Stainless, ferretic (annealed)	135–185	0.45	14
Tool steels	200–250	0.68	14
Nickel alloys	80–360	0.15	22
Titanium alloys	200–275	0.9	16
Copper alloys (soft) (free machining)	40–150	0.89	11
Zinc alloys (die cast)	80–100	0.89[a]	6.5[a]
Magnesium and alloys	40–90	0.89	6.5
Aluminum and alloys	30–80	0.89	6.5

Source: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

[a] Estimated values.

For external cylindrical grinding, multiply Z/w_t by 1.24 and multiply p_s by 0.81.

For internal grinding, multiply Zw/w_t by 1.15 and p_s by 0.87.

7.12.10 Finish Grinding

The time for a finish-grinding operation is usually determined by the desired surface finish. This means that the metal removal rate must be slow enough to generate an acceptable surface finish, and it therefore becomes independent of the parameters affecting the removal rate in rough grinding. From the *Machining Data Handbook* [2], typical average values of the removal rate per inch of wheel width are 0.16 in.^{3}/min for horizontal-spindle surface grinding, 0.08 in.^{3}/min for cylindrical grinding, and 0.06 in.^{3}/min for internal grinding. Recommended stock allowances for finish grinding range from 0.002 to 0.003 in. for horizontal grinding and 0.005 to 0.01 in. for cylindrical grinding.

7.12.11 Allowance for Grinding Wheel Wear

In his analysis of the economics of internal grinding, Lindsay [4] shows that the costs per component associated with wheel wear and wheel changing are proportional to the metal removal rate during rough grinding and that the wheel costs due to dressing and finish grinding are negligible in comparison. Thus, the total cost C_g of a grinding operation is given by

$$C_g = Mt_c + Mt_{gr} + C_w \tag{7.51}$$

where M is the total rate for the machine (including direct labor, depreciation, and overhead), t_c is a constant time that includes the wheel-dressing time (assumed to occur once per component), the loading and unloading time, the wheel advance and withdrawal time, and the finish-grinding time, t_{gr} is the rough-grinding time, and C_w represents the wheel wear and wheel-changing costs. If we substitute

$$C_w = k_1 Z_w \tag{7.52}$$

where k_1 is a constant and Z_w is the metal removal rate during rough grinding, and

$$t_{gr} = \frac{k_2}{Z_w} \tag{7.53}$$

where k_2 is a constant, into Equation 7.51, we get

$$C_g = Mt_c + Mk_2/Z_w + k_1 Z_w \tag{7.54}$$

Differentiating with respect to Z_w and equating to zero for minimum cost, we find that the optimum condition arises when the wheel wear and wheel-changing costs (represented by the third term on the right of Equation 7.54) are equal to the rough-grinding costs (represented by the second term). This means that if optimum conditions are used in a grinding operation, wheel wear and wheel-changing costs can be allowed by multiplying the rough-grinding time by a factor of 2.

However, it was pointed out earlier that the recommended conditions may exceed the power P_m available for grinding. In this case, the metal removal rate must be reduced—resulting in a reduction in wheel wear and wheel-changing costs and an increase in rough-grinding costs with a consequent increase in the total operation costs.

If Z_{wc} and Z_{wp} are the metal removal rates for optimum (recommended) and maximum power conditions, respectively, the corresponding costs C_c and C_p are given by

$$C_c = Mt_c + 2Mk_2/Z_{wc} \tag{7.55}$$

$$C_p = Mt_c + Mk_2/Z_{wp} + k_1 Z_{wp} \tag{7.56}$$

Also, since for optimum conditions

$$k_1 Z_{wc} = \frac{Mt_2}{Z_{wc}} \tag{7.57}$$

we can obtain, after substitution and rearrangement, the following expression for the cost C_p, under maximum power conditions:

$$\begin{aligned} C_p &= Mt_c + \frac{Mk_2}{Z_{wc}}\left(\frac{Z_{wc}}{Z_{wp}} + \frac{Z_{wp}}{Z_{wc}}\right) \\ &= Mt_c + Mt_{gp}\left[1 + \left(\frac{t_{gc}}{t_{gp}}\right)^2\right] \end{aligned} \tag{7.58}$$

where t_{gc} and t_{gp} are the rough-grinding times for recommended and maximum power conditions given by Equations 7.49 and 7.50, respectively, and where $t_{gp} > t_{gc}$.

This means that a multiplying factor equal to the term in square brackets in Equation 7.58 can be used to adjust the rough grinding time and thereby allow wheel wear and wheel-changing costs. Under circumstances where the recommended grinding conditions can be used (i.e., when $t_{gp} > t_{gc}$) the multiplying factor is equal to 2. If, for example, because of power limitations the metal removal rate were 0.5 of the recommended rate, then t_{gp} would be equal to $2t_{gc}$ and the correction factor would be 1.25. Under these circumstances, the rough-grinding costs would be double those for recommended conditions and the wheel costs would be half of those for recommended conditions.

EXAMPLE

Suppose the diameter d_w of a stainless-steel bar is 1 in. and it is to be traverse ground for a length l_w of 12 in. If the wheel width w_t is 0.5 in., the power available P_m is 3 hp and the rough-grinding stock a_r left on the radius is 0.005 in., we get the volume of metal to be removed:

$$\begin{aligned} V_m &= \pi d_w a_r l_w \\ &= \pi(1)(0.005)(12) = 1.189 \text{ in.}^3 \end{aligned}$$

From Table 7.8 the recommended metal removal rate per unit width of wheel Z_w/w_t is 0.45 in.^{2} /min for horizontal-spindle surface grinding. Using a correction factor of 1.24 for cylindrical grinding, the rough-grinding time for recommended conditions is given by

$$\begin{aligned} t_{gc} &= 60\, V_m/Z_w \\ &= 60(0.189)/(1.24)(0.45)(0.5) = 40.65 \text{ s} \end{aligned}$$

However, Table 7.8 gives a unit power value of $p_s = 14$ hp min/in.^{3} for stainless steels and, therefore, with a correction factor of 0.81, the rough-grinding time for maximum power would be

$$t_{gp} = 60\, V_m p_s / P_m$$
$$= 60(0.189)(14)(0.81)/(3) = 42.9 \text{ s}$$

Thus, insufficient power is available for optimum grinding conditions and the condition for maximum power must be used. Finally, using the multiplying factor to allow wheel costs, we get a corrected value t'_{gp} for the rough-grinding time of

$$t'_{gp} = t_{gp}\left[1 + (t_{gc}/t_{gp})^2\right]$$
$$= 42.9\left[1 + (40.6/42.9)^2\right]$$
$$= 42.9(1.9) = 81.3 \text{ s}$$

As explained earlier, the metal removal rate for finish grinding is basically independent of the material and is approximately 0.08 in.^{3}/min per inch of wheel width in cylindrical grinding. For the present example, where the wheel width is 0.5 in., this would give a removal rate Z_w of 0.05 in.^{3}/min with a correction factor of 1.24 applied. Assuming a finish-grinding radial stock allowance of 0.001 in., the volume to be removed is

$$V_m = \pi(1)(0.001)(12) = 0.038 \text{ in.}^3$$

and the finish-grinding time is

$$t_{gf} = 60(0.038)/(0.05) = 45.6 \text{ s}$$

7.12.12 Allowance for Spark-Out

In spark-out, the feed is disengaged and several additional passes of the wheel or revolutions of the workpiece are made in order to remove the material remaining because of machine and workpiece deflections. Since the number of passes is usually given, this is equivalent to removing a certain finish stock. For estimating purposes, the finish grinding time can be multiplied by a constant factor of 2 to allow spark-out.

7.12.13 Examples

We shall first estimate the machining cost for a facing operation on a free-machining steel bar 3 in. (76.2 mm) diameter and 10 in. (254 mm) long, where 0.2 in. (5.1 mm) is to be removed from the end of the bar using a brazed-type carbide tool. The surface area to be generated is

$$A_m = \left[\pi/4\right](0.05)^2 = 7.07 \text{ in.}^2 (4.5 \text{ m.m}^2)$$

and the volume of metal to be removed is

$$V_m = \left[\pi/4\right](3)^2(0.2) = 1.41 \text{ in.}^2 (23.1 \text{ m}^3)$$

For this work material–tool material combination, Table 7.6 gives a value of vf (speed × feed) of 100 in.^{2}/min. (0.065 m^2/min), and from Equation 7.46 the machining time is

$$t_{mc} = 60(2)(7.07/100) = 8.5 \text{ s}$$

where the factor of 2 allows the gradually decreasing cutting speed when a constant rotational speed is used in a facing operation.

The weight of the workpiece is estimated to be

$$W = [\pi/4](3)^2(10)(0.28) = 20 \text{ lb } (9.07 \text{ kg})$$

From Figure 7.47 the power available for machining on a CNC chucking lathe would be approximately given by

$$P_m = 10 \text{ hp } (7.76 \text{ kw})$$

Table 7.6 gives a value of specific cutting energy (unit power) of 1.1 hp min/in.^{3} (3 GJ/m^3) and so, from Equation 7.47, the machining time at maximum power is

$$t_{mp} = 60(2)(1.1)(1.41/10) = 18.6 \text{ s}$$

Again, the factor of 2 has been applied for facing a solid bar.

It can be seen that, in this case, the conditions for minimum cost cannot be used because of power limitations and that a machining time of 18.6 s is required. Now we can apply the factor given by Equation 7.45 to allow tool costs.

For carbide tools the Taylor tool-life index is approximately 0.25, and since the ratio t_{mc}/t_{mp} is 8.5/18.6, or 0.46, the correction factor is

$$\left\{1 + [0.25/(1-0.25)](0.46)^{(1/0.25)}\right\} = 1.01$$

and the corrected machining time is 18.6 (1.01), or approximately 18.9 s.

In this example, the correction factor for tool costs is quite small, because cutting speeds below those giving minimum costs are being employed. If optimum speeds could be used, the correction factor would be 1.33 and the corrected machining time would be 11.2 s.

Finally, in Figure 7.48, data are presented on the typical cost of various machine tools, where it can be seen that, for the present example of a CNC lathe, a cost of about $80,000 would be appropriate. Assuming that the total rate for the operator and the machine would be $30/h, or $0.0083/s, the machining cost for the facing operation would be $0,157.

Thus, using the approach described in this chapter, it is possible to estimate the cost of each machined feature on a component. For example, Figure 7.49 shows a turned component with the machining cost for each feature indicated. The small, nonconcentric hole and the keyway are relatively expensive features. This is because in order to machine them, the

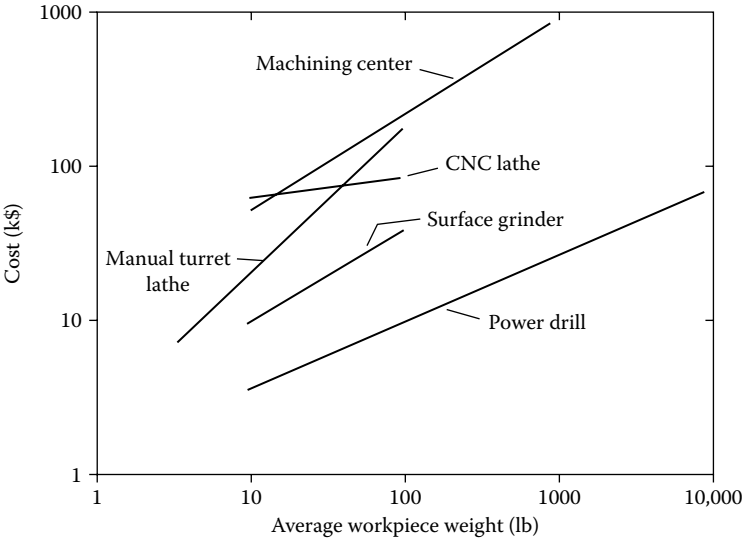


FIGURE 7.48
Relation between cost and workpiece weight for some machine tools.

component had to be loaded on separate machine tools—significantly increasing the non-productive costs. The designer who is able to make these estimates would clearly be encouraged to reconsider the securing operations that necessitated these features and therefore reduce the overall manufacturing costs of the product.

7.12.14 Machining Cost Estimating Worksheet

The various calculations required for estimating machining costs for turning and milling operations can be summarized in a worksheet as shown in Table 7.9. Each line on the

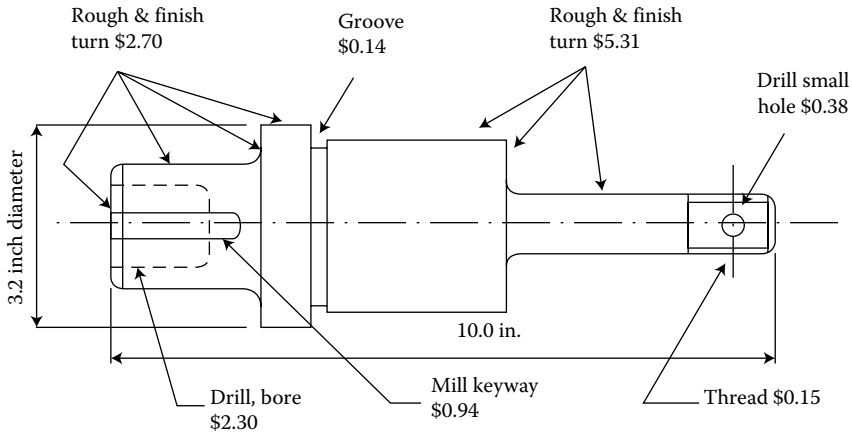


FIGURE 7.49
Turned component. Batch size, 1500; workpiece, 3.25 in. dia. × 10.25 in. long; material, low carbon free-machining steel.

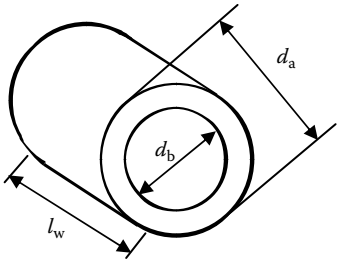
TABLE 7.9
Machining Cost Analysis Worksheet

Part name:																													
Material:																													
Density:																													
Workpiece weight:																													
Batch size (thousands):																													
Machine Tool	Operation	Tool Type (HCD)[a]	Setup Time Per batch (hr)	t_{su}	Load and Unload Time (s)	t_l	Tool Positioning Time (s)	t_{pt}	Dimension (in.)	l_w	Dimension (in.)	d_a	Dimension (in.)	d_b	Volume (in.^{3})	v_m	Specific Cutting Energy (hp min/in.^{3})	p_s	Available Power (hp)	P_m	Machining Time Max Power (s)	t_{mp}	Rate of Surface Generation (in.^{2}/min)	vf	Milling Feed Speed	v_f	Area (in.^{2})	A_m	Machining Time Recommended conditions (s)	t_{mc}	Time Corrected for Tool Wear (s)	t_m	Time Corrected for Extra Tool Travel (s)	t'_m
Totals							Total																										

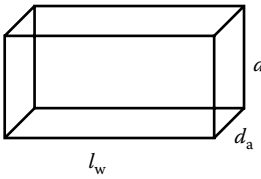
[a] H = high-speed steel, C = carbide (brazed), D = carbide disposable insert.

TABLE 7.10

Summary of Data and Calculations for Cost Estimation Worksheet



Operation	Area A_m	Volume V_m
Turn, thread	$\pi l_w d_b$	$\frac{\pi}{4} l_w (d_a^2 - d_b^2)$
bore, drill, tap, ream	$\pi l_w d_a$	
face, thread	$\frac{\pi}{2} d_a (d_a - d_b)$	$\frac{\pi}{2} l_w d_a (d_a - d_b)$



For milling:

$V_m = l_w d_a d_b$

$t_{mp} = 60\, p_s V_m / P_m$
$t_{mc} = 60\, A_m / f_v$ or $60\, l_w / v_f$

Variable	Source
Setup time, t_{su}	Table 7.4
Load/unload time, t_l	Table 7.3
Tool positioning time, t_{pt}	Table 7.4
Specific cutting energy, p_s	Tables 7.6 and 7.7
Power available, P_m	Figure 7.47
Rate of surface generation, vf	Table 7.6
Milling feed speed, v_f	Table 7.7
Machining time corrected for tool wear, t_m	Equations 7.42 and 7.45
Time corrected for approach allowance, t'_m	Factors from Table 7.6

worksheet is used for a specific cutting operation. The relevant tables and figures to be used for the required data are listed in Table 7.10. The following example illustrates the use of this worksheet for estimating the costs for a simple turning operation.

EXAMPLE

Figure 7.50 shows a stepped rotational part that requires a cylindrical rough turning operation followed by a finish turning operation for completion of the part. The various entries in the worksheet are shown in Table 7.11, assuming that a CNC turret lathe is used to produce the part. The workpiece is carbon steel bar 3.00 in. diameter and 5.00 in. long. From Table 13.10 the material density is 0.283 lb/in.^{3} and the material cost per unit weight is \$0.51/lb. The workpiece weight is therefore 10.052 lb and therefore the material cost per part is \$5.13.

From Figure 13.48, for the workpiece weight the estimated cost of the machine tool is \$80,000, and this gives with amortization and operator costs a machine rate of \$30.00/h.

The estimated setup time is 0.65 h and therefore the setup cost per part is

$$0.65 \times 30/1250 = \$0.016$$

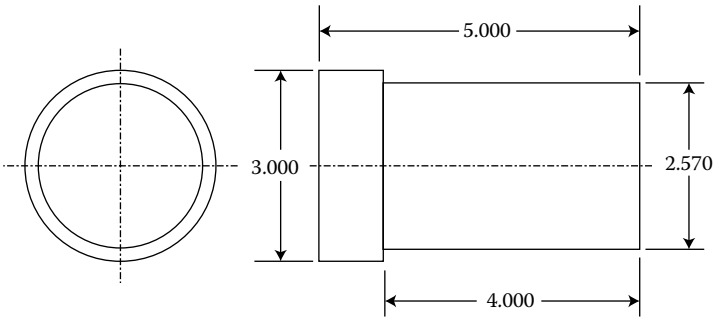
pjwstk|402064|1435559691

TABLE 7.11

Machining Cost Analysis Worksheet for steepped shaft (Figure 7.50)

Part name:																		
Material:																		
Density:																		
Workpiece Weight:																		
Batch size (thousands):		**Tool Type (HCD)**[a]	**Setup Time Per batch (hr)**	**Load and Unload Time (s)**	**Tool Positioning Time (s)**	**Dimension (in.)**	**Dimension(in.)**	**Dimension (in.)**	**Volume (in.^{3})**	**Specific Cutting Energy (hp min/in.^{3})**	**Available Power (hp)**	**Machining Time Max Power (s)**	**Rate of Surface Generation (in.^{2}/min)**	**Milling Feed Speed**	**Area(in.^{2})**	**Machining Time Recommended conditions (s)**	**Time Corrected for Tool Wear (s)**	**Time Corrected for Extra Tool Travel (s)**
Machine Tool	**Operation**		t_{su}	t_l	t_{pt}	l_w	d_a	d_b	v_m	p_s	P_m	t_{mp}	vf	v_f	A_m	t_{mc}	t_m	t'_m
CNC lathe	Rough turn	D	0.65	31.9	1.5	4	3	2.60	7.04	1.1	8	58	117	–	32.67	16.75	58.13	63.53
	Finish turn	D			1.5	4	2.60	2.57	0.05	1.1	8	0.4	70.2	–	32.30	27.6	36.7	42.1
Totals			0.65	31.9	3	Total												105.63

[a] H = high-speed steel, C = carbide (brazed), D = carbide disposable insert.



Workpiece: Carbon steel, 5.000 × 3.000 diameter

FIGURE 7.50
Simple stepped rotational part for cost estimating example.

The nonproductive time for workpiece loading and tool positioning is 31.9 + 3 = 34.9 s. Therefore, the nonproductive costs per part are

$$34.9 \times 30/3600 = \$0.29$$

The total machining time including allowances for tool wear and tool approach is 105.63 s from the worksheet. Therefore, the machining cost is

$$30 \times 105.63/3600 = \$0.88$$

Therefore, the total cost of the part is

$$\$5.13 + \$0.016 + \$0.29 + \$0.88 = \$6.316.$$

7.12.15 Approximate Cost Models for Machined Components

During the initial conceptual stages, the designer or design team considers a variety of solutions to the design problem. Selection of the most promising design may involve trade-offs between the cost of machined components and components manufactured by other methods. However, the designer or design team would not be in a position to specify all the details necessary to complete the type of analysis presented in the previous section. In fact, the information in the early stages of design may consist only of the approximate dimensions of the component, the material, and knowledge of its main features. Surprisingly, it is possible to obtain fairly accurate estimates of the cost of a component based on a limited amount of information. These estimates depend on historical data regarding the types of features usually found in machined components and the amount of machining typically carried out.

As an example, we can consider a rotational component machined on a CNC turret lathe. In a study of the turning requirements for British industry [5], it was found that the average ratio of the weight of metal removed to initial workpiece weight was 0.62 for light engineering. Also, in light engineering, only 2% of workpieces weighed over 60 lb (27 kg) and therefore required lifting facilities, and 75% of the workpieces were turned from bar. Usually, the proportion of initial volume of material removed by internal machining is relatively small for geometrical reasons.

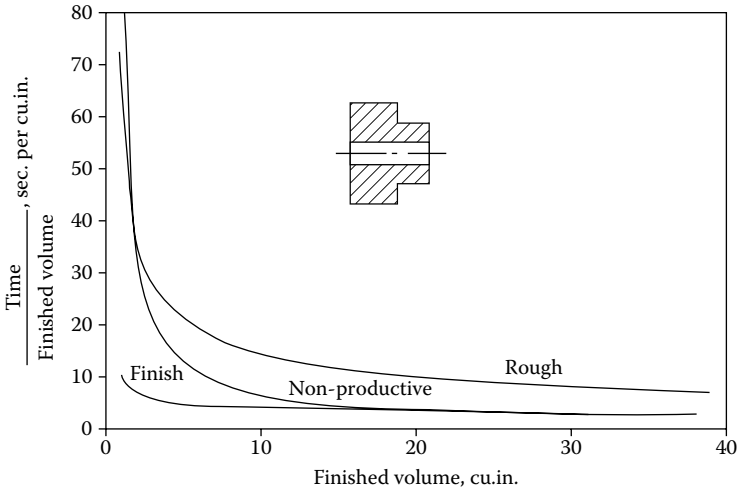


FIGURE 7.51
Effect of component size on rough machining, finish machining, and nonproductive times per unit volume.

The British survey [5] also showed a direct correlation between the length-to-diameter ratio and the diameter of turned components.

Using this type of data, Figure 7.51 shows, for a low-carbon-steel turned component, the effect of the finished size of the component on the rough machining, finish machining, and nonproductive times per unit volume. It can be seen that, as the size of the component is reduced below about 5 in.^{3} (82 μm^3), the time per unit volume and hence the cost per unit volume increases dramatically—particularly for the nonproductive time. This increase is to be expected for the nonproductive time, because it does not reduce in proportion to the weight of the component. For example, even if the component size were reduced to almost zero, it would still take a finite time to place it in the machine, to make speed and feed settings, and to start the cutting operations. For the rough-machining time, the higher times per unit volume for small components are a result of the reduced power available with the smaller machines used. The finish-machining time is proportional to the area machined. It can be shown that the surface area per unit volume (or weight) is higher for smaller components—thus leading to higher finish-machining times per unit volume.

These results have not taken into account the cost of the work material, and Figure 7.52 shows how the total cost of a finished steel component varies with component size. This total cost is broken down into material cost and machining cost, and it can be seen that material cost is the most important factor contributing to the total cost even though 62% of the original workpiece was removed by machining—a figure that results in relatively high rough-machining costs. In fact, for the larger parts, about 80% of the total cost is attributable to material costs.

From the results of applying the approximate cost models it is possible to make the following observations.

1. For medium-sized and large workpieces, the cost of the original workpiece mainly determines the total manufactured cost of the finished component.
2. The cost per unit volume or per unit weight of small components (less than about 5 in.^{3} or 82 μm^3) increases rapidly as size is reduced because:

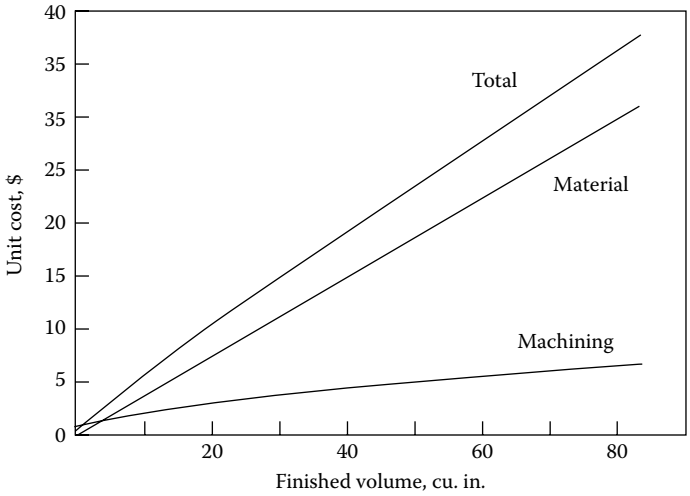
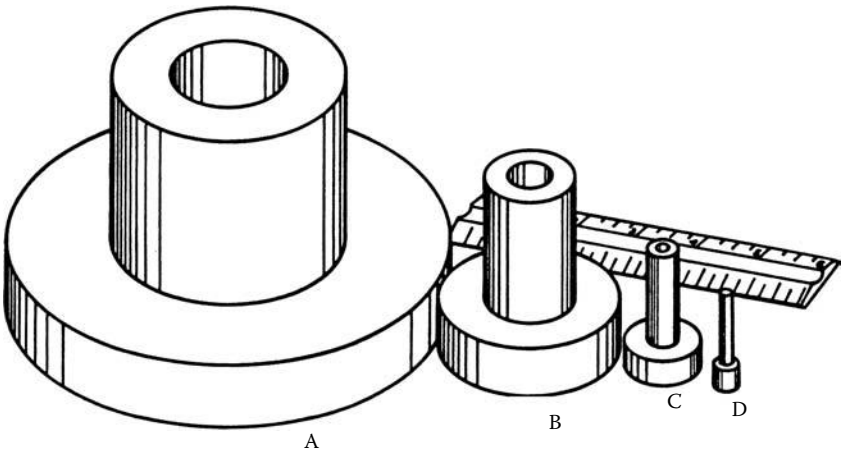


FIGURE 7.52
Effect of component size on total cost for machining a free-machining steel workpiece (cost 50 cents/lb) with an inserted carbide tool.

a. The nonproductive times do not reduce in proportion to the smaller component size.
b. The power available and hence the metal removal rate is lower for components.
c. The surface area per unit volume to be finish-machined is higher for smaller components.

This is illustrated in Figure 7.53, where a series of turned components are shown, each being one-tenth the volume of the previous component. Although the cost per unit volume for the material is the same for all the components, the machining cost per unit volume increases rapidly as the components become smaller. For example, the total cost of the smallest component is \$4.00/in.^{3}, whereas for the largest it is \$0.55/in.^{3} Stated another way, it would clearly be much less expensive to machine one of the largest components rather than 1000 of the smallest components when using the same types of machines.

3. The choice of tool materials and optimum machining conditions only affects the finish-machining time. Since finish machining represents only about 25% of the total manufacturing cost, which in turn represents only about 20% of the total component cost for larger components, the effects of changes in tool materials or recommended conditions can be quite small under many conditions.
4. The factors to be taken into account in making early estimates of machining costs are:
   a. The amount of material to be removed. This factor directly affects the material costs per unit volume of the finished product and, less importantly, the rough-machining time.
   b. The rate for the machine tool and operator.
   c. The power available for machining and the specific cutting energy of the work material.



	A	B	C	D
Volume of finished part (in.^{3})	40.00	4.00	0.40	0.04
Material cost/in.^{3} of finished part	0.44	0.44	0.44	0.44
Manufacturing cost/in.^{3}	0.11	0.35	1.32	3.56
Total cost/in.^{3} of finished part	0.55	0.79	1.76	4.00

FIGURE 7.53
Costs (dollars) for a series of turned components.

d. The nonproductive times—especially for smaller components.
e. The surface area to be finish machined.
f. The recommended finish-machining conditions, which are in turn affected by the work material and tool material used.

5. The factors that affect the nonproductive times are:
   a. The number of times the component must be clamped in a machine tool—each clamping involves transportation, loading and unloading, and setup.
   b. The number of separate tool operations required—each operation requires tool indexing, and other associated activities and increases setup costs.

It was found in previous studies [6] that common workpieces can be classified into seven basic categories. Knowledge of the workpiece classification and the production data not only allows the cost of the workpiece to be estimated, but also allows predictions to be made of the probable magnitudes of the remaining items necessary for estimates of nonproductive costs and machining costs.

For example, for the workpiece shown in Figure 7.49, the total cost of the finished component was estimated to be $24.32, a figure obtained from knowledge of the work material, its general shape classification and size, and its cost per unit volume. A cost estimate for this component, based on its actual machined features and using approximate Equations based on the type of data listed above, gave a total cost of $22.83 which is within 6%. A more detailed estimate obtained using the traditional cost-estimating methods presented

in this chapter gave a total cost of $22.95. Thus, approximate methods, using the minimum of information, can give estimates surprisingly close to the results of analysis carried out after detailed design has taken place.

PROBLEMS

1. Two thousand bars 80 mm in diameter and 300 mm long must he turned down to 65 mm diameter for 150 mm of their length. The surface-finish and accuracy requirements are such that a heavy roughing cut (removing most of the material) followed by a light-finishing cut are needed. The roughing cut is to be taken at maximum power. The light-finishing cut is to be taken at a feed of 0.13 mm, a cutting speed of 1.5 m/s, and at maximum power.
   If the lathe has a 2-kW motor and an efficiency of 50%, calculate the total production time in kiloseconds (ks) for the batch of work. Assume that the specific cutting energy for the work material is 2.73 GJ/m^3, the time taken to return the tool to the beginning of the cut is 15 s, and the time taken to load and unload a workpiece is 120 s.
2. A workpiece in the form of a bar 100 mm in diameter is to be turned down to 70 mm diameter for 50 mm of its length. A roughing cut using maximum power and a depth of cut of 12 mm is to be followed by a finishing cut using a feed of 0.1 mm and a cutting speed of 1.5 m/s.
   It takes 20 s to load and unload the workpiece and 30 s to set the cutting conditions, and set the tool at the beginning of the cut and engage the feed.
   The specific cutting energy for the material is 2.3 GJ/m^3 and the lathe has a 3-kW motor and 70% efficiency. Estimate:
   a. The machining time for the rough cut
   b. The machining time for the finish cut
   c. The total production time for each workpiece
3. A 1.5-m-diameter disc with a 600-mm-diameter hole in the center is to be faced, starting at the outside, on a vertical-boring machine. The rotational frequency of the table is 0.5 s^{-1}, the feed is 0.25 mm, and the back engagement (depth of cut) is 6 mm. The specific cutting energy for the work material and the particular cutting conditions is 3.5 GJ/m. Calculate
   a. The machining time, in kiloseconds
   b. The power consumption (in kW) at the beginning of the operation
   c. The power consumption just before the end of the operation
4. In a drilling operation using a twist drill, the rotational frequency of a drill is 5 s^{-1}, the feed 0.25 mm, the major cutting-edge angle 60 deg, and the drill diameter 12 mm. Assuming that the specific cutting energy for the work material is 2 GJ/m^3, calculate
   a. The maximum metal removal rate
   b. The undeformed chip thickness
   c. The drill torque, in Newton-meters (N-m)
5. In a slab-milling operation, the width of the medium carbon steel workpiece is 75 mm, its length is 200 mm, and a 5-mm layer is to be removed in one pass.
   a. What feed speed (mm/s) could be used if the power available for cutting is 3 kW and the specific cutting energy for the work material is 3.6 GJ/m^3?
   b. If the cutter diameter is 100 mm and the ideal surface roughness is 1.5 micrometers (μm), what should be the rotational frequency of the cutter?
   c. What is the cutting speed'?
   d. What is the machining time?
6. In a slab-milling operation, the cutter has 20 teeth and is 100 mm in diameter. The rotational frequency of the cutter is 5 s^{-1}, the work-piece feed speed is 1.3 mm/s. the working engagement (depth of cut) is 6 mm. and the back engagement (width

of the workpiece) is 50 mm. The relationship between the maximum undeformed chip thickness $a_{c_{max}}$ and the specific cutting energy p_s in gigajoules per cubic meter (GJ/m^3), for the work material is

$$p_s = 1.4[1 + (25 \times 10^{-6}) / a_{c_{max}}]$$

Estimate

a. The maximum metal removal rate
b. The maximum power, in kilowatts (kW), required at the cutter

7. In a slab-milling operation, the length of the workpiece is 150 mm, its width is 50 mm, and a layer 10 mm in thickness is to be removed from its upper surface. The diameter of the cutter is 40 mm and it has 10 teeth. The workpiece is of medium carbon steel, the feed speed selected is 2 mm/s. and the cutter speed is 2.5 rev/s. The specific cutting energy of the material, p_s, is 4 GJ/m^3. Estimate:
   a. The power required (in kW)
   b. The machining time for the operation
8. In a face-milling operation the back engagement (depth of cut) is 5 mm, the work feed speed is 0.65 mm/s. and the working engagement (width of the workpiece) is 50 mm. The cutter has a diameter of 100 mm and has 20 teeth. If the cutting speed is to be 1 rn/s. calculate
   a. The rotational frequency of the cutter
   b. The maximum metal removal rate
   c. The time taken to machine 1000 workpieces of length 150 mm if it takes 180 s to load and unload a workpiece and return the cutter to the beginning of the cut
9. In a finish-surface-grinding operation on a horizontal-spindle surface grinder, the length of the workpiece is 100 mm and its width 50 mm. The cross-feed is applied every stroke of the worktable and is set at 0.25 mm, the back engagement (depth of cut) is 0.1 mm. and the maximum traverse speed is 250 mm/s. The frequency of worktable reciprocation is 1^{-1}. Calculate:
   a. The machining time
   b. The maximum metal removal rate
   c. The maximum power consumption in watts (W) if the specific cutting energy for the conditions employed is 25 GJ/m^3
   d. The maximum tangential force on the grinding wheel if its diameter is 150 mm and has a rotational frequency of 60 s^{-1}.
11. A batch of 10,000 rectangular blocks $50 \times 25 \times 25$ mm is to be slab-milled on all faces. The material can be either mild steel costing \$4900/m^3 or aluminum costing \$6100/m^3. Estimate the total cost of the batch of components in each material if the average nonproductive time for each face = 60 s, the tool-changing time = 600 s, the cost of a sharp tool = \$20.00, the machine and operator rate = \$0.01/s, the tool-life index $n = 0.125$, the cutting speed for 60 s of tool life is 1 m/s for mild steel and 4 m/s for aluminum, the feed per revolution of the cutter = 1.25 mm, and the working engagement (depth of cut) = 2 mm. (Assume that the distance traveled by the 50-mm-diameter, 38-mm-wide cutter for each face of the workpiece is 5 mm greater than the length of the face.)
12. Aluminum rod is available in diameters of 1-mm increments to 25-mm diameter and in 2-mm increments from 26- to 50-mm diameter. In the design of a particular shaft, it has been determined that its finished diameter D should be within the range

$$33 - \frac{(L - 229)^2}{84.75} > D > 27.43 + \frac{(L - 254)^2}{127}$$

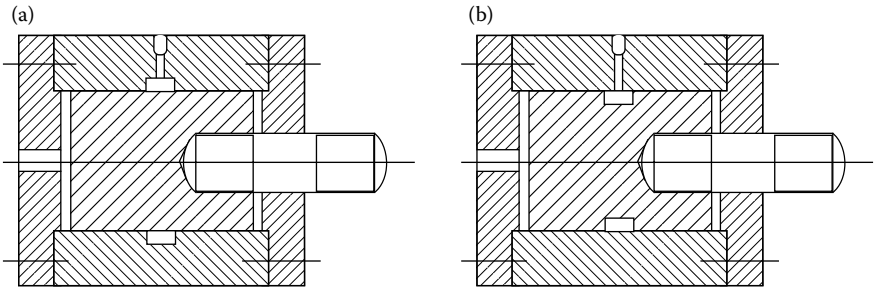


FIGURE 7.54
Alternative cylinder assembly designs.

where L is the length of the shaft. If an allowance of 2 mm in diameter is to be allowed for machining, what finished diameter should be chosen for the shaft?

13. Which of the two designs for a cylinder assembly shown in Figure 7.54 would be preferable from the manufacturer's point of view? Also, list other manufacturing and assembly aspects of both designs that could be improved. (Note that the omission of details of the bolting arrangements for the cylinder ends is not to be considered an error.)
14. The end covers shown in Figure 7.55 are to be milled from 10-mm-thick aluminum plate. Which of these two designs is preferable from the manufacturer's point of view? Also, what other aspects of the designs should be changed?
15. A designer has specified a surface finish on turned shafts of 0.4-pm arithmetical mean when a surface finish of 1.6 pm would suffice. Estimate the cost of this mistake when 2000 shafts are to be produced with a tool with a rounded corner if the machining time per component = 600 s, the number of components produced between tool regrinds = 4, the cost of a sharp tool = \$2.00, the machine and operator rate = \$00033/s, the tool-changing time = 120 s, and the nonproductive time per component = 240 s.
16. The part shown in Figure 7.56 is to be produced on a CNC turret lathe from free machining low carbon steel. Using the worksheet in Table 7.9 and the data in this Chapter, estimate the processing time and costs for machining a batch of 500 parts. Assume that 0.015 in. of material is faced off from the end of the part

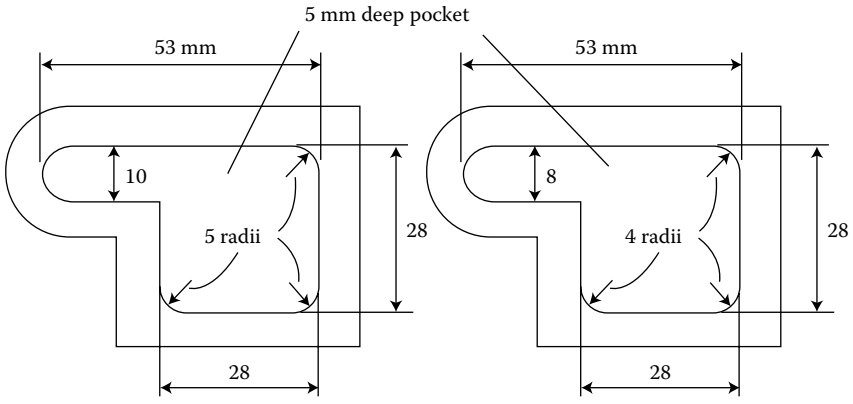


FIGURE 7.55
Alternative milled end cover designs.

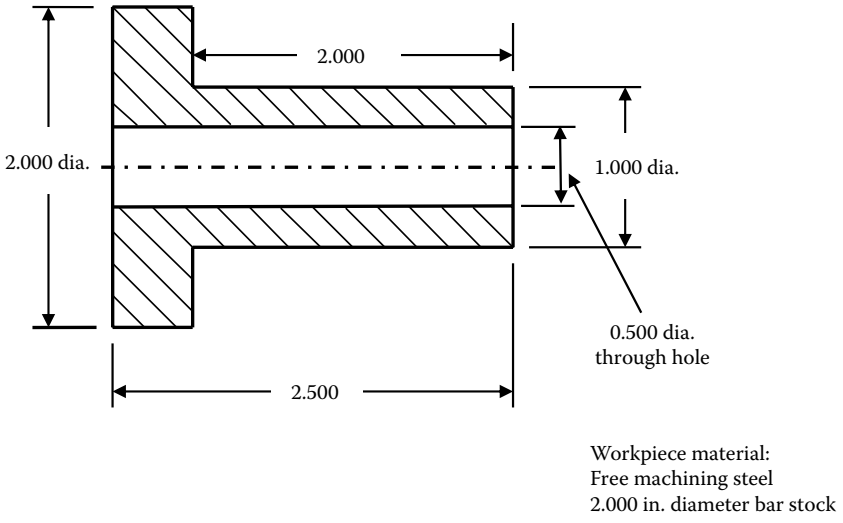


FIGURE 7.56
Mild steel turned part. *Note:* Dimensions in inches.

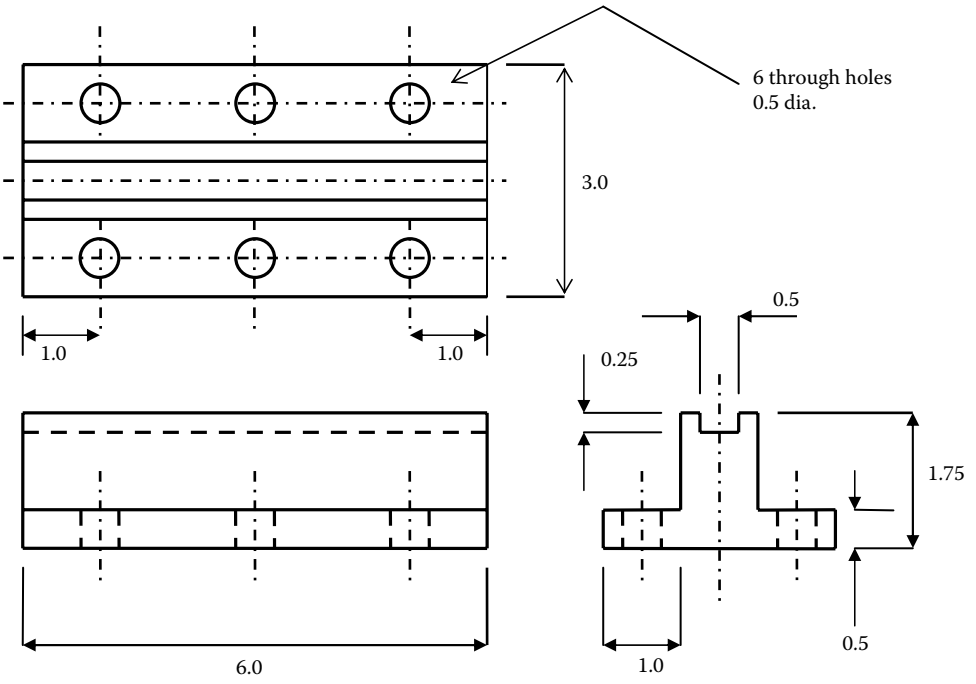


FIGURE 7.57
Aluminum alloy part produced on a small machining center. *Note:* Dimensions in inches; Material: alluminium alloy; Bactch size: 200.

prior to drilling the through hole. The center drilling operation prior to drilling the through-hole can be assumed to have a machining time of 5 s. The turning tool has a disposable carbide insert and the drill is made from high-speed steel.

17. The aluminum alloy part shown in Figure 7.57 is to be produced on a small machining center from a piece of bright drawn rectangular bar of cross-section 3 in. × 2 in. The machining operations required are as follows:
    a. Finish face mill the top surface to reduce the part height to 1.75 in. with a brazed carbide face milling cutter.
    b. Rough and finish the two 1 in. × 1.25 in. steps in the parts with a high-speed steel end milling cutter.
    c. Finish mill the 0.5 in. × 0.25 in. in the top surface of the part with a high-speed end milling cutter.
    d. Drill six 0.5 in. diameter holes with a high-speed steel drill.

    Using the worksheet in Figure 7.9 and the data in this chapter, estimate the processing time and costs for a batch of 200 parts.

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8

Design for Injection Molding

8.1 Introduction

Injection molding technology is a method of processing predominantly used for thermoplastic polymers [1,2]. It consists of heating thermoplastic material until it melts, then forcing this melted plastic into a steel mold, where it cools and solidifies. The increasingly sophisticated use of injection molding is one of the principal tools in the battle to produce elegant product structures with reduced part counts and the simplicity of assembly. The pioneering product development in this context was the Proprinter developed by IBM as the domestic competitor to the Japanese personal printers. Plastic components in the Proprinter incorporated the functions of cantilever springs, bearings, support brackets, alignment, and locating features into single snap-fit components. The result of this integration of features into single complex parts was a reduction of part count from 152 to 32, with a corresponding reduction of assembly time from 30 to 3 min [3], when compared with the Epson printer which IBM had previously been remarketing from Japan. This set the stage for a revolution in the manufacture of consumer products which continues even today.

In order to exploit the versatility of injection molding technology for economical manufacture, it is necessary to understand the basic mechanisms of the process and related aspects of the molding equipment and materials used. Also, since injection molding is a process that utilizes expensive tooling and equipment; it is vital to be able to obtain part and tooling cost estimates at the earliest stages of design. Only in this way can the design team be sure that the choice of the process is correct and that maximum economic advantage will be obtained from the process. For these reasons, this chapter first presents a review of injection molding materials and the injection molding process followed by the description of a procedure for estimating the cost of injection molded parts, which is applicable to the early phase of product design.

8.2 Injection Molding Materials

It is not possible to injection-mold all polymers. Some polymers, such as PTFE (polytetrafluoro ethylene), cannot be made to flow freely enough to make them suitable for injection molding. Other polymers, such as a mixture of resin and glass fiber in woven or mat form, are unsuitable by their physical nature for use in the process. In general, polymers that are capable of being brought to a state of fluidity can be injection-molded. These include both plain polymers and those reinforced with mineral particles or short random fibers of glass or carbon.

The vast majority of injection molding is applied to thermoplastic polymers. This class of materials consists of polymers that always remain capable of being softened by heat and hardening on cooling, even after repeated cycling. This is because the long-chain molecules always remain separate entities and do not form chemical bonds with one another. An analogy can be made to a block of ice that can be softened (i.e., turned back to liquid), poured into any shape cavity, and then cooled to become a solid again. This property differentiates thermoplastic materials from thermosetting ones. In the latter type of polymer, chemical bonds are formed between the separate molecule chains during processing. This chemical bonding, referred to as cross-linking, is the hardening mechanism. Thermosetting polymers are generally more expensive to mold than thermoplastics and represent only about 5% of plastics processing. In this chapter, we concentrate exclusively on the injection molding of thermoplastics.

In general, most thermoplastic materials offer good impact strength, corrosion resistance, and easy processing with good flow characteristics for molding complex designs. Thermoplastics are generally divided into two classes: crystalline and amorphous. Crystalline polymers have an ordered molecular arrangement, with a sharp melting point. Because of the ordered arrangement of molecules, the crystalline polymers reflect most incident light and generally appear opaque. They also undergo a high shrinkage or reduction in volume during solidification. Crystalline polymers are usually more resistant to organic solvents and have good fatigue and wear-resistance properties. Crystalline polymers are also generally denser and have better mechanical properties than amorphous polymers. The main exception to this rule is polycarbonate, which is the amorphous polymer of choice for high-quality transparent moldings and has excellent mechanical properties.

The mechanical properties of thermoplastics, while substantially lower than those of metals, can be enhanced for some applications by adding glass or carbon fiber reinforcement. This takes the form of short-chopped fibers, a few millimeters in length, which are randomly mixed with the thermoplastic resin. The fibers can occupy up to one-third of the material volume to considerably improve the material strength and stiffness. The negative effect of this reinforcement is usually a decrease in impact strength and an increase in abrasiveness. The latter also has an effect on processing, since the life of the mold cavity is typically reduced from about 1,000,000 cycles for plain resin parts to about 300,000 for glass-filled parts.

Perhaps, the main weakness of injection-molded parts is the relatively low service temperatures to which they can be subjected. Thermoplastic components can only rarely be operated continuously above 250°C, with an absolute upper service temperature of about 400°C. The temperature at which a thermoplastic can be operated under load can be defined qualitatively by the heat deflection temperature. This is the temperature at which a simply supported beam specimen of the material, with a centrally applied load, reaches a predefined deflection. The temperature value obviously depends upon the conditions of the test and the allowed deflection, and for this reason, the test values are only really useful for comparing different polymers.

Table 8.1 lists the more commonly molded thermoplastics together with typical mechanical property values.

8.3 Molding Cycle

The injection molding process cycle for thermoplastics consists of three major stages, as shown in Figure 8.1: (1) injection or filling, (2) cooling, and (3) ejection and resetting. During

TABLE 8.1

Commonly Used Polymers in Injection Molding

Thermoplastic	Yield Strength (MN/m^2)	Elastic Modulus (MN/m^2)	Heat Deflection Temperature (°C)	Cost[a] ($/kg)
High-density polyethylene	23	925	42	0.90
High-impact polystyrene	20	1900	77	1.12
Acrylonitrile–butadiene–styrene (ABS)	41	2100	99	2.93
Acetal (homopolymer)	66	2800	115	3.01
Polyamide (6/6 nylon)	70	2800	93	4.00
Polycarbonate	64	2300	130	4.36
Polycarbonate (30% glass)	90	5500	143	5.54
Modified polyphenylene oxide (PPO)	58	2200	123	2.75
Modified PPO (30% glass)	58	3800	134	4.84
Polypropylene (40% talc)	32	3300	88	1.17
Polyethylene terephthalate (30% glass)	113	7500	227	3.74

[a] Material costs are subjected to constant change and are strongly influenced by the quantity of purchase—text values are intended for design comparison exercises only.

the first stage of the process cycle, the material in the molten state is a highly nonlinear viscous fluid. It flows through the complex mold passages and is subject to rapid cooling from the mold wall on one hand, and internal shear heating on the other. The polymer melt then undergoes solidification inside the cooled mold, under the high packing and holding pressure of the injection system. Finally, the mold is opened, the part is ejected, and the machine is reset for the next cycle to begin.

8.3.1 Injection or Filling Stage

The injection stage consists of the forward stroke of the plunger or screw injection unit to facilitate the flow of molten material from the heating cylinder through the nozzle and into the mold. The amount of material to be transferred into the mold is referred to as the shot.

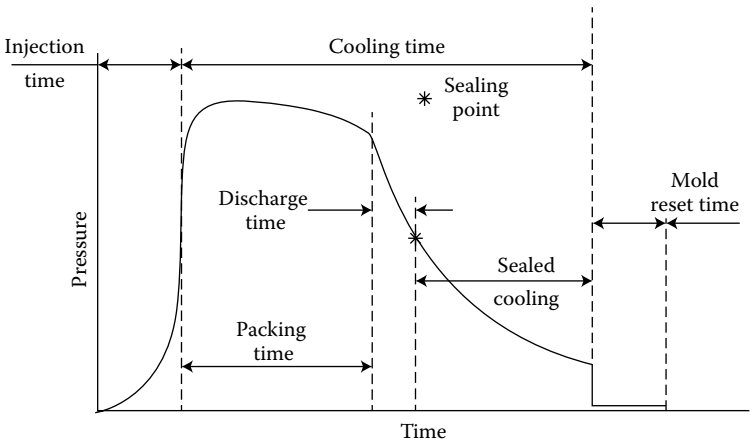

FIGURE 8.1
Injection molding cycle.

The injection stage is accompanied by a gradual increase in pressure. As soon as the cavity is filled, the pressure increases rapidly, and packing occurs. During the packing part of the injection stage, the flow of material continues, at a slower rate, to account for any loss in volume of the material due to partial solidification and associated shrinkage. The packing time depends on the properties of the materials being molded. After packing, the injection plunger is withdrawn or the screw is retracted and the pressure in the mold cavity begins to drop. At this stage, the next charge of material is fed into the heating cylinder in preparation for the next shot.

8.3.2 Cooling or Freezing Stage

Cooling starts from the first rapid filling of the cavity and continues during packing and then following the withdrawal of the plunger or screw, with the resulting removal of pressure from the mold and nozzle area. At the point of pressure removal, the restriction between the mold cavity and the channel conveying material to the cavity, referred to as the gate of the mold, may still be relatively fluid, especially on thick parts with large gates. Because of the pressure drop, there is a chance for a reverse flow of the material from the mold until the material adjacent to the gate solidifies and the sealing point is reached. Reverse flow is minimized by proper design of the gates such that quicker sealing action takes place upon plunger withdrawal [1,4].

Following the sealing point, there is a continuous drop in pressure as the material in the cavity continues to cool and solidifies in readiness for ejection. The length of the sealed cooling stage is a function of the wall thickness of the part, the material used, and the mold temperature. Because of the low thermal conductivity of polymers, the cooling time is typically the longest period in the molding cycle.

8.3.3 Ejection and Resetting Stage

During this stage, the mold is opened, the part is ejected, and the mold is then closed again in readiness for the next cycle to begin. Considerable amounts of power are required to move the often massively built molds, and mold opening and part ejection are usually executed by hydraulic or mechanical devices. Although it is economical to have quick opening and closing of the mold, rapid movements may cause undue strain on the equipment, and if the mold faces come into contact at speed, this can damage the edges of the cavities. Also, a relatively slow mold opening is required to avoid part damage during ejection, and a small time delay is needed for the part to drop clear of the mold. This latter time depends on the part dimensions, which determine the time taken for the part to fall free of moving parts between the machine platens. For parts to be molded with metal inserts, resetting involves the reloading of inserts into the mold. After resetting, the mold is closed and locked, thus completing one cycle.

8.4 Injection Molding Systems

An injection molding system consists of the machine and mold for converting, processing, and forming raw thermoplastic material, usually in the form of pellets, into a part of desired shape and configuration. Figure 8.2 shows a schematic view of a typical injection

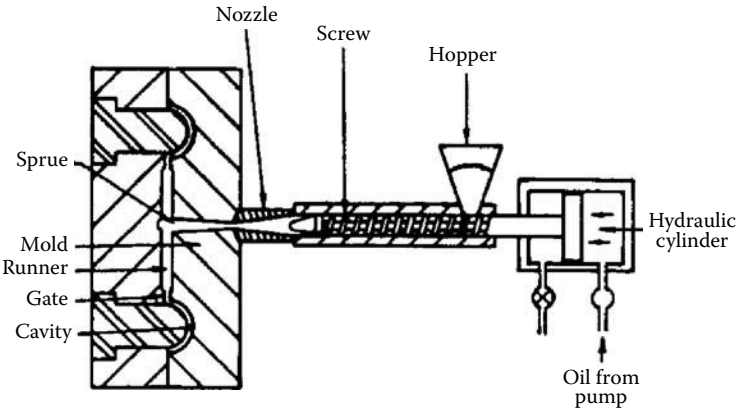

FIGURE 8.2
Injection molding system.

molding system. The major components of an injection molding system are the injection unit, the clamp unit, and the mold. These are described briefly in the following sections.

8.4.1 Injection Unit

The injection unit has two functions: to melt the pellets or powder, and to inject the melt into a mold. The most widely used types of injection units are (1) conventional units, consisting of a cylinder and a plunger that forces the molten plastic into the mold cavity, and (2) reciprocating screw units, consisting of a barrel or cylinder and a screw that rotates to melt and pump the plastic mix from the hopper to the end of the screw and then moves forward to push the melt into the mold.

Of the two types, reciprocating screw injection units are considered to be better designed because of their improved mixing action. The motion of the polymer melt along the screw flights helps to maintain a uniform melt temperature. It also facilitates a better blending of the materials and any coloring agents, resulting in the delivery of a more uniform melt to the mold. Because of these advantages, reciprocating screw units are found on the majority of modern injection molding machines.

The injection units are usually rated with two numbers: the first is the shot capacity, defined as the maximum volume of polymer that can be displaced by one forward stroke of the injection plunger or screw. It is usually recommended that an injection unit be selected so that the required shot sizes fall within 20–80% of the rated capacity.

The second rating number is the plasticating rate, which is the amount of material that can be plasticized or softened into a molten form by heating in the cylinder of the machine in a given time. This number is usually expressed as the number of pounds of polystyrene material that the equipment can heat to molding temperature in one hour. For further information on polymer processing requirements, consult Refs. [1,2] and [4–7].

8.4.2 Clamp Unit

The clamp unit has three functions: to open and close the mold halves, to eject the part, and to hold the mold closed with sufficient force to resist the melt pressure inside the mold as it is filled. The required holding force typically varies between 30 and

70 MN/m^2 of the projected area of the part (~2–5 ton/in.^{2}). The pressure developed in the mold during filling and packing, and the shrinkage of the part onto its cores, may cause the part to stick, thus making the separation of the two mold halves difficult. The magnitude of the initial opening force required depends on the packing pressure, material, and part geometry (depth and draft), and is approximately equal to 10–20% of the nominal clamp force [4,8].

There are two common types of clamp designs:

1. *Linkage or toggle clamp*: This design utilizes the mechanical advantage of a linkage to develop the force required to hold the mold during the injection of the material. Mechanical toggle clamps have very fast closing and opening actions and are lower in cost than alternative systems. The major disadvantage is that the clamp force is not precisely controlled, and for this reason the clamps are found only on smaller machines.
2. *Hydraulic clamp units*: These use hydraulic pressure to open and close the clamp and to develop the force required to hold the mold closed during the injection phase of the cycle. The advantages of this type of design are the long-term reliability and precise control of clamp force. The disadvantage is that hydraulic systems are relatively slow and expensive compared to toggle clamp systems.

After the mold halves have opened, the part that has a tendency to shrink and stick to the core of the mold (usually the half of the mold furthest from the injection unit) has to be ejected by means of an ejector system provided in the mold system of plates.

8.5 Injection Molds

Molds for injection molding are as varied in design, degree of complexity, and size as are the parts produced from them. The functions of a mold for thermoplastics are basically to impart the desired shape to the plasticized polymer and then to cool the molded part.

A mold is made up of two sets of components: (1) the cavities and cores, and (2) the base in which the cavities and cores are mounted. The size and weight of the molded parts limit the number of cavities in the mold and also determine the equipment capacity required. Considering the molding process, a mold has to be designed to safely absorb the forces of clamping, injection, and ejection. Also, the design of the gates and runners must allow efficient flow and uniform filling of the mold cavities.

8.5.1 Mold Construction and Operation

Figure 8.3 illustrates the parts in a typical injection mold. The mold basically consists of two parts: a stationary half (cavity plate), on the side where molten polymer is injected, and a moving half (core plate) on the closing or ejector side of the injection molding equipment. The separating line between the two mold halves is called the parting line. The injected material is transferred through a central feed channel, called the sprue. The sprue is located in the sprue bushing and is tapered to facilitate the release of the sprue material from the mold during mold opening. In multicavity molds, the sprue feeds the polymer melt to a runner system, which leads into each mold cavity through a gate.

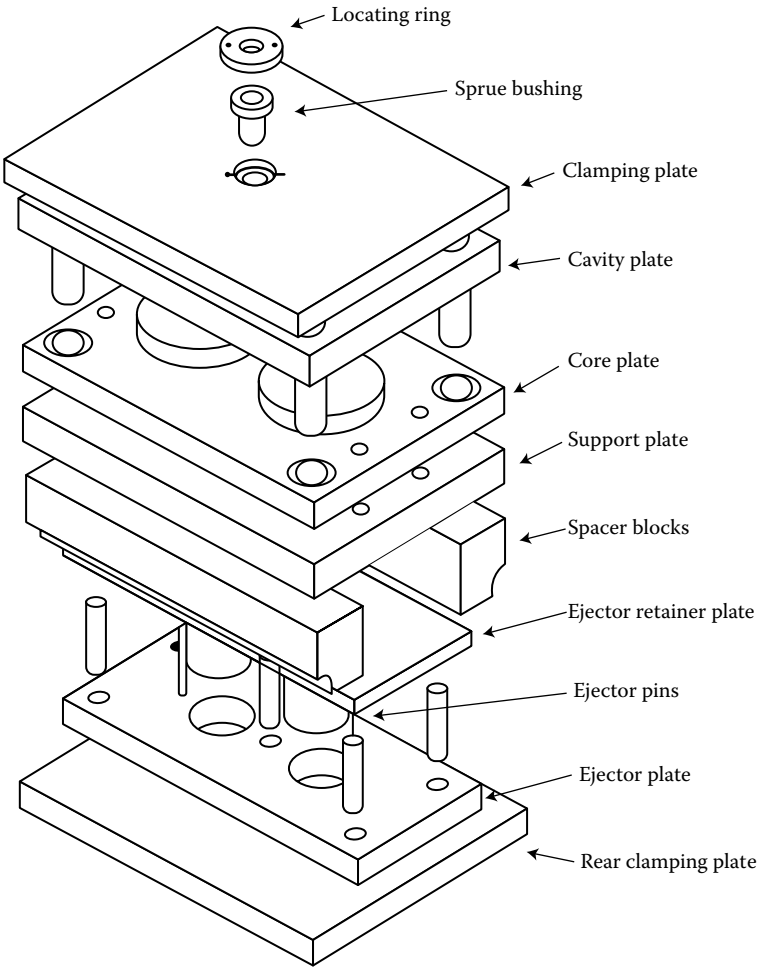

FIGURE 8.3
Injection mold.

The core plate holds the main core, or cores for multicavity molding. The purpose of the main core is to establish the inside configuration of the part. The core plate has a backup or support plate. The support plate is in turn supported by pillars against the U-shaped structure known as the ejector housing, which consists of the rear clamping plate and spacer blocks. This U-shaped structure, which is bolted to the core plate, provides the space for the ejection stroke also known as the stripper stroke. During solidification, the part shrinks around the main core so that when the mold opens, part and sprue are carried along with the moving mold half. Subsequently, the ejector plate, which carries the ejector pins, stops against the rear clamping plate. The core plate then continues to move outwards so that the ejector pins can push the part off the core.

Both mold halves are provided with cooling channels through which cooled water is circulated to absorb the heat delivered to the mold by the hot thermoplastic polymer melt, and then to cool the part to the required ejection temperature. The mold cavities also incorporate fine vents (0.02 to 0.08 mm $\times$ 5 mm) to ensure that no air is trapped during filling.

8.5.2 Mold Types

The most common types of molds used in industry today are (1) two-plate molds, (2) three-plate molds, (3) side-action molds, and (4) unscrewing molds.

A two-plate mold consists of two active plates (cavity and core plates in Figure 8.3) into which the cavity and core inserts are mounted, as shown in Figure 8.4. In this mold type, the runner system, sprue, runners, and gates solidify with the part being molded and are ejected as a single connected item. Thus, the operation of a two-plate mold usually requires continuous machine attendance. The machine operator must spend time separating the runner system from parts (which break easily at the narrow gates) and periodically shredding the runner systems into small pieces that can be reintroduced into the machine hopper. This task is accomplished in an ancillary piece of equipment that operates like a small wood chipper, and the chips are somewhat confusingly referred to as regrind.

The three-plate mold consists of: (1) the stationary or runner plate, which contains the sprue and half of the runner; (2) the middle or cavity plate, which contains the other half of the runner, the gates, and cavities and is allowed to float when the mold is open; and (3) the movable or core plate, which contains the cores and the ejector system. This type of mold design facilitates the separation of the runner system and the part when the mold opens; the two items usually fall into separate bins below the mold.

For very high rates of production, full automation can be achieved with a hot runner system, sometimes called a runnerless molding system. In this system, which also uses three main plates, the runner is completely contained in the fixed plate, which is heated and insulated from the rest of the cooled mold. The runner section of the mold is not opened during the molding cycle. The advantages of this design are that there are no side products (gates, runner, or sprues) to be disposed of or reused, and there is no need for the separation of the gate from the part. Also, it is possible to maintain a more uniform melt temperature.

Side-acting molds are used in molding components with external depressions or holes parallel to the parting plane. These features are sometimes referred to as undercuts or cross-features. These undercuts prevent the molded parts from being removed from the cavity in the axial direction and are said to create a die-locked situation. The usual way of providing the side action needed to release the part is with side cores mounted on slides. These are activated by angle pins, or by air or hydraulic cylinders that pull the side cores

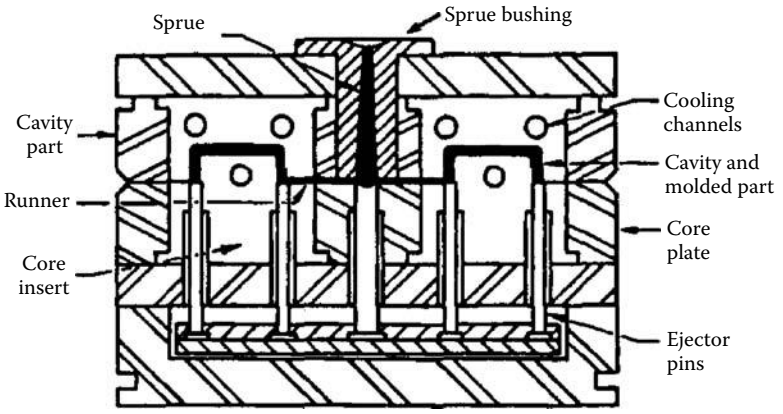

FIGURE 8.4
Two-plate injection mold.

outward during opening of the mold. Because of this action, the side core mechanisms are often referred to as side-pulls.

The mechanism of an angle-pin side action mold for a part with an undercut formed by a hole is illustrated in Figure 8.5. The slide, which carries the secondary side core pin, is moved by the angle pin mounted in the stationary half of the mold. As the two halves of the mold move apart during mold opening, the slide, which is mounted on the moving plate, is forced to move sideways by the angle of the pin. This allows the undercut to become free of the core pin, and the part can then be ejected. Note that side-pull is needed for each cross-feature or group of cross-features that lie on a particular axis. Molds have been built with as many as nine separate side-pulls to release particularly complex parts.

The mechanism for unscrewing molds is shown in Figure 8.6. The rack and pinion gear mechanism shown in the illustration is the most common method used to free the undercuts formed by internal or external threads. With this method, a gear rack moved by a hydraulic cylinder engages with a spur gear attached to the threaded core pin. The rotating action imparted to the core pin through the gear transmission thus frees the undercuts formed by the threads. This additional unscrewing mechanism increases the mold cost and mold maintenance cost to a great extent, but eliminates the need for a separate thread-cutting operation. Note that external thread forms with axes that lie on the molding plane can be separated from the mold without the need for an unscrewing device.

A final category of mold mechanisms is required to mold depressions or undercuts on the inside of plastic parts. The design of a part with internal die-locking features of this type requires the mold maker to build the core pin retraction device within the main core. This is clearly much more difficult and expensive to manufacture than a corresponding side-pull outside the cavity. In the latter case, adequate plate area can readily be provided for the machining of slideways. For this reason, the need for internal core retraction mechanisms,

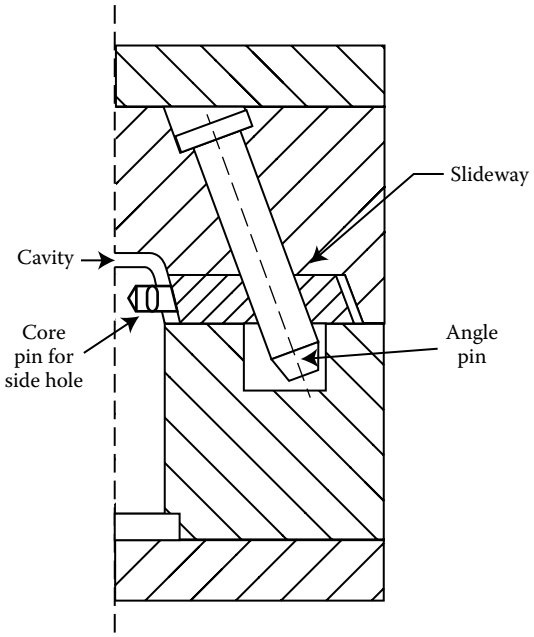

FIGURE 8.5
Angle-pin-activated side-pull.

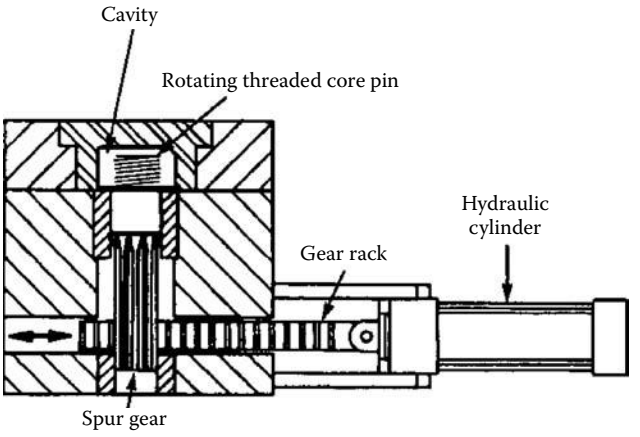

FIGURE 8.6
Unscrewing mold.

called lifters by mold makers, should be avoided whenever possible. The obvious way to do this is to replace internal depressions with either external ones or through holes.

The injection molding process can handle unusual shapes because many different types of gates, ejection systems, and mold movement mechanisms can be combined into one mold. The resulting mold may be highly complex and often extremely expensive to both build and maintain. However, the general rule for efficient manufacture is to incorporate as many features as possible into a single molded part, provided, of course, that the required number of parts to be produced is sufficiently large to justify the mold costs.

8.5.3 Sprue, Runner, and Gates

A complete runner system connecting the sprue and the mold cavities is shown in Figure 8.4. The sprue bushing acts as an inlet channel for molten material from the heating chamber into the mold or runner system. The solid material in the form of a carrot called the "sprue" acts as a transition from the hot molten thermoplastic in the chamber to the relatively cooler mold. Runner systems are used in multiple cavity molds and act as channels to connect the sprue bush to the cavity gates. The gate, a constriction between the feed system and the mold cavity, serves several purposes. It freezes rapidly and prevents materials from flowing out of the cavity when the injection pressure is removed. It provides an easy way of separating moldings from the runner system. It also suddenly increases the rate at which the polymer is sheared, which helps to align the polymer chains for more effective cavity filling.

In multiple-cavity molds, great care is taken to balance the runner system in order to produce identical parts. Different-length runners of the same cross-sectional area would result in different cavity pressures with resulting size and density variations among the multicavity parts.

8.6 Molding Machine Size

Determination of the appropriate size of an injection molding machine is primarily based on the required clamp force. This in turn depends upon the projected area of the cavities

TABLE 8.2

Runner Volumes (Du Pont)

Part Volume (cm^3)	Shot Size (cm^3)	Runner %
16	22	37
32	41	28
64	76	19
128	146	14
256	282	10
512	548	7
1024	1075	5

in the mold and the pressure in the mold during mold filling. The former parameter is the projected area of the part, or parts if a multicavity mold is used, and runner system, when viewed in the direction of the mold opening, that is, the area projected onto the surface of the mold cavity plate. The value for this parameter should not include any through-holes molded in the direction of the mold opening. Thus, for a 15 cm diameter plain disk, the projected area is 176.7 cm^2. However, if the disk has a single 10 cm diameter through-hole in any position, the projected area is 98.2 cm^2 since this is the area over which the polymer pressure acts during filling.

The size of the runner system depends upon the size of the part. Typical runner volumes as a percentage of the part volume are shown in Table 8.2. As a first approximation, these figures are also applied to give the projected area of the runner system as a percentage of the projected area of the part. Note, however, this is strictly correct only if a part is flat and if the runner system is of the same thickness as the part.

Estimation of polymer pressure in the cavity during mold filling is a much more difficult problem. The flow characteristics of polymers are highly nonlinear, and models for mold filling can only be analyzed for individual runner and cavity geometries through the use of computer-intensive finite-element procedures, which in turn require a complete solid model of the mold cavities and runner system. However, it appears that as a general rule, approximately 50% of the pressure generated in the machine injection unit is lost because of the flow resistance in the sprue, runner systems, and gates [9,10]. This rule is applied in machine selection as illustrated in the example below.

EXAMPLE

A batch of 15 cm diameter disks with a thickness of 4 mm are to be molded from acrylonitrile–butadiene–styrene (ABS) in a six-cavity mold. Determine the appropriate machine size:

1. The projected area of each part equals 177 cm^2 and the part volume is 71 cm^3. From Table 8.2, the percentage increase in shot volume, and the increase in the projected area due to the runner system is approximately 15%. Thus, the total projected shot area of the six cavities and associated runner system is $6 \times 1.15 \times 177 = 1221.3$ cm^2
2. The recommended injection pressure for ABS from Table 8.3 is 1000 bars. Thus, the maximum cavity pressure is likely to be 500 bars, or 500×10^5 N/m^2.
3. The estimate of maximum separating force F is thus given by

$$F = (1221.3 \times 10^{-4}) \times 500 \times 10^5 N = 6106.5 \text{ kN}$$

If the available machines are those listed in Table 8.4, then the appropriate machine would be the one with a maximum clamp force of 8500 kN.

TABLE 8.3

Processing Data for Selected Polymers

Thermoplastic	Specific Gravity (g/cm^3)	Thermal Diffusivity (mm^2/s)	Injection Temp. (°C)	Mold Temp. (°C)	Ejection Temp. (°C)	Injection Pressure (bars)
High-density polyethylene	0.95	0.11	232	27	52	965
High-impact polystyrene	1.59	0.09	218	27	77	965
Acrylonitrile–butadiene–styrene (ABS)	1.05	0.13	260	54	82	1000
Acetal (homopolymer)	1.42	0.09	216	93	129	1172
Polyamide (6/6 nylon)	1.13	0.10	291	91	129	1103
Polycarbonate	1.20	0.13	302	91	127	1172
Polycarbonate (30% glass)	1.43	0.13	329	102	141	1310
Polycarbonate ABS blend (30% glass)	1.37	0.13	315	90	126	1252
Modified polyphenylene oxide (PPO)	1.06	0.12	232	82	102	1034
Modified PPO (30% glass)	1.27	0.14	232	91	121	1034
Polypropylene (40% talc)	1.22	0.08	218	38	88	965
Polyester teraphthalate (30% glass)	1.56	0.17	293	104	143	1172

This machine must be checked to ensure that it has a large enough shot size and clamp stroke. The required shot size is the volume of the six disks plus the volume of the runner system. This equals

$$6 \times 1.15 \times (177 \times 0.4) = 489 \text{ cm}^3$$

which is easily within the maximum machine shot size of 3636 cm^3.

The final check on machine suitability is the available machine clamp stroke. For the 8500 kN machine, this is shown to be 85 cm. This stroke is sufficient to mold a hollow part up to a depth of approximately 40 cm. For such a part, the 85 cm stroke would separate the molded part from both the cavity and the core with a clearance of approximately 5 cm for the part to fall between the end of the core and the cavity plate. This stroke is thus excessive for the molding of 4 mm thick flat disks. The stroke is, however, adjustable, and to speed up the machine cycle it would be reduced in this case to just a few centimeters.

TABLE 8.4

Injection Molding Machines

Clamping Force (kN)	Shot Size (cc)	Operating Cost[a] ($/h)	Dry Cycle Times (s)	Maximum Clamp Stroke (cm)	Driving Power (kW)
300	34	28	1.7	20	5.5
500	85	30	1.9	23	7.5
800	201	33	3.3	32	18.5
1100	286	36	3.9	37	22.0
1600	286	41	3.6	42	22.0
5000	2290	74	6.1	70	63.0
8500	3636	108	8.6	85	90.0

[a] Machine rates will vary by country, region, and year—text values are intended for design comparisons only.

8.7 Molding Cycle Time

After the appropriate machine size for a particular molded part has been established, the molding cycle time can next be estimated. This estimation is essential in any consideration of the merits of alternative part designs or the choice of alternative polymers. As described earlier in this chapter, the molding cycle can be effectively divided into three separate segments: injection or filling time, cooling time, and mold-resetting time. The time estimates for these three separate segments are established in this section.

8.7.1 Injection Time

A precise estimate of injection time requires an extremely complex analysis of the polymer flow as it travels through the runners, gates, and cavity passages. This kind of detailed study which would involve a complete design of the mold cavity and runner system, and the use of solid modeling and nonlinear finite-element analysis, would clearly not be justified as a basis for initial comparisons of alternative part design concepts. To circumvent this problem, some major simplifying assumptions are made about the machine performance and the polymer flow. First, modern injection molding machines are equipped with powerful injection units specifically to achieve the required flow rates for effective mold filling. It is assumed that at the commencement of filling, the full power of the injection unit is utilized, and that the polymer pressure at the nozzle of the injector is that recommended by the polymer supplier. Under these circumstances, which may not be realizable for a particular mold design, the flow rate, Q, using elementary mechanics, would be given by

$$Q = \frac{P_j}{p_j}, \text{ m}^3/\text{s} \tag{8.1}$$

where

$$P_j = \text{injection power, W}$$

and

$$p_j = \text{recommended injection pressure, N/m}^2$$

In practice, the flow rate gradually decreases as the mold is filled, due to both flow resistance in the mold channels and a constriction of the channels as the polymer solidifies against the walls. It will further be assumed that the flow rate suffers a constant deceleration to reach an insignificantly low value at the point at which the mold is nominally filled. Under these circumstances, the average flow rate would be given by

$$Q_{av} = \frac{0.5P_j}{p_j}, \text{ m}^3/\text{s} \tag{8.2}$$

and the fill time would be estimated as

$$t_f = \frac{2V_s p_j}{P_j} \text{ seconds} \tag{8.3}$$

where
V_s = required shot size, m^3.

EXAMPLE

For the 15 cm diameter disks molded in a six-cavity mold, described in Section. 8.6, the required shot size is 489 cm^3. The recommended injection pressure for ABS is 1000 bars, or 100 MN/m^2. The available power at the injection unit of the 8500 kN machine is 90 kW, as shown in Table 8.4.

Thus, the estimated fill time is

$$t_f = \frac{2\times(489\times10^{-6})\times(100\times10^{6})}{(90\times10^{3})} = 1.09 \text{ s}$$

8.7.2 Cooling Time

In the calculation of cooling time, it is assumed that cooling in the mold takes place almost entirely by heat conduction. Negligible heat is transferred by convection, since the melt is highly viscous and it is clear that radiation cannot contribute to the heat loss in a totally enclosed mold. Since the relationship between cooling time and wall thickness is a major cost driver in the injection molding of thermoplastics, we will consider this subject in some detail below. The resulting simple relationship is fundamental to all processing of thermoplastics.

An estimation of cooling time can be made by considering the cooling of a polymer melt of initial uniform temperature T_i, between two metal plates, distance h apart, and held at constant temperature T_m. This situation is analogous to the cooling of the wall of an injection-molded component between the mold cavity and core as illustrated in Figure 8.7. The two vertical lines represent the surface of the cavity and core, separated by the molded wall thickness, h. A vertical temperature scale shows the initial injection temperature T_i, the mold temperature T_m, and the recommended ejection temperature T_x. Because of the rapid fill rate, it is reasonable to assume that the initial temperature of the polymer in the mold has constant value, T_i, across the wall thickness, as indicated by the upper

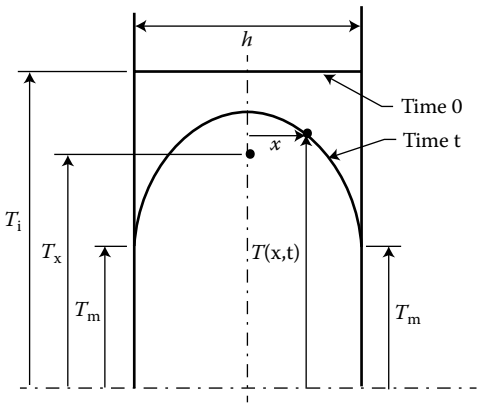

FIGURE 8.7
Wall cooling between cavity and core surfaces.

temperature line. At any later time, t, the temperature distribution, across the wall, takes the form shown by the curve in Figure 8.7. The part can be ejected from the mold when the temperature at the center of the wall reaches the recommended ejection temperature, T_x. This variation of temperature across the wall thickness and with changing time is described by the one-dimensional heat conduction equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{8.4}$$

where

x = coordinate distance from center plane of wall normal to the plate surface, mm
T = temperature, °C
t = time, s
α = thermal diffusivity coefficient, mm^2/s.

The thermal conductivity of thermoplastic materials is about three orders of magnitude lower than that of the steel mold. Under this situation it is reasonable to neglect the thermal resistance of the mold, which then merely becomes a heat sink at an assumed constant temperature T_m, as illustrated in Figure 8.7. A classical series solution to this boundary condition applied to Equation 8.4 has been given by Carslaw and Jaeger [11] as

$$\frac{T - T_m}{T_i - T_m} = \frac{4}{\pi} \sum_{0}^{\infty} \frac{(-1)^n}{2n+1} e^{-(2n+1)^2 \pi^2 \alpha t / h^2} \cos\left(\frac{(2n+1)\pi x}{h}\right) \tag{8.5}$$

Note that the dimensionless temperature group on the left-hand side has the value 1 when $T = T_i$ at injection (time $t = 0$), and decreases asymptotically to the value 0 as the polymer temperature approaches the mold temperature T_m. Elapsed time reaches the recommended cooling time t_c, when $T(0,t_c) = T_x$. The interested reader may differentiate the term in the summation with respect to t, and also twice with respect to x, to show that the results satisfy the equality in Equation(8.4). It can also be seen that at the cavity or core surface $T = T_m$ as required, since all of the cosine functions are zero when $x = \pm h/2$. The infinite number of terms in the solution given in Equation 8.5 are only needed to produce the initial square step solution from T_m to T_i at the instant of mold filling (time $t = 0$). Beyond the initial time increments, a dramatic approximation to Equation 8.5 can be obtained as shown in the example below. The temperatures and thermal diffusivity parameter needed for making cooling-time predictions from Equation 8.5 are given in Table 8.3, which contains a list of the most widely injection-molded thermoplastics.

EXAMPLE

An ABS injection-molded part has a uniform wall thickness of 3 mm. Using the data from Table 8.3, estimate the temperature at the center of the wall for $t = 1$, 2, and 4 seconds.

Setting $x = 0$ in Equation 5.8, the wall center temperature is given by

$$\frac{T - T_m}{T_i - T_m} = \frac{4}{\pi}\left(e^{-\pi^2 \alpha t / h^2} - \frac{1}{3} e^{-9\pi^2 \alpha t / h^2} + \frac{1}{5} e^{-25\pi^2 \alpha t / h^2} - \frac{1}{7} e^{-49\pi^2 \alpha t / h^2} + \cdots\right)$$

From Table 8.3, the required parameters are $T_i = 260°C$, $T_m = 54°C$, and $\alpha = 0.13$ mm²/s. We can also note that the recommended wall center temperature at ejection is $T_x = 82°C$, which we will use following this example.

To simplify the calculations, first evaluate the 4th term for time $t = 1$. Note that the part of the exponent $\pi^2\alpha/h^2 = 0.143$ in each term. With $t = 1$ the 4th term gives 0.0001 and succeeding terms in the series are much smaller. Thus, at most, only the first three terms are needed after only 1 second of cooling. The values of the first three terms for selected times early in the cooling process are

t (s)	Term1	Term2	Term3
1	0.867	–0.092	0.006
2	0.752	–0.026	0.000
4	0.565	–0.002	0.000

We can thus see that all terms in the series, after the first term, become insignificant in the first few seconds of cooling. If we calculate the temperature, T, at the wall center from just the first term, we obtain 281°C, 251°C, and 202°C for $t = 1$, 2, and 4 s. The corresponding temperatures obtained by taking all three terms are 259°C, 245°C, and 202°C. Since cooling times in injection molding are never less than 3 s, these results suggest that only the first term is needed for cooling time estimation. This approximation was suggested by Ballman and Shusman [12].

Thus, we can write

$$\frac{T - T_m}{T_i - T_m} = \frac{4}{\pi} e^{-\pi^2 \alpha t / h^2} \tag{8.6}$$

Recognizing that the inverse of the exponential function is a natural logarithm, and noting that when the temperate T has fallen to the recommended ejection temperature T_x the time t is the required cooling time t_c, Equation 8.6, can be rearranged to give

$$t_c = \frac{h_{max}^2}{\pi^2 \alpha} \log_e \frac{4(T_i - T_m)}{(T_x - T_m)} \text{s} \quad \text{for } t_c > 3\text{s}$$

$$t_c = 3\,\text{s otherwise (see below)} \tag{8.7}$$

where

h_{max} = maximum wall thickness, mm
T_x = recommended part ejection temperature, °C
T_m = recommended mold tempeature, °C
T_i = polymer injection temperature, °C
α = thermal diffusivity coefficient, mm²/s.

Note that for an injection molded part with variable wall thickness, the largest section thickness should be used in calculating the required cooling time. Hence, the replacement of h by h_{max} in Equation 8.7. It should also be noted that the analytical expression is made in Equation 8.7 underestimates the cooling time for very thin wall moldings. For such parts,

the thickness of the runner system is typically greater than the parts themselves and the greater delay is needed to ensure that the runners can be ejected cleanly from the mold. It is suggested that 3 s be taken as the minimum cooling as indicated in Equation 8.7.

The most important observation to make about Equation 8.7 is that for a given polymer, with given molding temperatures, the cooling time varies with the square of the wall thickness of the molded part. This is the principal reason why injection molding is often uneconomical for thick-walled parts. It should also be noted that Equation 8.7 applies only to a rectangular plate which is representative of the main wall of an injection-molded part. For a solid cylindrical section, a correction factor of 2/3 should be used on the diameter, since cooling takes place more rapidly for this boundary condition. Thus, a 3 mm thick flat part with a 6 mm diameter cylindrical projection would have an equivalent maximum thickness of $2/3 \times 6 = 4$ mm. This would be a very poor design. Not only would the cooling time increase by the factor $(4/3)^2 = 1.78$, but the large section thickness at the junction of the cylindrical projection would continue to cool and shrink long after the surrounding main wall has solidified. This would result in a large depression, or sink mark, on the main wall surface opposite the projection. The fundamental design rule is that injection-molded parts must have a main wall, as uniform in thickness as possible. Any projections off the main wall should have a maximum thickness of 2/3 of the main wall to avoid both sink marks and distortion from uneven cooling.

8.7.3 Mold Resetting

Mold opening, part ejection, and mold closing times depend upon the amount of movement required for part separation from the cavity and core and on the time required for part removal from between the mold plates; the latter usually just a tiny (1 s) delay free fall. The summation of these three machine operation times is referred to as the resetting time. Approximate times for these machine operations have been suggested by Ostwald [13] for three general part shape categories: flat, box-shaped, and deep cylindrical parts. These are given in Table 8.5.

It is clear that these estimates can only be viewed as very rough approximations, since they do not include the effect of part size. Part size influences resetting time in two ways. First, the projected area of the part together with the number of cavities determines the machine size and hence the power available for mold opening and closing. Second, the depth of the part, of course, determines the amount of mold opening required for part ejection.

In order to take an account of the preceding factors, injection molding machine data where typical maximum clamp strokes and dry cycle times for various sizes of molding machines are given will be used. Dry cycle time is defined as the time required to operate the injection unit and then to open and close an appropriately sized mold by an amount equal to the maximum clamp stroke. Table 8.4 gives values of these parameters for a wide range of currently available injection molding machines.

TABLE 8.5

Machine Clamp Operation Times (s)

	Flat	Box	Cylindrical
Mold open	2	2.5	3
Part eject	0	1.5	3
Mold close	1	1	1

It should be realized that the dry cycle time given by a machine supplier bears little relationship to the actual cycle time when molding parts. This is because the dry cycle time is based on an empty injection unit, and it takes only milliseconds to inject air through the mold. Moreover, there is obviously no required delay for cooling, and the machine clamp is operated during both opening and closing at maximum stroke and at maximum safe speed.

In practice, the clamp stroke is adjusted to the amount required for the molding of any given part. If the depth of the part is given by D cm, then for the present time estimation purposes it is assumed that the clamp stroke is adjusted to a value of $2D + 5$ cm. This gives the mold opening required for a complete separation of the part from the cavity and matching core with a clearance of 5 cm for the part to fall away.

It can be noted from Table 8.5 that mold opening usually takes place more slowly than mold closing. This is because, during mold opening, ejection of the part takes place usually with a significant level of force to separate the part from the core onto which it will have shrunk. Rapid mold opening may thus result in warping or fracture of the molded part. For present time estimation purposes it is assumed that opening takes place at 40% of the closing speed; this corresponds to the average of Ostwald's data in Table 8.5.

The precise motion of a clamp unit depends upon the clamp design and its adjustment. To obtain a simple estimate of resetting time, it is assumed that for a given clamp unit the velocity profile during a clamp movement (opening or closing) has identical shape irrespective of the adjusted stroke length. Under these conditions, the time for a given movement is proportional to the square-root of the stroke length.

Thus, if the maximum clamp stroke is L_s for a given machine and the dry cycle time is t_d, then the time for clamp closing at full stroke is assumed as equal to $t_d/2$. However, if a part of depth D is to be molded, then the adjusted clamp stroke is $2D + 5$ cm and the time for mold closing is

$$t_{close} = 0.5t_d\left[\frac{(2D+5)}{L_s}\right]^{1/2} \tag{8.8}$$

If we now use the assumption of 40% opening speed and a dwell of 1 s for the molded part to fall between the plates, then this gives an estimate for mold resetting as

$$t_r = 1 + 1.75t_d\left[\frac{(2D+5)}{L_s}\right]^{1/2} \tag{8.9}$$

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Example: Resetting Time

Assume that plain 15 cm diameter cylindrical cups, with a depth of 20 cm, are to be manufactured from ABS in a six-cavity mold. From the example in Section 8.6, we know that the appropriate machine size is 8500 kN and from Table 8.4 the corresponding values of dry cycle time, t_d, and maximum clamp stroke, L_s are 8.6 s and 85 cm, respectively. Substituting the values of $D = 20$, $L_s = 85$, and $t_d = 8.6$ into Equation 8.9 gives an estimated resetting time of 12.0 s.

If the depth of the cylindrical cups is 10 cm, then the estimate of resetting time changes to 9.2 s, while if 15 cm diameter disks with a thickness of only 3 mm are to be molded, then Equation 8.9 predicts the resetting time to be 4.9 s. These estimates can be seen to be at some variance with Ostwald's data, which were only reasonable averages for typical small parts.

8.8 Mold Cost Estimation

The skills needed for mold design and construction differ substantially from those required for all the other steps in the injection molding process. As a consequence, mold design usually takes place in isolation from the various other functions involved. This presents a serious hurdle to the exchange of information and ideas between the tool maker and molder on one side, and the part designer on the other. Desirable changes in part design often become evident only after major investments in tooling and testing have already been made. The consequences of such a belated recognition can be very significant in terms of final cost and part quality. On the other hand, mold cost estimations made during the concept design stage itself help in identifying acceptable part and mold configurations before actual investment in the mold is made.

The mold cost can be broken down into two major categories: (1) the cost of the prefabricated mold base consisting of the required plates, pillars, guide bushings, and so on, and (2) cavity and core fabrication costs. These will be discussed separately in the following sections.

8.8.1 Mold Base Costs

From a survey of currently available prefabricated mold bases, it has been shown by Dewhurst and Kuppurajan [14] that mold base cost is a function of the surface area of the selected mold base plates and the combined thickness of the cavity and core plates. Figure 8.8 shows mold base costs plotted against a single parameter based on area and thickness values. The data in Figure 8.8 can be represented by

$$C_b = 1000 + 0.45 A_c h_p^{0.4} \ \$ \tag{8.10}$$

where

C_b = cost of mold base, \$
A_c = area of mold base cavity plate, cm^2
h_p = combined thickness of cavity and core plates in mold base, cm.

The selection of an appropriate mold base is based on the depth of the part, its projected area, and the number of cavities required in the mold. In addition to the cavity size, extra allowance has to be given for molds with mechanical action side-pulls and other complicated mechanisms, such as unscrewing devices for the molding of screw threads.

To determine the appropriate mold base size for a particular part, it is necessary to imagine the molded part (or parts for a multicavity operation) embedded within the mold base plates. The part(s) must have adequate clearance from the plate surfaces (and from each other) to provide the necessary rigidity against distortion from the cavity pressure during molding and to allow space for cooling channels and any moving core devices. Typically, the minimum clearance between adjacent cavities and between cavity surface and the edges and rear surfaces of cavity plates should be 7.5 cm. The core mounting plate should also be a minimum of 7.5 cm. The extra plate size required to accommodate side-pulls and unscrewing devices depends upon the actual mechanisms used. However, for the purpose of the present cost-estimating procedure, it is assumed that side-pulls or side unscrewing devices require twice the minimum clearance from the edges, while rear

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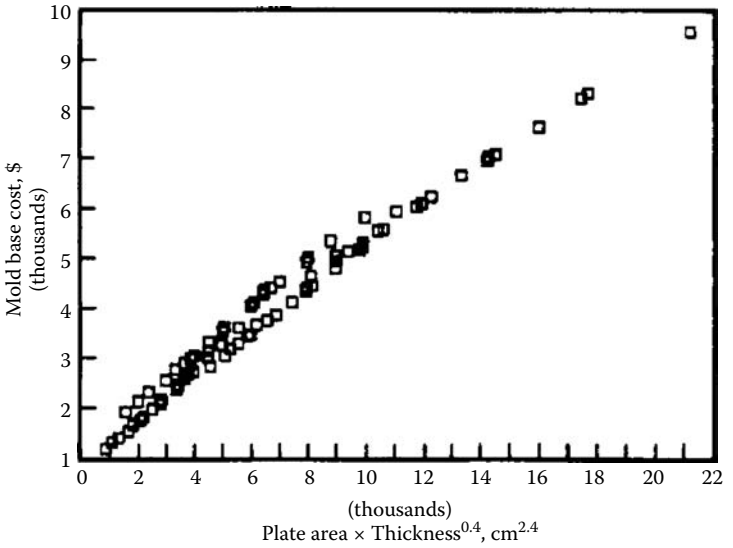

FIGURE 8.8
Principal mold base cost driver.

unscrewing devices require a doubling of the material at the rear of the cavity. Thus, one side-pull increases the plate width or length by an additional 7.5 cm. Additional side-pulls, on other sides of the mold, results in further plate size increases, so that four or more pulls, one or more on each side of a part, require a plate that is 15 cm larger in both length and width. It should also be noted that the use of two opposing side-pulls restricts the mold design to a single row of cavities, while side-pulls on three sides limits the number of cavities to two opposing ones, and side-pulls on all four sides requires single-cavity operation.

EXAMPLE

As an application of the preceding rules, assume that 10 cm diameter plain cylindrical cups with a depth, D, of 15 cm are to be molded in a six-cavity mold. A 3×2 array of cavities with clearances as specified above gives the required plate area A_c is 2550 cm^2. The combined cavity and core plate thickness h_p is $D + 15 = 30$ cm. Hence, the mold base cost parameter $A_c h_p^{0.4}$ is 9940 cm$^{2.4}$ and applying this value to the graph in Figure 8.8 leads to an estimated mold base cost of $5500.

If a more complex cylindrical part of the same size is imagined, with two diametrically opposed holes in the side surfaces and an internal thread, the estimated plate size increases will be as follows. The cavity plate will now hold a single row of six cavities in order to accommodate the diametrically opposed side-pulls. Using 15 cm clearance along each side of the cavities to house the side core mechanisms, the plate area is 112.5×40 or 4500 cm^2. To support the unscrewing device, the combined plate thickness increases to an assumed value of 37.5 cm, which results in a new value of $A_c h_p^{0.4}$ equal to 19,179 cm$^{2.4}$. Referring to Figure 8.8, this corresponds to a new mold base cost of approximately $9000.

Mold makers often increase the clearances between cavities as the cavity area increases. From assessment of a large number of molds, it seems the typical clearance may increase by about 0.5 cm for every 100 cm^2 of cavity area. This rule of thumb would have a marginal

effect on the estimated mold base costs in the preceding example. However, it should be applied for larger parts to obtain a better estimate of mold base size and cost. The costs above are only for the mold base with square flat plates. The costs to manufacture the necessary cavities and moving cores are discussed in the next section.

8.8.2 Cavity and Core Manufacturing Costs

Initial cost estimates in the present work are based on the use of a standard two-plate mold. The decisions regarding the use of three-plate molds, hot runner systems, and so on. can only be made by comparing the increased cost of the mold system with the reduced machine supervision associated with semiautomatic or fully automatic operation.

As discussed in the last section, mold making starts with the purchase of a preassembled mold base from a specialist supplier. The mold base includes the main plates, pillars, bushings, and so on. However, in addition to the manufacture of the cavities and cores, a substantial amount of work has to be performed on the mold base in order to transform it into a working mold. The main tasks are the deep hole drilling of the cooling channels and the milling of pockets in the plates to receive the cavity and core inserts. Additional tasks are associated with custom work on the ejector plate and housing to receive the ejection system, the insertion of extra support pillars where necessary, and the fitting of electrical and coolant systems. A rule of thumb [14] in mold manufacture is that the purchase price of the mold base should be doubled to account for the custom work that has to be performed on it. For consistency in the mold manufacturing estimation procedure to follow, the cost of a mold base, including the custom work to be performed on it, is to be approximated by the equivalent number of mold manufacturing hours. Using the average rate for moldmaking in the United States at the time of the Dewhurst and Kuppurajan study [14] of \$40/h, gives the equivalent mold-making hours M_b as

$$M_b = 50 + 0.023 A_c h_p^{0.4} \text{ hours} \tag{8.11}$$

Determination of the cost of an injection mold involves knowledge of the number of ejector pins to be used. This information would not usually be available at the early stages in part design. Discussions with experienced mold makers have indicated that the number of ejector pins is governed by such factors as the size of the part, the depth of the main core, the depth and closeness of ribs, and other features contributing to part complexity. However, the analysis of a range of parts for which the corresponding number of ejector pins could be determined yielded no strong relationships between number of pins and part depth, part size, or part complexity. The closest relationship was found to be based simply on the projected cross-sectional area of the parts at right angles to the direction of molding. With some considerable scatter, the number of ejector pins used was found to be approximately equal to the square root of the cross-sectional area when measured in square centimeters, that is,

$$N_e = A_p^{0.5} \text{ hours} \tag{8.12}$$

where

N_e = number of ejector pins required
A_p = projected part area, cm^2.

Equation 8.12 is used in the estimation of the cost of the ejection system for a molded part. An investigation of mold-making costs by Sors et al. [15] suggests an approximate

value of 2.5 manufacturing hours for each ejector pin, and this will be used in the present work. From Equation 8.12 this gives the additional number of manufacturing hours for the ejection system of a part as

$$M_e = 2.5 \times A_p^{0.5} \text{ hours} \tag{8.13}$$

It is recognized that part ejection is not always accomplished through the use of ejector pins. Nevertheless, Equation 8.13 represents a reasonable basis for estimating the cost of an ejection system at the concept design stage.

The geometric complexity of a part to be molded is handled in the present mold cost estimation scheme by assigning a complexity score for both the inner and outer surface of the part. The number of mold-manufacturing hours, associated with the geometrical features of the part, for one cavity and matching core(s) is then estimated from

$$M_x = 5.83(X_i + X_o)^{1.27} \text{ hours} \tag{8.14}$$

where X_i, and X_o are the inner and outer complexities of the part, respectively.

This empirical relationship was obtained by Archer [16] from the analysis of a wide range of injection-molded parts ranging from small brackets to large cabinets and items of furniture.

It is expected that for rapid cost estimating a quick judgment can be made as to the appropriate complexity numbers. However, in order to gain confidence in the assignment of the different levels of geometrical complexity, a simple complexity counting procedure has been established as described below.

Before proceeding to define the procedure for estimating cavity and core manufacture, it is important to consider the role of the learning or progress curve in mold making. Although the manufacture of injection molds is custom work which involves a mixture of high-precision complex tasks, the work often involves the making of multiple identical features or multiple identical items of tooling, and an account must be taken of the increase in efficiency resulting from this if reasonable estimates are to be made. Since the cost of the tooling is usually dominated by the skilled labor costs involved in its production, the cost reductions enabled when making multiple identical items can be modeled by the Wright learning curves [17] as described in Chapter 3. Thus, if the number of hours required for making a particular piece of tooling, or adding a particular feature to a tool is denoted M_1, then the average number of hours to make n identical pieces or add n identical features would be

$$M_{1,n} = M_1 n^b \tag{8.15}$$

The improvement in performance in this case stems both from worker improvement in doing multiple identical tasks, and also from improvements from using custom cutting tools, EDM electrodes, fixtures, and so on, multiple times. For this type of progress, as discussed in Chapter 3, an 85% learning curve is appropriate, for which $b = \ln(0.85)/\ln(2) = -0.234$. The total time to make n identical features or tooling pieces would thus be

$$M_n = nM_{1,n} = M_1 n^{1+b} = M_1 n^{0.766} \tag{8.16}$$

This relationship is particularly important when making a multicavity mold. In this case, the value 0.766 is referred to as the multicavity index, *m*, and the cost of multiple identical cavities and cores is represented by

$$C_n = C_1 n^m \tag{8.17}$$

where C_1 is the cost of a single cavity and core set. Testing this relationship with a wide range of multicavity mold makers suggests that values of *m* typically range from 0.7 to 0.8. It will be shown later that the cost of a mold base per cavity, as the number of cavities is increased and the mold base cost increases, fits closely to a multicavity index of 0.8. This corresponds to an 87% learning curve relationship, and since the mold base is typically a small proportion of the total mold cost, we will use an 85% learning curve, corresponding to a multi-index of 0.766 for all mold cost calculations.

The complexity measure used by the authors for mold and die cost estimating is based on the number of separate surface patches defining the part geometry. This enables estimates to be made at the early sketch stage before dimensions are fully defined. Count all separate surface segments on the part's inner surface. The inner surface is the surface that is in contact, during molding, with the main core and other projections or depressions in the core plate. Surface segments are either planar or have a constant or smoothly changing curvature. The junction of different surface segments can be a sudden change (discontinuity) in either slope or curvature. The complexity of the inner surface is given by

$$X_\mathrm{i} = 0.1 N_\mathrm{sp} \tag{8.18}$$

where N_sp is the number of surface patches.

This procedure is repeated for the part outer surface to obtain the outer surface complexity level, X_o. When counting surface patches, small connecting blend surfaces should not be included.

When counting multiple identical features on the surface of a part, a power index of 0.766, as discussed above, may be used to account for the savings that come from machining identical features in the mold. For example, if the surface of a part is covered by 100 spherical dimples, then the equivalent number of surface patches to be counted is $100^{0.766} = 34$.

Let us take as an example; a plane conical component with recessed base that is to be injection-molded; see Figure 8.9. The inner and outer surface complexity levels are established as follows. The inner surface comprises the following surface segments:

1. Main conical surface
2. Flat base

Thus

$$X_\mathrm{i} = 0.1 \times 2 = 0.2$$

The outer surface comprises:

1. Main conical surface
2. Flat annular base

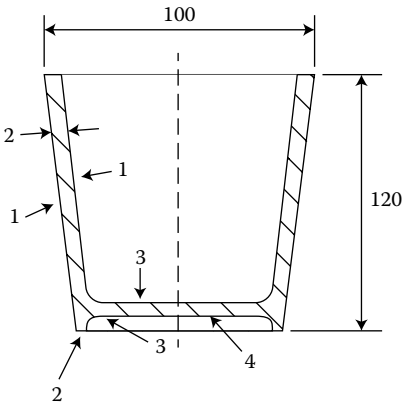

FIGURE 8.9
Surface segments of plain conical components. *Note:* All dimensions in millimeters.

3. Cylindrical recess in the base
4. Flat recessed base

Thus

$$X_o = 0.1 \times 4 = 0.4$$

Note: the small fillet radii around inner or outer edges are not counted unless they are larger than the wall thickness. If this was the case in the present example, then there would be two additional surface patches; namely the fillets around the base of the inside surface and around the bottom of the depression. The surface generated at the parting "plane" between the two mold halves is not counted if it is indeed just the flat surface between the two plates. However, if this parting surface is more complex, then its surface patches should be included in the estimation of X_o or X_i. Also this involves even greater difficulties in mold making since the mold must seal over correspondingly complex mating surfaces. Allowances for this added difficulty in mold making are addressed at the end of this section. In general, for functional engineering components, surface patches are flat, cylindrical, spherical or toroidal (circular fillets), and are separated from one another by changes of slope or curvature. In surface counting, it is useful to list the main shapes and features in tabular form including repeats and the breakdown of surface patch counts. Such a table, established at the sketch stage of design, is shown in Problem 3 at the end of the chapter.

In addition to geometrical complexity, the size of the part to be molded clearly also affects the cost of the cavity and core inserts. Building on a part area relationship given by Sors et al. [15], Archer [16] has shown, from the analysis of a wide range of injection molds, that for parts with very simple geometry the number of manufacturing hours for one cavity and core can be represented by

$$M_{po} = 5 + 0.085 \times A_p^{1.2} \text{ hours} \tag{8.19}$$

where

$$A_p = \text{part projected area, cm}^2$$

The sum of the point scores from Equations 8.13, 8.14, and 8.19 provides a base estimate of the number of manufacturing hours to make one cavity and core, and the ejection system for a part of given size with a known degree of geometrical complexity. However, in order to complete a mold cost-estimating system, six additional important factors need to be considered. These are:

1. The need for retractable side-pulls or internal core lifters
2. The requirement for one or more unscrewing cores to produce molded screw threads
3. The surface finish and appearance specified for the part
4. The average tolerance level applied to the part dimensions
5. The requirement for one or more surfaces to be textured (e.g., checkered, leather-grain finish, shallow lettering, etc.)
6. The shape of the surface across which the cavity and core separate: referred to in die design as the parting line

From discussions with a number of mold makers, it appears that the slideways and associated angle pins or withdrawal mechanisms for a side-pull, excluding manufacture of the core, have an associated manufacturing time of 50–80 h. However, constructing an internal mechanism in the main core (sometimes called a lifter) to retract an internal core pin is substantially more difficult and may take between 100 and 200 h. Still more difficult is the building of an unscrewing mechanism for the molding of screw threads, which may require 200–300 tool-making hours. For the present early costing procedure, manufacturing hours for side-pulls, internal lifters, or unscrewing devices are assumed to correspond to the average of these estimates.

The incorporation of texture into mold cavity surfaces is often carried out by specialist companies that offer a wide range of standard texture patterns. It appears that the cost of texturing is proportional to both the complexity and size of the part and that a fairly good estimate is obtained by allowing 5% of the basic cavity manufacturing cost. The cost of shallow lettering that can be etched or engraved into the mold can be considered equivalent to texture and estimated in the same way.

The hand finishing of cavities required to produce high-quality surfaces on molded parts is extremely costly and time-consuming. The time involved is clearly dependent on the size of the cavity, its geometrical complexity, and the required appearance of the molded part. In this context, it is necessary to differentiate between opaque and transparent parts. For opaque parts, the required appearance can be separated into four categories: not critical, standard (Society of Plastics Engineers No. 3 finish), high gloss (SPE No. 2), and highest gloss (SPE No. 1). On the other hand, transparent parts are generally produced according to only two categories: standard finish and with some internal flaws permissible, or highest quality with internal blemishes unacceptable. These two categories are more difficult to achieve than SPE No. 3 and No. 1 finishes, respectively, for opaque parts. From discussions with mold makers it appears that the time taken to finish a cavity and core to achieve the required appearance levels can be represented as a percentage increase applied to the basic time for cavity and core manufacture. For the present estimating system, this translates into a percentage increase to the sum of the manufacturing hours predicted by Equations 8.13, 8.14, and 8.19. Note that the manufacturing hours associated with the ejection system (Equation 8.13) are included. The requirement for improved appearance is usually accompanied by the need for a decrease in any blemishes from ejection, and

TABLE 8.6

Percentage Increases for Different Appearance Levels

Appearance	Percentage Increase
Not critical	10
Opaque, standard (SPE #3)	15
Transparent, standard internal flaws or waviness permissible	20
Opaque, high gloss	25
Transparent, high quality	30
Transparent, optical quality	40

resulting extra attention to the ejection system components. Reasonable percentage values for the different part appearance categories are given in Table 8.6.

The tolerances given to the dimensions of an injection-molded part must clearly be within the capabilities of the process. These capabilities will be addressed later in this chapter. However, the part tolerances also indirectly affect the cost of mold manufacture. The reason for this is that the mold maker is required to work within a small portion of the part tolerances in order to leave the remainder of the tolerance bands to cover variations in the molding process. Tighter tolerances thus result in more careful cavity and core manufacture. Evidences from mold makers suggest that this effect, while less significant than surface finish requirements, depends on the number of features and dimensions rather than on the part size. In terms of the present cost-estimating procedure, the part tolerance affects the time estimate for geometrical complexity given by Equation 8.14. Acceptable percentage increases for the six different tolerance levels, which should be applied to the result of Equation 8.14, are given in Table 8.7.

The final consideration is the shape of the plane separating the cavity and core inserts. Whenever possible, the cavity and core inserts should be mounted in flat opposing mold plates. This results in a flat parting plane (straight parting line) which only requires surface grinding to produce a well-fitting mold. Flat bent parts or hollow parts whose edge separating the inner and outer surface does not lie on a plane, cannot be molded with a flat parting plane. For these cases, the parting surface should be chosen from the six classifications given in Table 8.8.

For each of these separate categories, industrial data suggest that the additional number of manufacturing hours required to manufacture the mold is approximately proportional to the square root of the cavity area as given by the following relationship

$$M_s = f_p A_p^{1/2} \text{ hours} \tag{8.20}$$

TABLE 8.7

Percentage Increases for Tolerance

Tolerance Level	Description of Tolerances	Percentage Increase
0	All greater than ±0.5 mm	0
1	Most approx. ±0.35 mm	2
2	Several approx. ±0.25 mm	5
3	Most approx. ±0.25 mm	10
4	Several approx. ±0.05 mm	20
5	Most approx. ±0.05 mm	30

TABLE 8.8

Parting Surface Classification

Parting Surface Type	Factor (f_p)
Flat parting plane	0
Canted parting surface or one containing a single step	1.25
Two to four simple steps or a simple curved surface	2
Greater than four simple steps	2.5
Complex curved surface	3
Complex curved surface with steps	4

where

A_p = projected area of cavity, cm^2
f_p = parting plane factor, given in Table 8.8
M_s = additional mold manufacturing hours for nonflat parting surface.

8.9 Mold Cost Point System

Following the preceding discussions, a point system for mold cavity and core cost estimating can now be established. The main cost drivers are simply listed in order, and associated graphs or tables are referred to for determination of the appropriate number of points. The mold manufacturing cost is determined by equating each point to one hour of mold manufacture.

1. Mold base plate area A_c (cm^2) and combined plate thickness h_p (cm) for single-cavity mold
   - Refer to Equation 8.11 to estimate equivalent number of manufacturing hours for the mold base including the custom work to be performed on it.
2. Projected area of Part A_p (cm^2)
   - Refer to Equations 8.13 and 8.19, which include points for the size effect on manufacturing cost plus points for an appropriate ejection system.
3. Geometric Complexity X
   - Identify complexity ratings for inner and outer surfaces according to the procedure described earlier. For multiple identical features, apply the 85% learning curve index $m = 0.766$.
   - Apply Equation 8.14 to determine the appropriate point score
4. Side-pulls
   - Identify the number of holes or apertures requiring separate side-pulls (side cores) in the molding operation.
   - Allow 65 points for each side-pull. For multiple identical side-pulls apply the 85% learning curve index $m = 0.766$.
5. Internal lifters
   - Identify number of internal depressions or undercuts requiring separate internal core lifters.

- Allow 150 points for each lifter. For multiple identical lifters apply the 85% learning curve index $m = 0.766$.

6. Unscrewing devices
   - Identify the number of screw threads that would require an unscrewing device.
   - Allow 250 points for each unscrewing device. For multiple identical unscrewing devices, apply the 85% learning curve index $m = 0.766$.
7. Surface finish/appearance
   - Refer to Table 8.6 to identify the appropriate percentage value for the required appearance category.
   - Apply the percentage value to the sum of the points determined for (2) and (3) to obtain the appropriate point score related to part finish and appearance.
8. Tolerance level
   - Refer to Table 8.7 to identify the appropriate percentage value for the required tolerance category.
   - Apply the percentage value to the geometrical complexity points determined for (3) to obtain the appropriate point score related to part tolerance.
9. Texture
   - If portions of the molded part surface require standard texture patterns, such as checkered, leather grain, shallow lettering and so on, and then add 5% of the point scores from (2) and (3).
10. Parting plane
    - Determine the category of parting plane from Table 8.8 and note the value of the parting plane factor, f_p.
    - Use f_p to obtain the point score from Equation 8.20.

To determine the cost to manufacture a single cavity and matching core(s) the total point score is multiplied by the appropriate average hourly rate for tool manufacture.

EXAMPLE

It is anticipated that 2,000,000 plain hollow conical components are to be molded in acetal homopolymer. The component, illustrated in Figure 8.9, has a material volume of 78 cm^3 and a projected area in the direction of molding of 78.5 cm^2. The mold manufacturing points are first established as follows:

		Points
i.	Mold base [substitute $A_c = 625$ cm^2 and $h_p = 27$ cm into Equation 8.11]	104
ii.	Projected area of part [substitute $A_p = 78.5$ cm^2 into Equations 8.13 and 8.19]	43
iii.	Geometrical complexity (established earlier as $X_i = 0.2$ and $X_o = 0.4$ for this part-apply Equation 8.14 for points)	3
vi.	Number of side-pulls	0
v.	Number of internal lifters	0
vi.	Number of unscrewing devices	0

vii.	Surface finish/appearance (Opaque standard (SPE#3); see Table 8.6—add 15% of 43 + 3)	7
viii.	Tolerance level (category 3; see Table 8.7— insignificant effect for low complexity)	0
ix.	Texture	0
x.	Parting plane (category 0)	0
		Total point score = 157

Assuming an average rate of \$40 per hour for mold manufacturing, the estimated cost for one single-cavity mold is 157 × \$40 or approximately \$6300.

A useful overview of typical injection mold costs is obtained by plotting the above Equations for assumed average conditions of SPE#3 appearance level and tolerance level number 3. The result is shown in Figure 8.10. To relate the projected area of the part to the equivalent hours required to obtain and customize the mold base it is necessary to make a further assumption about the envelope of the part. To produce Figure 8.10 it was assumed that the mold cavity occupies a square region on the mold plate and that the depth of the cavity is 25% of the side of the square; that is, the mold cavity has proportions length = width = 4 × depth. For the conical cup example above, we can see that extrapolating closely below the $A_p = 100$ cm^2 curve with a complexity value of 3 would give an estimate somewhere between \$6000 and \$7000 in agreement with the calculations above. The fact that this part is deeper than the typical length/4 selected for the plot has made little difference in this case, because the part is relatively small. However, for large parts with low complexity, the cost of the mold base tend to dominate the mold cost and part depth can then have a substantial cost influence. Figure 8.10 also underestimates costs for parts with large internal through holes which substantially decrease the projected area compared to the plan area. Note that mold cost estimates are based entirely on mold-making hourly rates. Thus, if the mold for this part was to be made in the North-East US, with a mold-making rate of \$60 per hour, then the mold would be estimated to cost \$6300(60/40) ≃ \$9500.

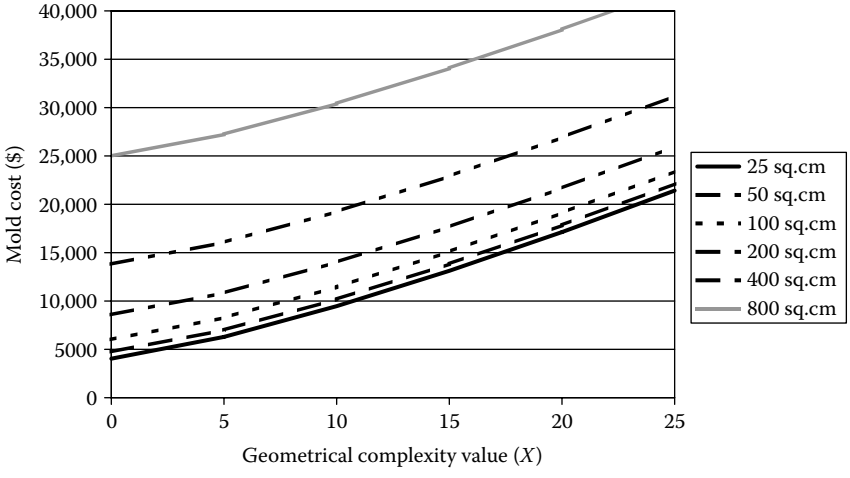

FIGURE 8.10
Approximate mold cost curves for increasing projected area, A_p. (Costs for class of typical parts as described in the text with \$40/h mold-making rate.)

8.10 Estimation of the Optimum Number of Cavities

A major economic advantage of injection molding is its ability to make multiple parts in one machine cycle through the use of multicavity molds. Sometimes the cavities in a mold may be for different parts that are to be used together in the same product. This type of mold is referred to as a family mold. It is used infrequently since it requires the existence of a family of parts, made of the same material and having similar thicknesses. It also has the obvious disadvantage of individual reject parts always requiring the remanufacture of the entire family.

The common practice is to use multicavity molds to make sets of identical parts with each molding cycle. The motivation is to reduce the processing cost through an initially higher mold investment. The effect of the chosen number of cavities on part cost can be dramatic. This means that the cost of alternative designs of a particular part can only be estimated if the appropriate number of cavities is known. The identification of the appropriate number of cavities for a particular part is explored in this section.

When a multicavity mold is used, three principal changes occur:

1. A larger machine with a greater hourly rate is needed than for a single-cavity mold.
2. The cost of the mold is clearly greater than for a single-cavity one.
3. The manufacturing time per part decreases in an approximately inverse proportion to the number of cavities.

In order to identify the optimum number of cavities, the increase in the hourly rate with machine size increase must be known. Also, an estimate must be available of the cost of a multicavity mold compared to the cost of a single-cavity mold for the same part. With regard to the first requirement, Figure 8.11 shows a national survey of injection molding machine rates that was carried out by *Plastics Technology Magazine* [18]. It can be seen that the hourly rate can be represented almost precisely as a linear relationship based on the machine clamp force, that is, the machine hourly rate is

$$C_r = k_1 + m_1 F, \ \$/\text{hour} \tag{8.21}$$

where

F = clamp force, kN
k_1, m_1 = machine rate coefficients.

For the machine rate data given in Table 8.4, $k_1 = 25$ \$/h and m_1=0.0091 \$/h/kN.

Turning now to the cost of multicavity mold manufacture, evidence in the literature [19] suggests that the cost of multiple cavity and core inserts, compared with the cost of one unique cavity/core set, follows an approximate power-law relationship. That is, if the cost of one cavity and matching core is given by C_{c1}, then the cost, C_{cn}, of producing identical sets of the same cavity and core can be represented by

$$C_{cn} = C_{c1} n^m \tag{8.22}$$

where m is a multicavity mold index and n is the number of identical cavities.

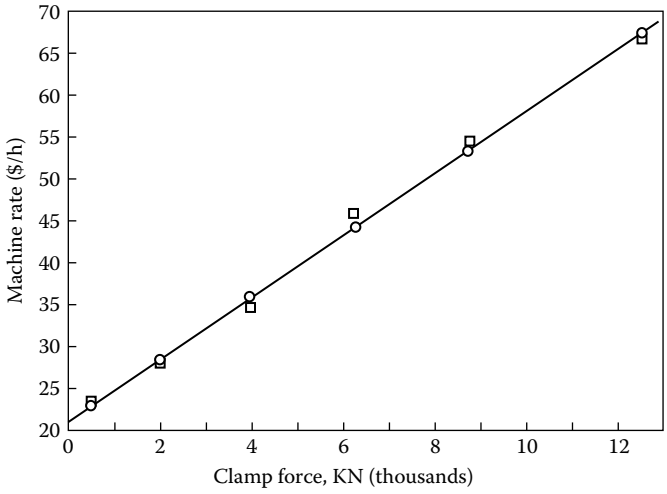

FIGURE 8.11
National average injection molding machine rates.

Testing of this relationship for a wide range of multicavity molds suggests that a reasonable value of m for most molding applications is between 0.7 and 0.8. Rather than accepting this range based on a limited number of observations, it is more reasonable to assume an 85% learning or progress curve which gives a value of $m = 0.766$ as discussed in Chapter 3 and Section 8.9.

Savings also occur in the mold base cost per cavity when increasing the number of cavities. This can readily be established from the discussion of mold base costs in the previous section. For the case of cavities occupying a square region with increasing areas from 100 to 400 cm^2, Figure 8.12 illustrates the relationship between the plate area required for a

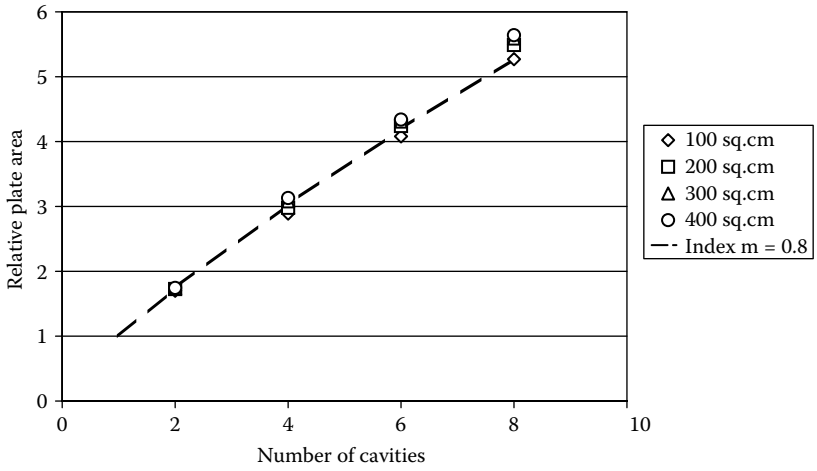

FIGURE 8.12
Relative plate cavity area.

single cavity and the plate area required for an increasing number of cavities. It can be seen that a power law curve closely matches this data and so we can write

$$A_{cn} = A_{c1} n^m \tag{8.23}$$

where A_{c1} and A_{cn} represent the areas of a single-cavity and n-cavity mold base plate, respectively. Furthermore, since the plate thicknesses are the same in both cases, the mold base costs from Equation 8.10 can be equally represented by

$$C_{bn} = C_{b1} n^m \tag{8.24}$$

If we make a further simplification that m can reasonably be given the 85% progress curve value of 0.766, then Equations 8.22 and 8.24 can be combined as

$$C_n = (C_{bn} + C_{cn}) = (C_{b1} + C_{c1}) n^m = C_1 n^m \tag{8.25}$$

where C_1 and C_n represent the completed costs of a single-cavity mold and an n-cavity mold, respectively.

Using the preceding relationship, the total cost, C_t, of producing N_t molded components over the mold payback period, can be expressed as

$$\begin{aligned} C_t &= \text{processing cost} + \text{mold cost} + \text{polymer cost} \\ &= (N_t / n)(k_1 + m_1 F)t + C_1 n^m + N_t C_m \end{aligned} \tag{8.26}$$

where

t = machine cycle time, hrs
N_t = the number of components produced over the mold payback period
n = number of cavities (= number of parts per machine cycle)
C_1 = total cost of a single-cavity mold, \$
C_m = cost of polymer material per part, \$.

Assuming that an infinite variety of different clamp force machines were available, then one with just sufficient force would be chosen since the hourly rate increases with clamp force (Figure 8.11). Thus, we can write

$$F = nf \tag{8.27}$$

where f is the separating force on one cavity. Substituting Equation 8.27 into Equation 8.26 gives

$$C_t = N_t (k_1 f / F + m_1 f)t + C_1 (F/f)^m + N_t C_m \tag{8.28}$$

For a given part, molded in a particular polymer, of which N_t are required, the only variable in Equation 8.22 is clamp force F. Thus, the minimum value of C_t occurs when dC_t/dF is equal to zero or when

$$-N_t k_1 ft / F^2 + m C_1 F^{(m-1)} / f^m = 0 \tag{8.29}$$

Multiplying Equation 8.23 by F and substituting $n=F/f$ gives the expression for the optimum number of cavities as

$$n = \left(\frac{N_t k_1 t}{(mC_1)} \right)^{1/(m+1)} \tag{8.30}$$

The value of n obtained from Equation 8.30 should be rounded to one or the nearest even integer. A number of simplifying assumptions were used to derive Equation 8.30, and for this reason the value predicted for the optimum number of cavities should be regarded as a first approximation. However, Equation 8.30 is very easily applied and provides a reasonable basis for comparing alternative designs during the concept phase of a new injection-molded part.

8.11 Design Example

Figure 8.13 shows an injection-molded cover manufactured by a US automobile company. The cover has a flange that has thickened pads at locations around the periphery, where bolts secure it to the assembly. The main body of the part is 2 mm thick and the bolt pads have a thickness of 4.6 mm.

The design can be considered to be produced from a 2 mm thick basic shape, referred to in injection molding jargon as the main wall. Features are then added to the main wall. In the present design, the features are:

1. The eight triangular stiffening ribs (called gussets) that support each pad to the side wall
2. The six through holes
3. The four pads of thickness 2.6 mm that rest on top of the main wall to give a combined thickness of 4.6 mm

Adding features to the main wall always increases the mold cost. In addition, if they result in an increase in wall thickness, then the cycle time also increases.

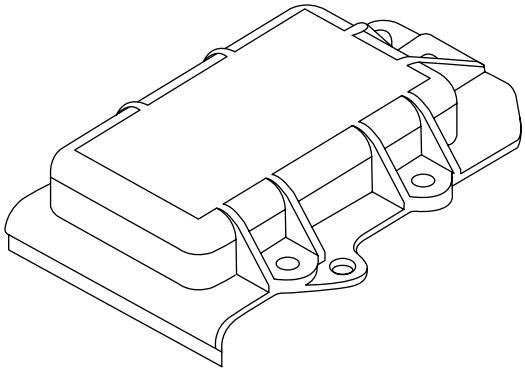

FIGURE 8.13
Heater core cover.

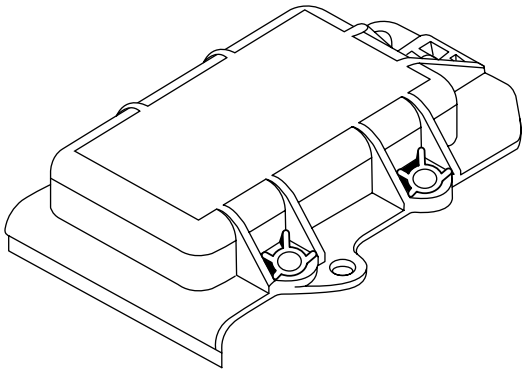

FIGURE 8.14
Proposed redesign of heater core cover.

Using the point system in Section 8.8, it can readily be shown that for the cover design the increase in mold cost due to all eighteen features is approximately 23%, or $1150, and that the cost of one cavity and core set would be approximately $8000. Thus, for a fairly modest production volume of 50,000 parts per cavity the added mold cost is only 2.3 cents, or 0.13 cents per feature.

In contrast, the cooling Equation in Section 8.6 shows that the addition of the thickened pads increases the cooling time by factor $(4.6/2)^2$; that is, more than 5 times as long. This results in an additional processing cost per part of 12.3 cents.

Thus, if we wish to reduce the cost of the cover, the obvious way is to reduce the material thickness in the stiffened areas around the bolt clearance holes. The way in which this can be achieved is through the use of ribbed structures, as shown in Figure 8.14. The projecting circular rib around each hole is known as a boss, and it is supported by a network of intersecting straight ribs as shown. The rib structure can be deep enough to give an equivalent stiffness to the solid 4.6 mm thick pads. Also, the recommended rib thickness would be two-third of the main wall thickness, or 1.67 mm. For a production volume of 50,000 parts the new design would have an associated cavity and core cost of approximately $10,500, corresponding to an increase in mold cost per part of 5 cents. However, this would be more than an offset by the 12.3 cents decrease in processing cost. Just as important, the new design is likely to result in high-quality, distortion-free moldings. The existing design, in contrast, is difficult to mold because of the different wall thicknesses. The problems are due to the continued cooling of the pads after the main wall has fully solidified. This results in a buildup of residual or locked-in stresses as the pad material continues to shrink while constrained by the surrounding solidified wall.

An added benefit in this case would be a decrease in the optimum number of cavities, and hence a decrease in the cost of the multicavity mold even though the number of features has increased. This part was actually being manufactured in an 8-cavity mold, whereas a 4-cavity mold would be the most economic with the redesigned cover.

8.12 Insert Molding

Insert molding refers to the common practice of molding small metal items, such as pins or bushings, into injection-molded parts. Most typically, the inserts are hand-loaded into

the mold cavity, or cavities, prior to closing of the mold and activation of the injection unit. For this reason, insert molding machines are of a vertical design so that inserts can be placed into a horizontal cavity plate when the mold is open. Machine rates can be assumed to be the same as for conventional molding machines. An approximate estimate of the cost of an insert-molded part can be obtained by adding 2 s per insert to the molding cycle time. Thus, for a four-cavity mold, with two inserts per cavity, the cycle time would be increased by 16 s.

For high-volume manufacture of insert-molded parts, special-purpose machines can be obtained that employ multiple stations. The simplest type has a shuttle table that moves two separate cavity plates alternately under the core plate, which is attached to the injection unit. With this system, inserts can be loaded into one mold while the other one is being filled and allowed to cool. Following this procedure, insert loading takes place within the machine cycle but with a higher-cost machine and a larger mold investment. For the additional engineering required to manufacture two sets of cavities, which have to mate with precision to a single core plate, it is suggested that 50% should be added to an estimated cost of a conventional single-cavity mold.

It should be noted that insert molding does not find universal favor. Many manufacturing engineers feel that the high risk of mold damage due to misplaced inserts offsets any advantage of the process. The alternative is simply to mold the depressions needed to accept inserts, which can then be secured later by ultrasonic welding. This process is described briefly later in the chapter.

8.13 Design Guidelines

Suppliers of engineering thermoplastics have in general provided excellent support to the design community. Several have published design manuals or handbooks that are required reading for those designing injection molding components. Information can be obtained from them on the design of ribbed structures, gears, bearings, spring elements, and so on.

The interested reader may wish to write, in particular, to Du Pont, G.E. Plastics Division, or Mobay Corporation for design information associated with their engineering thermoplastics.

Generally accepted design guidelines are listed below.

1. Design the main wall of uniform thickness with adequate tapers or draft for easy release from the mold. This minimizes part distortion by facilitating even cooling throughout the part.
2. Choose the material and the main wall thickness for minimum cost. Note that a more expensive material with greater strength or stiffness may often be the best choice. The thinner wall this choice allows reduces material volume to offset the material cost increase. More important, the thinner wall significantly reduces cycle time and hence processing cost.
3. Design the thickness of all projections from the main wall with a preferred value of half of the main wall thickness and do not exceed two-third of the main wall thickness. This minimizes cooling problems at the junction between the projection and main wall, where the section is necessarily thicker.

4. If possible, align projections in the direction of molding or at right angles to the molding direction lying on the parting plane. This eliminates the need for mold mechanisms.
5. Avoid depressions on the inner surfaces of the part, which would require moving cores to be built inside the main core. The mechanisms to produce these movements (referred to in mold making as lifters) are very expensive to build and maintain. Through-holes on the side surfaces, instead of internal depressions, can always be produced with less expensive side-pulls.
6. If possible, design external screw threads so that they lie in the molding plane. Alternatively, use a rounded or rolled-type thread profile which can be stripped from the cavity or core without rotating. In the latter case, polymer suppliers should be consulted for material choice and appropriate thread profiles, and permissible thread depth to diameter ratios.

In addition to these general rules, design books should be consulted for design tips and innovative design ideas. Many of these are concerned with methods for producing undercuts and side features without using mold mechanisms. This will be explored a little further in the next section when snap fit elements are discussed.

One important cautionary note should be made with regard to design guidelines. Guidelines, aimed at minimizing individual part cost, should only be followed if they do not produce a correspondingly larger negative effect on the cost or quality of the assembly as a whole. This applies particularly to the guidelines aimed at avoiding mechanisms in the mold. The only valid rule in this regard is that the need for mold mechanisms should be recognized by the designer, and if they are unavoidable, then their cost should be justified in the early stages of design. This cost may be simply the cost of the mechanisms or it may also include the increase in processing cost if they restrict the number of cavities below the optimum value. The worst case is a high-volume component with side-pulls or unscrewing devices on all sides so that it must be made uneconomically in a single-cavity mold.

8.14 Assembly Techniques

One of the major advantages of injection molding is its ability to easily incorporate, in the molded parts, effective self-securing techniques. In the present context, self-securing refers to the ability to achieve a secure assembly without the use of separate fasteners or a separate bonding agent. Two of these self-securing techniques are also widely used with metal parts: press fitting and riveting. With press fitting, much larger interferences are possible with injection-molded parts than with metal parts. This has the advantage of requiring a less precise tolerance control for the press fit. The negative aspect of plastic press fit joints is that the material is constantly under stress and invariably relaxes over a period of time to produce some degradation of the joint strength. Testing of press fits under the expected loading conditions is therefore essential. With regard to riveting, integral rivets are of course easily produced by adding an inexpensive feature to the mold. On assembly the rivet heads are also easily formed by cold heading or by the use of heated forming tools; the latter operation is sometimes referred to as staking.

A third self-securing method, which is unique to plastic parts, is the use of ultrasonic welding. This is a method of joining two or more plastic molded parts through the

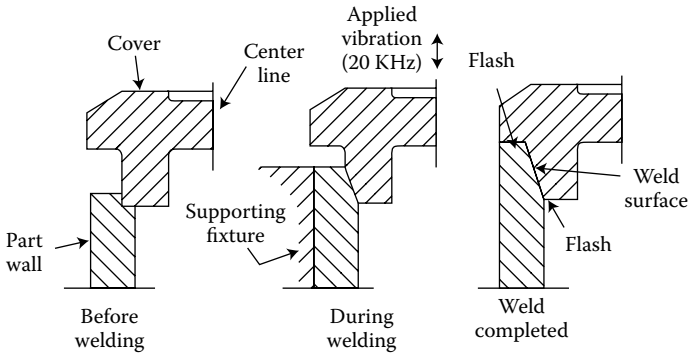

FIGURE 8.15
Ultrasonic welding joint design by Du Pont.

generation of intermolecular frictional heat at the assembly interfaces. Ultrasonic welding equipment simply involves a special fixture to hold and clamp the parts and through which a high-frequency vibration of approximately 20 kHz is passed. The detail design of the butting or overlapping joints is critical for successful joining of the parts. Figure 8.15 shows typical recommended joint designs. Ultrasonic welding is a good economic choice where sealed joining is required, since the equipment is relatively inexpensive and the process is fast. Welding is accomplished typically in about 2 s.

The final and most widely recognized self-securing method for molded parts is through the use of snap fit elements. It is no exaggeration to claim that the establishment of high integrity snap-fit designs has revolutionized the manufacturability of wide ranges of high-volume consumer products. These can be separated into two main types. The first type of annular snap fit was developed for mating parts with circular cross-section and involves the use of an undercut and mating lip. The male partner of the mating pair may be molded with the parting plane along its axis with very little added cost, simply the cost of adding the groove feature to the cavity and core geometries. However, if the male cylinder cannot be designed at right angles to the direction of mold opening, then its separation from the mold requires the use of side-pulls. In contrast, the female or undercut part is almost always stripped off the core by the mold ejection system and is, therefore, inexpensively produced. Snap fits of this type are only satisfactory for parts whose

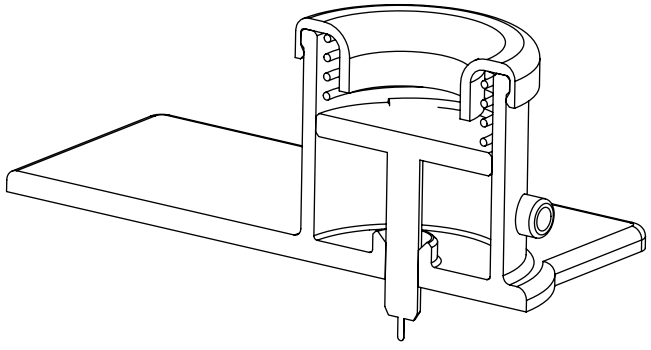

FIGURE 8.16
Section of assembly illustrating annular snap-fit cover.

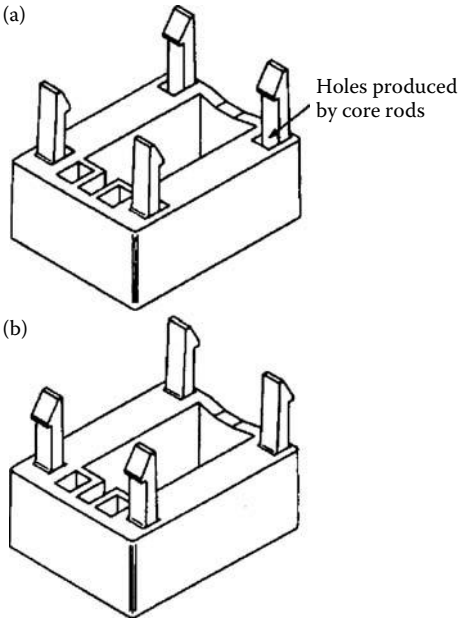

FIGURE 8.17
Cantilever snap fit elements, (a) Undercuts formed by core rods; (b) undercuts formed by side-pulls.

edges follow closed contours with generous radii at corners of edge direction changes. The further part shapes deviate from open curves, the more difficult it becomes to eject parts from the mold and the less robust is the assembly mate. Figure 8.16 shows the cross-section of a pneumatic piston assembly switch device which been redesigned to combine a piston stop, a flat sheet metal cover, and two screws, into an annular snap fitted cover. The cover has a deep inner projection to serve the function of the previously separate piston stop. The undercuts, on the inside of the cover and on the outside of the mating cylindrical boss, have generous chamfers to facilitate stripping from the molds and product disassembly if required.

The second type of snap fit design involves the use of one or more cantilever snap elements, as shown in Figure 8.17. If possible, the cantilever snap element and its mating undercut should be designed for molding without mold mechanisms; one such design is shown in Figure 8.17a. The alternative design, illustrated in Figure 8.17b, requires two side-pulls for the molding of the cantilever and the undercuts. However, even in the latter case, for a large enough production volume the extra mold costs can be easily outweighed by the subsequent savings in assembly cost. Polymer manufacturers should be contacted for detailed information on snap fit design; for example, see reference [20].

PROBLEMS

In all the calculations use material data and machine hourly rates from the tables, and use $40/h as the mold-making rate.

1. Figure 8.18 illustrates an annular ring component with eight hollow cylindrical bosses. There are no hidden features on the reverse side. The outer and inner diameters of the ring are 200 and 160 mm respectively. The main wall is 3 mm

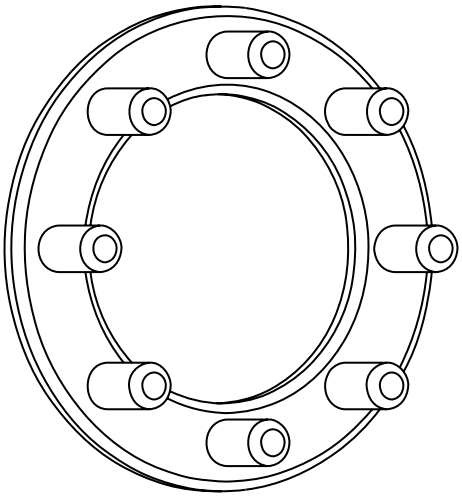

FIGURE 8.18
Annular ring design.

thick, and the boss projections are 12 mm outer diameter, 6 mm inner diameter and 30 mm high. The material proposed for the design is high-density polyethylene, which is a very inexpensive polymer. However the poor material mechanical properties give rise to the substantial wall thickness.

a. Estimate the material cost for the part, assuming the runner system will be reused in the machine (use the data in Tables 8.1 and 8.3).
b. Estimate the appropriate machine size from the list in Table 8.4.
c. Estimate the cycle time (use the data in Table 8.3).
d. Estimate the process cost per part using the machine rate in Table 8.4. Assume in this calculation that the molding shop has 85% plant efficiency; that is, machines are typically stopped at 15% of the time for batch setup, adjustments, and miscellaneous stoppages. Increase the process cost appropriately to account for this.

2. Continuing from Problem 1, for the ring design in Figure 8.18, you propose a design change to use polyethylene terephthalate (PET) with 30% glass fill. PET is used for soda bottles, and you have located a quality recycled material supplier who can deliver the glass filled PET for $2.25/kg. Using the data in Table 8.1, calculate the main wall thickness required to give the same wall bending stiffness as for the high-density polyethylene part in the original design proposal. Decrease the wall thickness of the bosses in the same proportion.

   Recalculate the material and process cost for this proposed redesign, using the same steps as in problem 1. Is your redesign idea a sound economic proposal? If the recycled material was unavailable and you had to pay the full supplier price of $3.74/kg would the change still be worthwhile?

   (*Hint:* recall from Chapter 2 that for equivalent bending stiffness the wall thickness should change in proportion to the cube root of the modulus)
3. A cable company is considering the possibility of changing their current die cast utility pole mounted distribution box to an injection molded one. The motivation is to eliminate the costs of trimming, plating (for corrosion resistance) and machining of screw threaded holes for securing. In addition, the new design will have snap-fit hinges and an integral snap-fit latch plate for self securing. The specifications of the box cover are estimated from concept sketches, and calculations of equivalent strength and stiffness of the die cast model. The cover is to be

molded using polypropylene (PP) with 40% talc fill. The global specifications are estimated to be

Weight = 170 g;	Envelope length=25 cm
Envelope width = 15 cm;	Envelope depth = 4 cm
Projected area = 322 cm^2;	Wall thickness = 2.54 mm

The appearance level (Table 8.6) is to be standard-opaque and the tolerance should be level 3 (Table 8.7). In addition, from the sketches, the complexity has been estimated as shown in the table below, which gives a breakdown of the number of surface patches on the inner and outer surfaces of the main wall, and on the separate features which make up the cover design. The complexity numbers are calculated in the last column. Note that for the repeated features the number of patches on a single feature are multiplied by the number of repeats, *r*, raised to the 85% progress curve index.

Name of the Feature	Surface Patches (N_s)	Repeats (r)	Complexity X ($0.1N_s * r^{0.766}$)
Outer surface	29	1	2.90
Side projections	6	2	1.02
Latch plate & gussets	11	1	1.10
Hinges	12	2	2.04
			$X_o = 7.06$
Inner surface	8	1	0.80
Flange/edge	15	1	1.50
Side projections	10	2	1.70
Latch plate underside	3	1	0.30
Hinges	8	2	1.36
			$X_i = 5.66$

Initially 50,000 covers are required, which can be made most economically in a single cavity mold.

a. Estimate the sum of the material and process costs (known as the piece part cost) for this component. Use the material data and the machine specifications from Chapter 8. Select the appropriate machine from Table 8.4. Allow 15% downtime and assume the runners are reused at the machine.

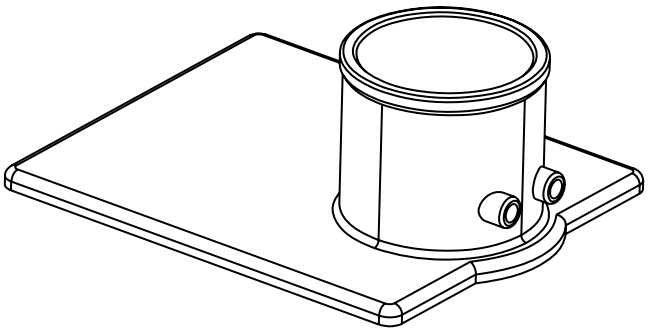

FIGURE 8.19
Pneumatic piston assembly base part.

b. Estimate the cost of a single-cavity mold for the distribution box cover. The design requires no mold mechanisms. Compare your estimated number of manufacturing hours with a quick estimate from Figure 8.10.

4. A particular manufacturing company uses a simple internal cost accounting method in which all the machines of a particular type are given the same hourly rate. In addition, in the company's internal tool-making division, no account is made for the savings in making multiple identical items of tooling. Under this costing system all of the different injection molding machines of different sizes are assigned an hourly rate of $C_r = k_1$ \$/h, and the cost of an n-cavity mold is n times that of a single-cavity mold (i.e., $m = 1$).

   By making appropriate changes to Equations in Section 8.10, show that this cost accounting system would lead to the conclusion that the optimum number of cavities for a particular part would be obtained when the mold cost per part was equal to the process cost per part.

5. The base part of the piston assembly illustrated in Figure 8.16 is shown in Figure 8.19. The part outer dimensions are: length 76 mm, width 64 mm, height 30 mm. The part volume is 29 cm^3 and it is to be molded from ABS. The maximum wall thickness is 3.0 mm.

   You have obtained a quote of \$8000 for a single-cavity mold for the part. However, large quantities of the part are required justifying the use of a 4-cavity mold. For the proposed 4-cavity mold production, estimate the following:

   a. The appropriate machine size from the selection in Table 8.4, making an approximate allowance for the projected area of the runner system as well as the four cavities.
   b. The likely molding machine cycle time.
   c. The processing cost per part, assuming 85% plant efficiency and the machine rate in Table 8.4.
   d. The likely 4-cavity mold cost assuming an 85% progress curve in the manufacture of the four cavities.

6. Figure 8.20 shows two views of a hose clamp which is to be injection molded using 30% glass-filled polycarbonate; see Table 8.3. The envelope size of the part is 60×80 mm and the wall thickness is 3.0 mm. A total of 4 million clamps is required over the mold amortization period of 30 months. You have already estimated the cycle time to be 19.6 s for a single-cavity mold operation on a 300 kN

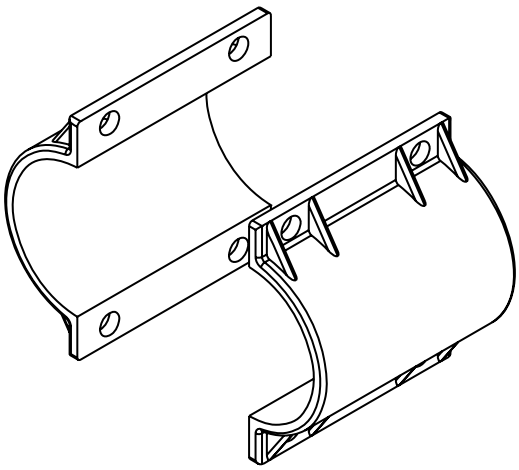

FIGURE 8.20
Pair of identical injection-molded hose clamps.

machine, and have obtained a quote of $7000 for a single-cavity mold. Assume that the injection molding machine rate can be represented for your company by

$$C_r = 33.25 + 0.012F \quad \$/\text{hr}\ (F = \text{clamp force, kN})$$

a. Using the 85% learning curve, determine the optimum number of cavities for the mold which should be used to produce this part.
b. Since this is a simple geometry to mold, you decide to experiment with a lower mold temperature of 80°C. Assuming negligible effect on fill time and no effect on reset time, by how much would this reduce the cycle time? (*note that* $h = 3$ mm).
c. If you adopt the lower mold temperature for processing, what would then be the optimum number of cavities in the mold?

7. Saturn Corporation uses injection moldings for many of the body panels, including the doors. In doing so, they replaced the traditional low alloy steel sheet metal panels which were nominally 1 mm thick. As previously described in the problems in Chapter 2, the material they chose to use is a 30% glass-reinforced polycarbonate, blended with ABS for improved mold flow characteristics. The elastic modulus of this blended reinforced thermoplastic is $E = 5$ GN/m^2, and the yield stress is $Y_t = 80$ MN/m^2. The steel panels had a nominal thickness of 1 mm and corresponding material properties of $E = 200$ GN/m^2, and $Y_t = 300$ MN/m^2.
   a. Estimate the wall thicknesses Saturn would have needed to use to obtain the same panel bending stiffness and strength as the sheet steel ones being replaced (hint: review the information on material selection and derived parameter in Chapter 2).
   b. Using the processing parameters for this polymer blend in Table 8.3, determine the cooling time for the panels during injection molding.
   c. Estimate the projected area of a Saturn automobile front door (do not include the window cutouts!). Determine the likely separating force and hence the likely machine size. Extrapolate the data in Table 8.4 to estimate a likely hourly operating rate for the machine. Your answer is probably conservative, since these were custom made machines, much larger than any standard machines available at the time.
   d. The Saturn roof panels were still manufactured as sheet metal formed parts. Can you offer any explanation as to why these were not changed to injection moldings?

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9

Design for Sheet Metalworking

9.1 Introduction

Parts are made from sheet metal in two fundamentally different ways. The first way involves the manufacture of dedicated dies which are used to shear pieces of required external shape, called blanks, from metal stock that is in strip form. The strip stock may be in discrete lengths that have been cut from purchased sheets or may be purchased as long lengths supplied in coil form. With this method of manufacture, dies are also used to change the shape of the blanks, by stretching, compressing, or bending, and to add additional features through piercing operations. The dies are mounted on vertical presses into which the sheet metal stock may be manually loaded or automatically fed from coil.

The alternative method of manufacture involves the use of computer numerically controlled (CNC) punching machines which are used to make arrays of sheet metal parts directly from individual sheets. These machines usually have a range of punches available in rotating turrets and are referred to as turret presses. The method of operation is to first produce all of the internal part features in positions governed by the spacing of parts on the sheet. The external contours of the parts are then produced through punching with curved or rectangular punches or by profile cutting. The latter operation is usually performed by plasma or laser cutting attachments affixed to the turret press. Parts produced on a turret press are essentially flat, although internal features may protrude above the sheet surface. For this reason it is common practice to carry out secondary bending operations, if required, on separate presses. These are typically performed on wide, shallow bed presses, called press brakes, onto which standard bending tools are mounted.

Using either of these manufacturing methods, sheet metal parts can be produced with a high degree of geometrical complexity. However, the complex geometries are not free form, in the sense of molding or casting but are usually achieved through a combination of individual features that must conform to strict guidelines. These guidelines will be discussed in Section 9.6. Some of the guidelines are material-dependent and most of these are based on the ability of the selected sheet metal to be stretched during the required forming operations. In most cases, this limit of ductility can be defined by the maximum uniform tensile strain which the material can be subjected to before the onset of ductile failure. The exception to this is the process of deep drawing, discussed in Section 9.2.5, which is accomplished by inducing mainly compressive strains as perimeters of deep-formed parts are reduced. For this case a process-based limitation of drawing ratio is used. Descriptions of the manufacturing equipment and tooling will be presented in sufficient detail to understand the contributions to processing time and manufacturing costs. However, the interested reader may wish to consult some of the classic texts on manufacturing processes

TABLE 9.1

Standard U.S. Sheet Metal Thickness

Steels		Aluminum Alloys	Copper Alloys	Titanium Alloys
Gage No.	(mm)	(mm)	(mm)	(mm)
28	0.38	0.41	0.13	0.51
26	0.46	0.51	0.28	0.63
24	0.61	0.63	0.41	0.81
22	0.76	0.81	0.56	1.02
20	0.91	1.02	0.69	1.27
19	1.07	1.27	0.81	1.60
18	1.22	1.60	1.09	1.80
16	1.52	1.80	1.24	2.03
14	1.91	2.03	1.37	2.29
13	2.29	2.29	2.06	2.54
12	2.67	2.54	2.18	3.17
11	3.05	3.17	2.74	3.56
10	3.43	4.06	3.17	3.81
8	4.17	4.83	4.75	4.06
6	5.08	5.64	6.35	4.75

[1–5] for further information. The dedicated text on techniques of sheet metal pressworking by Eary and Reed [6] is of particular interest.

Sheet metal is available from metal suppliers in sheet or coil form, in a variety of sizes and thicknesses, for a wide range of different alloys. Table 9.1 shows the range of gage thicknesses available for the four alloy types that represent almost all the materials used in sheet metalworking. For historical reasons, steels are ordered according to gage numbers, whereas other material types have just a thickness designation. Steels are the most widely used sheet metal group. The reason for this is evident in Table 9.2, which gives typical properties and comparative costs of a sample of materials from the four alloy groups. The maximum tensile strain values are for the materials in an annealed or lightly cold-worked condition suitable for forming. The maximum tensile strain value of 0.22 for commercial-quality steel gives it excellent forming qualities and it has high strength and elastic modulus at very low cost. The combination of modulus and cost gives it unsurpassed stiffness per unit cost in sheet form, and this is the reason for its dominance in the manufacture of such items as automobile and major-appliance body components.

9.2 Dedicated Dies and Pressworking

A typical sheet metal part is produced through a series of shearing and forming operations. These may be carried out by individual dies on separate presses or at different stations within a single die. The latter type of die is usually termed a progressive die, and in operation the strip is moved incrementally through the die while the press cycles. In this way, the punches at different positions along the die produce successive features in the part. We will first consider the use of individual dies.

TABLE 9.2

Sheet Metal Properties and Typical Costs

Alloy	Cost[a] ($/kg)	Scrap[a] Value ($/kg)	Specific Gravity (g/cc)	UTS (MN/m^2)	Elastic Modulus (GN/m^2)	Maximum Tensile Strain
Steel, low-carbon commercial quality	0.80	0.09	7.90	330	207	0.22
Steel, low-carbon, drawing quality	0.90	0.09	7.90	310	207	0.24
Stainless steel T304	6.60	0.40	7.90	515	200	0.40
Aluminum, 1100, soft	3.00	0.80	2.70	90	69	0.32
Aluminum, 1100, half hard	3.00	0.80	2.70	110	69	0.27
Aluminum, 3003, hard	3.00	0.80	2.70	221	69	0.02
Copper, soft	9.90	1.90	8.90	234	129	0.45
Copper, 1/4 hard	9.90	1.90	8.90	276	129	0.20
Titanium, Grade 2	19.80	2.46	4.50	345	127	0.20
Titanium, Grade 4	19.80	2.46	4.50	552	127	0.15

[a] Material costs are subjected to constant change and are strongly influenced by the quantity of purchase—text values are intended for design comparison exercises only.

9.2.1 Individual Dies for Profile Shearing

Sheet metal dies are manufactured by mounting punches and die plates into standard die sets. The die sets, as shown in Figure 9.1, consist of two steel or cast iron plates that are constrained to move parallel to one another by pillars and bushings mounted on the separate plates. Small die sets typically have two guide pillars, whereas larger ones have four. In operation, the lower plate is mounted to the bed of a mechanical or hydraulic press and the upper plate is attached to the moving press platen. As the press cycles, the die set opens and closes so that the punches and dies mounted on the two plates move in precise alignment. Figure 9.2 shows a typical mechanical press with a die set mounted in position.

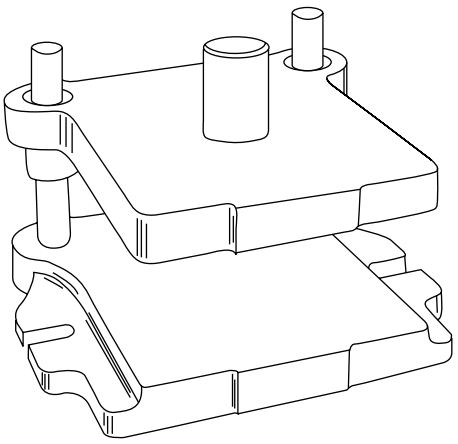

FIGURE 9.1
Die set.

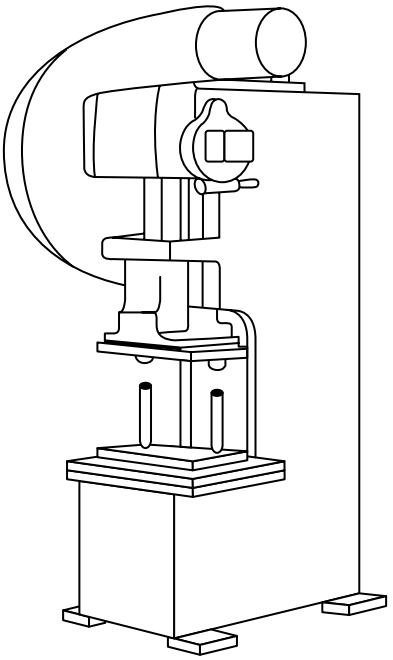

FIGURE 9.2
Mechanical press.

When individual die sets are used, the first operation is typically shearing of the external profile of the part. The way in which this is carried out can be divided into three categories depending on the part design. The most efficient method is a simple cut-off operation, which applies to parts that have two parallel edges and that "jigsaw" together along the length of the strip. For the basic cut-off operation, the trailing edge of the part must be the precise inverse of the leading edge, as shown in Figure 9.3.

Parts designed for cut-off operations may not have the aesthetically pleasing shapes required for some applications. However, for purely functional parts, cut-off type designs have the advantage of simple tooling and the minimization of manufactured scrap. The term "manufactured" scrap refers to the scrap sheet metal produced as a direct result of the manufacturing process, as opposed to the scrap metal of defective parts. For cut-off-type

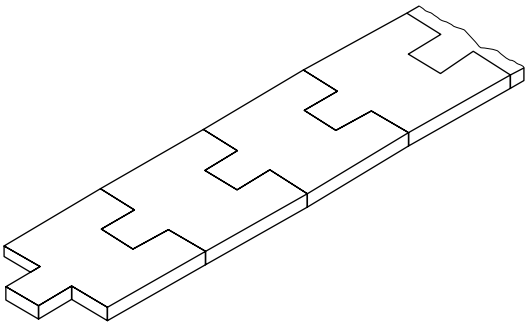

FIGURE 9.3
Cut-off part design.

designs the only manufactured scrap is the sheet edges left over from the shearing of purchased sheets into part-width strips. Some scrap also results from the ends of the strips as they are cut into parts. Shearing of sheets is normally carried out on special presses called power shears, which are equipped with cutting blades and tables for sliding sheets forward against adjustable stops.

For situations where a sheet metal part can be designed with two parallel edges, but where the ends cannot jigsaw together, the most efficient process to produce the outer contour is with a part-off die. This die employs two die blocks and a punch that passes between them to remove the material separating the ends of adjacent parts. The principal design rule for this process, and for the cut-off process, is that the sheared ends should not meet the strip edges at an angle less than about 15°. This ensures that a good-quality sheared edge is produced with a minimum of tearing and edge distortion at the ends of the cut. Thus, full semicircular ends or corner blend radii should be avoided. A simple part that could be produced with a part-off die is illustrated in Figure 9.4. The part-off process offers the same advantage as cut-off in that the part edges are produced inexpensively with a minimum of scrap by power shear operations. The die, however, is a little more complex than a cut-off die, involving the machining and fitting of an extra die block. Scrap is also increased, because the adjacent parts must be separated by at least twice the sheet metal thickness to allow adequate punch strength. The main elements of cut-off and part-off dies are illustrated in Figure 9.5.

For sheet metal parts that do not have two straight parallel edges, the die type used to shear the outer profile is called a blanking die. A typical blanking die is shown in Figure 9.6. This illustrates the blanking of circular disks, but the shape of the "blank" can be almost any closed contour. The disadvantage of blanking as opposed to cut-off or part-off is mainly the increase in manufactured scrap. This arises, because the edges of the part must be separated from the edges of the strip by approximately twice the sheet metal thickness to minimize edge distortion. Thus, extra scrap equal in area to four times the material thickness multiplied by part length is produced with each part. In addition, blanking dies are more expensive to produce than cut-off or part-off dies. The reason for this is that the blanking die has an additional plate, called a stripper plate, which is positioned above the die plate with separation sufficient to allow the sheet metal strip to pass between. The stripper plate aperture matches the contour of the punch so that it uniformly supports the strip while the punch is removed from it on the upward stroke of the press. Note that

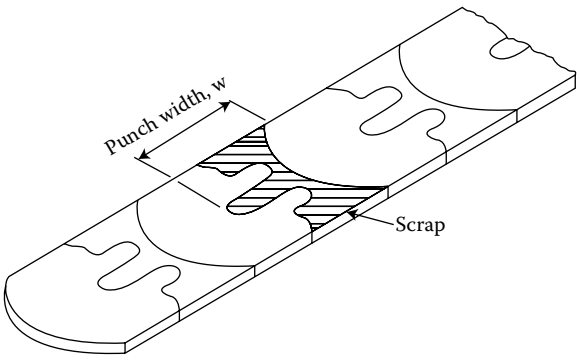

FIGURE 9.4
Part-off part design.

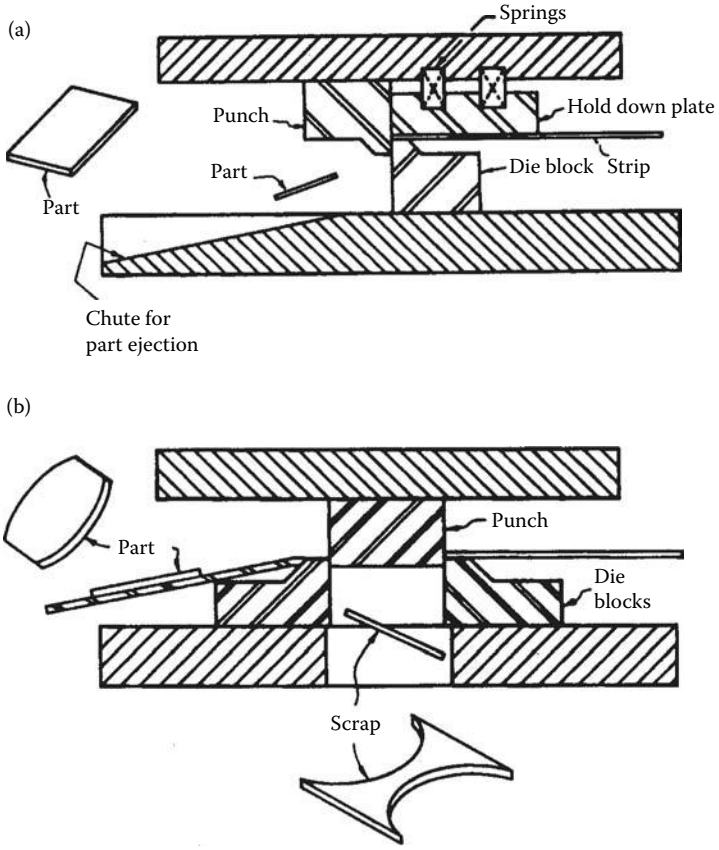

FIGURE 9.5
Die elements of cut-off and part-off dies, (a) cut-off die, (b) part-off die.

in comparison the cut-off die has a simple spring action hold-down block to keep the strip from lifting during the shearing operation.

A less common design for the contour of a sheet metal part is shown in Figure 9.7. This uses a part-off die to produce parts whose ends are 180° symmetric. The opposite part ends shown in Figure 9.7 have a similar appearance, but this need not be the case. If both

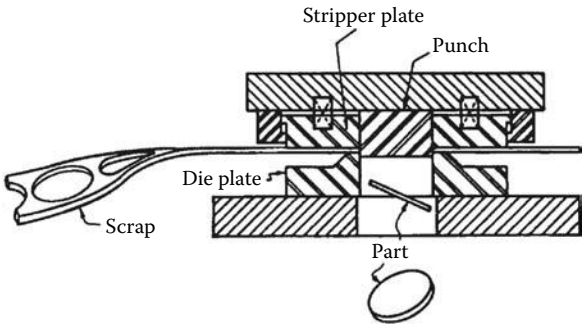

FIGURE 9.6
Blanking die.

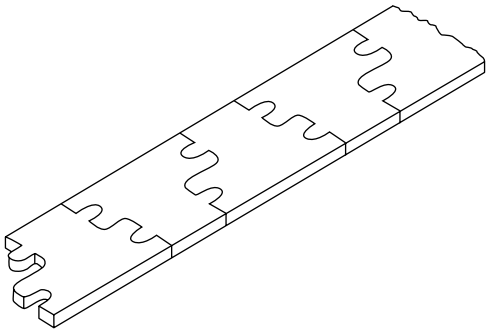

FIGURE 9.7
Part design for cut-off and drop-through.

ends are symmetric, then adjacent parts can be arranged on the strip at a 180° orientation to each other. With this design the portion that is normally removed as scrap in a part-off die is now an additional part. Each press stroke thus produces two parts, and the die is called a cut-off and drop-through die. The general symmetry rule for this type of part seems not to have been applied in practice, and the only examples appear to be simple trapezoid-shaped parts. A problem with cut-off and drop-through is associated with the nature of the shearing process, which tends to produce a rounded edge on the die side of the part from the initial deformation as the sheet is pressed downward against the die edge. However, the final separation of the part from the strip is by brittle fracture, which leaves a sharp edge, or burr, on the punch side of the part. Thus parts made by cut-off and drop-through have the sharp edges on opposite sides of adjacent parts. This lack of edge consistency may be unacceptable for some applications.

Irrespective of the die type used, the sharp edges produced by punching must be removed. This deburring process is carried out, for small parts, by tumbling them in barrels with abrasive slurry. For larger parts, the usual practice is to pass the flat parts, before forming, through abrasive belt machines. In either case, the added cost is small.

9.2.2 Cost of Individual Shearing Dies

Zenger and Dewhurst [7] have investigated the cost of individual dies. For each type of die, the cost always includes a basic die set as shown in Figure 9.1. Current costs of die sets were found to be directly proportional to the usable area between the guide pillars and to satisfy the following empirical equation:

$$C_{ds} = 120 + 0.36A_u \tag{9.1}$$

where
C_{ds} = die set purchase cost, \$
A_u = usable area, cm^2.

For consistency with the cost-estimating procedure adopted below for the punch and die elements, the die set "cost" is represented as an equivalent number of tool making hours. Using a tool-making rate of \$40/h gives the corresponding die-set manufacturing hours as

$$M_{ds} = 3 + 0.009A_u \tag{9.2}$$

To estimate the cost of the tooling elements such as die plate, punch, punch retaining plate, stripper plate, and so on, a manufacturing point system was developed. The system includes the time for manufacturing the die elements and for assembly and tryout of the die. Assembly includes custom work on the die set, such as the drilling and tapping of holes and the fitting of metal strips or dowel pins to guide the sheet metal stock in the die.

The basic manufacturing points were found to be determined by the size of the punch and by the complexity of the profile to be sheared. Profile complexity is measured by index X_p as

$$X_p = \frac{P}{(LW)^{1/2}} \tag{9.3}$$

where

P = perimeter length to be sheared, cm

L, W = length and width of the smallest rectangle that surrounds the punch, cm.

(Please note that X_p has been redefined from earlier versions of the text, where it was represented as $X_p = P^2/(LW)$. A reassessment of the original data showed that a simple linear relationship exists with the square root of the former perimeter complexity measure.)

For a blanking die, or a cut-off and drop-through die, L and W are the length and width of the smallest rectangle that surrounds the entire part. For a part-off die, L is the distance across the strip, while W is the width of the zone removed from between adjacent parts. For a cut-off die, L and W are the dimensions of a rectangle surrounding the end contour of the part. Note that for either cut-off or part-off, a minimum punch width W of about 6 mm should be allowed to ensure sufficient punch strength. Basic manufacturing points for blanking dies were found to be linearly related to the perimeter complexity, as shown in Figure 9.8.

Zenger [8] has shown that the basic manufacturing points for a part-off die are about 9% less than for a blanking die, while those for a cut-off die are approximately 12% less than for blanking. Note that this does not represent the differences in die costs since the punch envelope area LW is less for cut-off and part-off dies and X_p is also generally smaller for

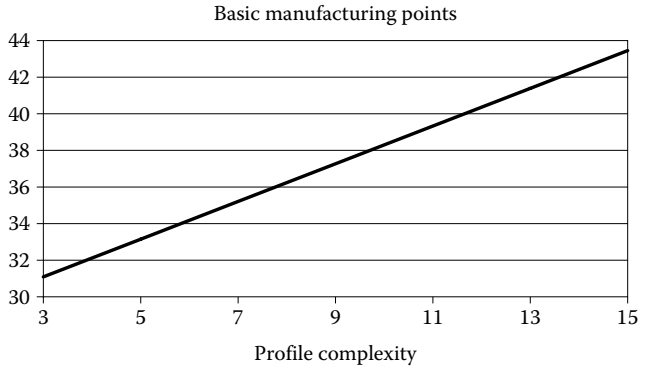

FIGURE 9.8
Basic manufacturing points for blanking die.

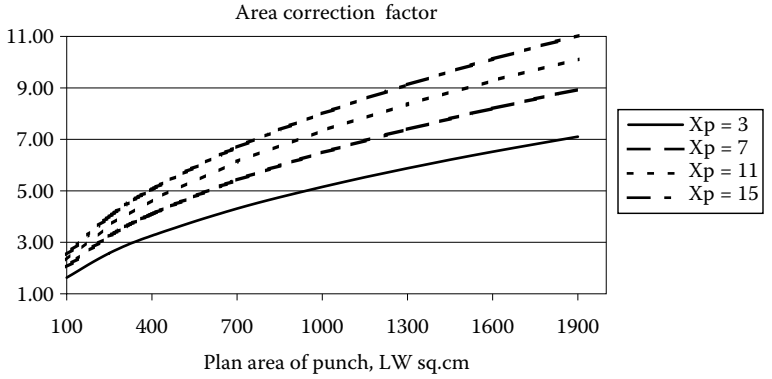

FIGURE 9.9
Area correction factor for die manufacturing points.

these processes. Combining this with the linear relationship from Figure 9.8 gives the basic die-manufacturing hours associated with perimeter complexity to be

$$M_{p0} = f_d(28 + 1.03X_p) \tag{9.4}$$

where die-type factor f_d satisfies:
f_d = 1.0 for a blanking die,
f_d = 0.91 for a part-off die, and
f_d = 0.88 for a cut-off die.

This basic point score is then multiplied by a correction factor for the plan area, *LW*, of the punch. This correction factor, f_{LW}, depends upon both the plan area and the perimeter complexity, as shown in Figure 9.9.

Multiplying the basic points in Figure 9.8 with the area correction factors in Figure 9.9, and adding the equivalent die set points from Equation 9.2, provides a convenient look-up chart (Figure 9.10) for total manufacturing points for a standard blanking die. Values obtained from this chart may be multiplied by the appropriate die-type factor, f_d, to obtain approximate manufacturing point estimates for part-off or cut-off dies. Note that in order

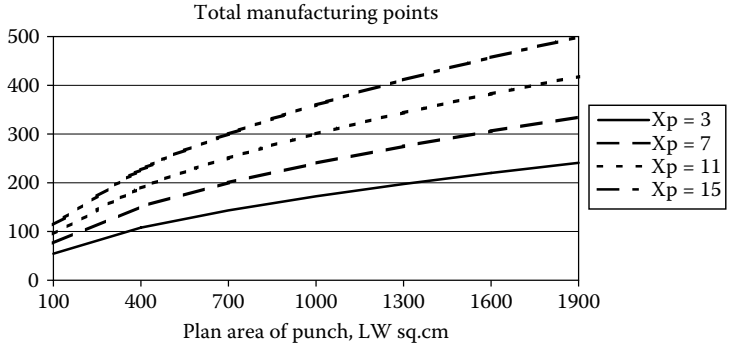

FIGURE 9.10
Total manufacturing points for blanking die.

to obtain this single look-up chart, it was necessary to use the envelope area LW as an estimate of the die usable are A_u in Equation 9.1 for the die-set manufacturing points. This leads to an underestimate of the die-set cost, which in most estimates of the complete die cost is not significant.

For die manufacturing, where computer-controlled wire electro-discharge machining is used to cut the necessary profiles in die blocks, punch blocks, punch holder plates, and stripper plates, each manufacturing point in Figure 9.10 corresponds to one equivalent hour of die making. This also includes the time for cutting, squaring, and grinding the required tool steel blocks and plates. Note that, as for dies and molds for other processes, the cost of the die materials is insignificant compared to the cost of die making.

The estimated point score from Figures 9.8 and 9.9 does not include the effect of building more robust dies to work thicker-gage or higher-strength sheet metal, or to make very large production volumes of parts. To accommodate such requirements it is usual practice to use thicker die plates and correspondingly thicker punch holder plates, stripper plates, and larger punches, together with a more robust die set. This allows the die plate to handle longer-term abuse and also provides additional material for the greater number of times that the punch and die faces must be surface-ground to renew edge sharpness. Recommendations on die plate thickness h_p given by Nordquist [9] fit quite well with the relationship

$$h_p = 9 + 2.5 \log_e \left(\left(\frac{U}{U_{lc}} \right) V h^2 \right) \text{mm} \tag{9.5}$$

where

U = the ultimate tensile stress of the sheet metal to be sheared
U_{lc} = the ultimate tensile stress of annealed low-carbon steel
V = required production volume, expressed in thousands
h = sheet metal thickness, mm.

In practice, in U.S. industry the value of h_p is usually rounded to the nearest one-eighth of an inch to correspond with standard tool steel plate stock sizes.

The manufacturing points obtained from Figures 9.8 and 9.9 were determined for the condition

$$\left(\frac{U}{U_{lc}} \right) V h^2 = 625 \tag{9.6}$$

or

$$h_p = 25 \text{ mm}$$

Zenger and Dewhurst [7] have shown that the cost of dies changes with die plate thickness approximately according to a thickness factor f_p given by

$$f_p = 0.5 + 0.02 h_p \tag{9.7}$$

or

$$f_p = 0.75$$

whichever is larger. If the production quantity is unknown, use $f_p = 1.0$ which corresponds to a standard 2.5 cm thick die plate.

Thus, the manufacturing points M_p for a shearing die (blanking, part-off, or cut-off) are given by

$$M_p = f_p(f_{1w} f_d M_{po} + M_{ds}) \tag{9.8}$$

where

M_{po} = basic manufacturing points from Figure 9.8
M_{ds} = equivalent manufacturing points for the die set from Equation 9.2
f_p = die plate thickness correction factor from Equations 9.5 and 9.7
f_{1w} = plan area correction factor from Figure 9.9
f_d = die-type factor; see Equation 9.4.

EXAMPLE

A sheet metal blank is 200 mm long × 150 mm wide and has plain semicircular ends with radius 75 mm; see Figure 9.11a. It is proposed that 500,000 parts should be manufactured using 16 gage low carbon steel.

Estimate the cost of a blanking die to produce the part and the percentage of manufactured scrap that would result from the blanking operation.

If the part were redesigned with 80 mm radius ends as shown in Figure 9.11b, it could then be produced with a part-off die. What would be the die cost and percentage of manufactured scrap for this case?

The required blank area is 200×150 mm^2. If 50 mm space is allowed around the part for securing the die plate and installation of strip guides, then the required die set usable area A_u is

$$A_u = (20 + 2 \times 5) \times (15 + 2 \times 5) = 750 \text{ cm}^2$$

and so from Equation 9.2 the equivalent tool-making hours for the die set is given by

$$M_{ds} = 3 + 0.009(750) = 9.8 \text{ h.}$$

For the design shown in Figure 9.11a the required blanking punch would have perimeter P equal to 571 mm and envelope dimensions L, W equal to 150 and 200 mm, respectively. Thus, the perimeter complexity index X_p is given by

$$X_p = \frac{571}{(150 \times 200)^{0.5}} = 3.3$$

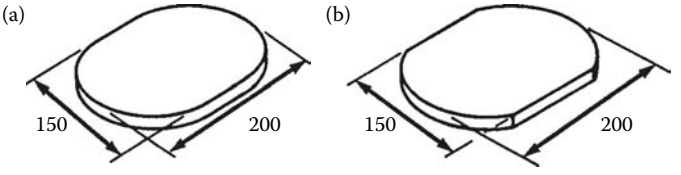

FIGURE 9.11
Sheet metal part (dimensions in mm), (a) blanking design, (b) part-off design.

The basic manufacturing point score from Equation 9.4 is thus $M_{po} = 31.4$. With plan area LW equal to 300 cm^2, the correction factor from Figure 9.9 is approximately 2.5. Thus, the manufacturing points for a basic blanking die are $9.8 + 2.5(31.4) = 88.3$ Note that a rough estimate taken directly from Figure 9.10 is 90 points.

For 500,000 parts of thickness 1.52 mm (equivalent to 16 gage), the die plate thickness from Equation 9.3 is $h_{pl} = 26.6$ mm. The die plate thickness correction factor from Equation 9.5 is thus $f_d = 1.03$.

The total die manufacturing points are therefore

$$M_p = 1.03 \times 88.3 = 90.9$$

Assuming \$40/h for die making, the cost of a blanking die is estimated to be

$$\text{Blanking die cost} = 90.9 \times 40 \simeq \$3600$$

The area of each part is

$$A_p = 251.7 \text{ cm}^2$$

Since the separation between each part on the strip and between the part and the strip edges should be 3.04 mm (equal to twice the material thickness), the area of sheet used for each part is

$$A_s = (200 + 3.04) \times (150 + 2 \times 3.04) \text{ mm}^2$$

$$= 316.9 \text{ cm}^2$$

Thus the amount of manufactured scrap is given by

$$\text{Scrap per cent} = \frac{(316.9 - 251.7)}{316.9 \times 100}$$

$$= 20.6$$

For the alternative design shown in Figure 9.11b, the perimeter to be sheared is the length of the two 80 mm arcs, which can be shown to be given by

$$P = 388.9 \text{ mm}$$

With 3.04 mm separating the parts end to end on the strip, the cross-sectional dimensions L, W of the part-off punch equal 106.5 and 150 mm, respectively.

Thus, the required die area, A_u, equals 516 cm^2, and $M_{ds} = 7.6$. The complexity index X_p, is given by

$$X_p = \frac{388.9}{(106.5 \times 150)^{0.5}} = 3.1$$

The basic manufacturing point score from Equation 9.4 is now $M_{po} = 31.2$. With plan area LW equal to $(10.65 \times 15) = 160$ cm^2 the correction factor from Figure 9.10 is again approximately 2.0. Thus, the manufacturing points for a basic blanking die are $7.6 + 2.0(31.2) = 70.0$.

Since part-off dies are typically 9% less expensive than equivalent blanking dies ($f_d = 0.91$), and the value of f_d is unchanged, the total die-manufacturing hours are

$$M_p = (0.91)(1.03)(70.0) = 65.6$$

Assuming \$40/h for die making as before, the cost of a part-off die is estimated to be

$$\text{Part-off die cost} = 65.6 \times 40 \simeq \$2600$$

The area of each part shown in Figure 9.11b can be shown to be 257.9 cm^2. Since the edges of the strip now correspond to the edges of the part, the area of sheet used for each part is

$$A_s = (200 + 3.04) \times 150 \text{ mm}^2$$

$$= 304.6 \text{ cm}^2$$

Thus, the amount of manufactured scrap for the part-off design is

$$\text{Scrap percent} = \frac{(304.6 - 257.9)}{304.6 \times 100}$$

$$= 15.3$$

It is of interest to compare the die-estimating procedure above with a quick method of determining sheet metal tooling costs developed by Harig [10]. This uses a so-called unit formula system, where a 5 h tool-manufacturing allowance is given for each inch of perimeter length to be sheared. For the above dies, this would give approximate estimates, using the same tool-manufacturing rate, of \$4500 and \$3100 for the blanking and part-off dies, respectively. Note that the Harig values do not take into account geometrical complexity or the required robustness of the die set. However, the method can be used for very easily obtained approximate estimates.

9.2.3 Individual Dies for Piercing Operations

A piercing die is essentially the same as a blanking die except that the material is sheared by the punching action to produce internal holes or cut-outs in the blank. Thus, the die illustrated in Figure 9.6 could also be a piercing die for punching circular holes into the center of a previously sheared blank. However, piercing dies are typically manufactured with several punches to simultaneously shear all of the holes required in a particular part.

It has been shown by Zenger [8] that with piercing dies, the individual punch areas have only a minor effect on final die cost. The main cost drivers are the number of punches, the size of the part, and the perimeter length of the cutting edges of any nonstandard punches. For cost estimation purposes a nonstandard punch is one with cross-sectional shape other than circular, square, rectangular, or obround as illustrated in Figure 9.12. These standard punch shapes are available at low cost in a very large number of small sizes. Any punch shapes other than those in Figure 9.12 will be referred to as nonstandard or custom.

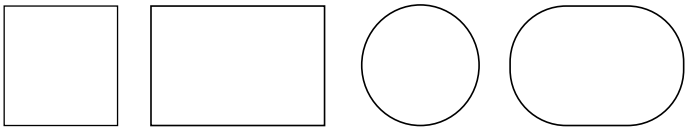

FIGURE 9.12
Standard punch shapes.

Following the procedure developed by Zenger, a manufacturing point score is determined for a piercing die from three main components. First, based only on the area of the part to be pierced, the base manufacturing score is given by

$$M_{po} = 23 + 0.03LW \tag{9.9}$$

where
L, W = length and width of the rectangle that encloses all the holes to be punched, cm.

Equation 9.9 predicts the number of hours to manufacture the basic die block, punch retaining plate, stripper plate, and die backing plate. This must be added to the time to manufacture the punches and to produce the corresponding apertures in the die block. This time depends upon the number of required punches and the total perimeter of nonstandard punches. From a study of the profile machining of punches from punch blocks and of apertures in die blocks, Zenger [8] has shown that the manufacturing points M_{pc} for custom punches can be represented approximately by

$$M_{pc} = 8 + 0.6P_p + 3N_p \tag{9.10}$$

where
P_p = total perimeter of all custom punches, cm
N_p = number of custom punches.

Equation 9.10 is used for estimating the time to manufacture nonstandard or custom punches and for cutting the corresponding die apertures. For the standard punch shapes, shown in Figure 9.12, typical supplier costs for punches and die plate inserts (called die buttons) can be divided by the appropriate tool-manufacturing hourly rate to obtain the equivalent number of manufacturing hours. With this approach, Zenger has shown that manufacturing hours M_{ps} for standard punches and die inserts, and for the time to cut appropriate holes in the punch retaining plate and die plate, can be given approximately by

$$M_{ps} = 3N_p \tag{9.11}$$

where
N_p = number of standard punches.

Combining Equations 9.2, 9.9 through 9.11 gives the total manufacturing points for a piercing die as

$$M_p = 34 + 0.039LW + 0.6P_p + 3N_p \tag{9.12}$$

where
P_p = total perimeter of all custom punches, cm
N_p = total number of all punches.

Note that, as in Section 9.2.2, we have used the plan area LW as the required useable area of the die set in order to arrive at a single empirical cost equation.

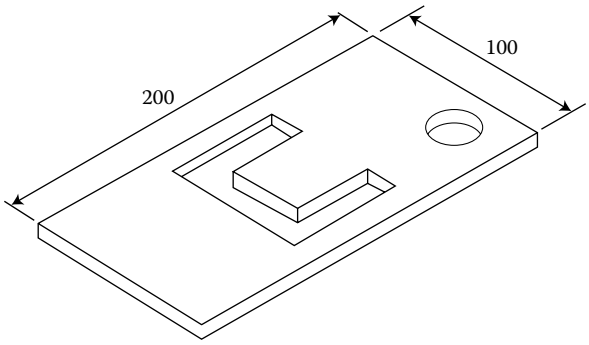

FIGURE 9.13
Part design with three punched holes.

EXAMPLE

Determine the cost of the piercing die to punch the three holes in the part shown in Figure 9.13. The rectangle that surrounds the three holes has dimensions 120×90 mm, and the nonstandard "C"-shaped hole has a perimeter length equal to 260 mm.

The total manufacturing score from Equation 9.12 is thus

$$M_{po} = 34 + 0.039(12 \times 9) + 0.6(26) + 3(3) = 63.3$$

Thus, the estimated piercing die cost, assuming \$40/h for die making, is

$$63.3 \times 40 \simeq \$2500$$

9.2.4 Individual Dies for Bending Operations

Bends in sheet metal parts are typically produced by one of two die-forming methods. The simplest method is by using a v-die and punch combination as shown in Figure 9.14a. This is the least expensive type of bending die, but it suffers because of the difficulty of precisely positioning the metal blank and a resulting lack of precision in the bent part. The alternative method, which allows greater control of bend location on the part, is the wiper die shown in Figure 9.14b. This method is most commonly used for the high-volume production of parts [6]. With the use of dedicated bending dies it is common practice to produce multiple bends in a single press stroke. The basic die block configurations for doing this are the u-die (which is a double-wiper die) shown in Figure 9.15a and the z-die (double v-die) illustrated in Figure 9.15b. It can readily be visualized how a combination of die

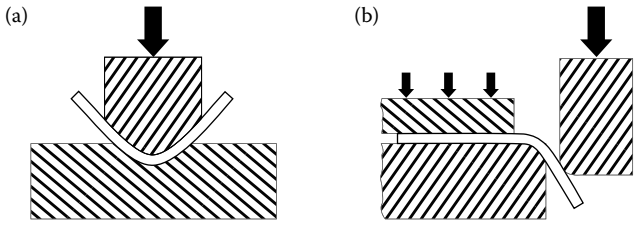

FIGURE 9.14
Basic bending tools, (a) v-die, (b) Wiper die.

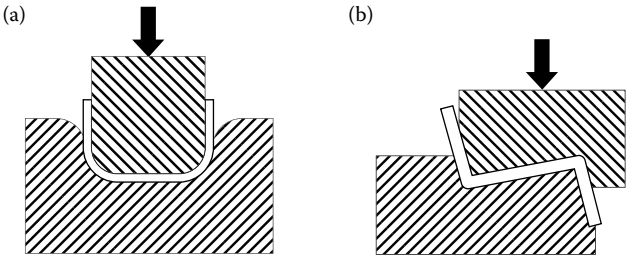

FIGURE 9.15
Basic methods of producing multiple bends, (a) u-die, (b) z-die.

blocks and punches using v-forming and wiper techniques can form a combination of several bends in one die. With the use of die blocks that can move under heavy spring pressure, a combination of bends can be made that displace the material upward and downward. For example, the part shown in Figure 9.16 can be formed in a single die. In this case, a z-die first forms the "front step." The lower die block then proceeds to move downward against spring pressure so that stationary wiper blocks adjacent to the three other sides displace the material upward.

In order to determine the number of separate bending dies required for a particular part, the following rules may be applied:

1. Bends that lie in the same plane, such as the four bends surrounding the central area in Figure 9.16, can usually be produced in one die.
2. Secondary reverse bends in displaced metal, such as the lower step in Figure 9.16, can often be produced in the same die using a z-die action.
3. Secondary bends in displaced metal that would lead to a die-locked condition are usually produced in a separate die.

For example, consider the part shown in Figure 9.17. Bends a, c, and d or bends a, b, and d could be formed in one die by a combination of a wiper die and a z-die. The remaining

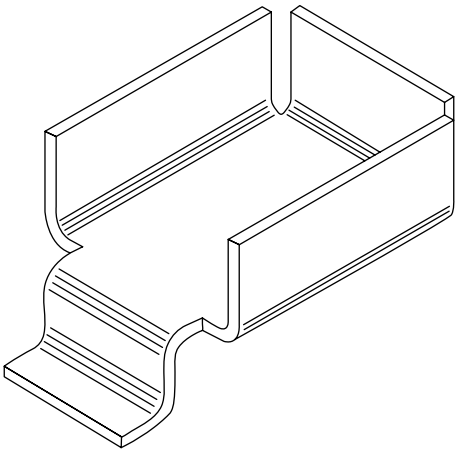

FIGURE 9.16
Multiple bends produced in one die.

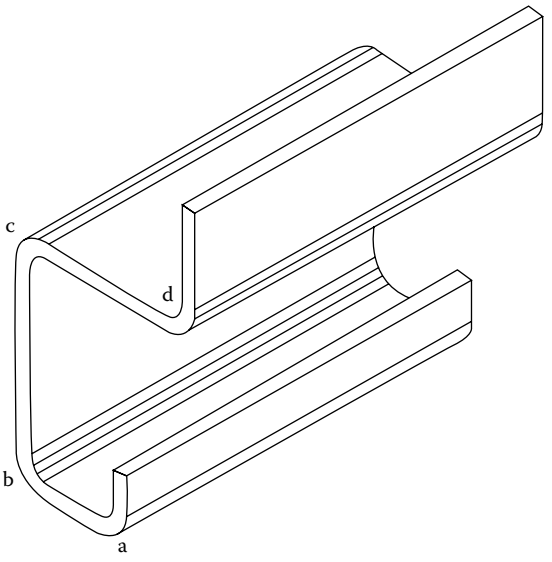

FIGURE 9.17
Part design requiring two bending dies.

bend would then require a second wiper die and a separate press operation. For example, bend b could be produced in the second die using a tooling arrangement, as shown in Figure 9.18.

Referring once more to the early cost-estimating work by Zenger [7], the following relationships were established from investigations of the cost of bending dies. The system is based on a point score that relates directly to tool-manufacturing hours as before. First, based on the area of the flat part to be bent the base die-manufacturing score for bending is given by

$$M_{\text{po}} = (18 + 0.023LW) \tag{9.13}$$

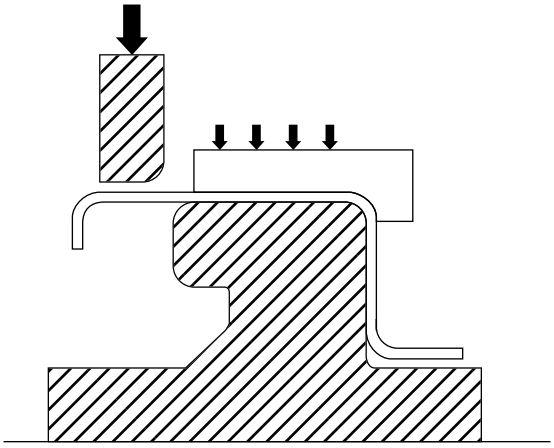

FIGURE 9.18
Wiper-die arrangement to produce bend b in Figure 9.17.

where
L, W = length and width of rectangle that surrounds the part, cm.

An additional number of points are then added for the length of the bend lines to be formed and for the number of separate bends to be formed simultaneously. These are given by

$$M_{pn} = 0.68L_b + 5.8N_b \tag{9.14}$$

where
L_b = total length of bend lines, cm
N_b = number of different bends to be formed in the die.

The total manufacturing points, including those for the die set from Equation 9.2, can thus be represented by

$$M_p = 21 + 0.032LW + 0.68L_b + 0.58N_b \tag{9.15}$$

Zenger [7] has shown that for parts, whose final bent depth D is greater than 5 cm, the base manufacturing points in Equation 9.13 should be multiplied by factor $(0.9 + 0.02D)$, leading to a corresponding change in Equation 9.15.

EXAMPLE

The part shown in Figure 9.16 is produced from a flat blank 44 cm long by 24 cm wide. There are five bends and the total length of the bend lines is 76 cm. Thus, Equation 9.14 gives

$$M_p = 21 + 0.032(44 \times 24) + 0.68(76) + 5.8(5) = 135.5$$

Again using \$40/h for tool making, the cost of the bending die is given by

$$C_d = 135.5 \times 40 \simeq \$5400$$

9.2.5 Individual Dies for Deep Drawing

Deep drawing is a the process used to make deep hollow components from flat shapes, called blanks, which have been produced by an initial shearing operation. This is the most complex of sheet metal forming operations, and the process is usually limited to large production volumes because of the high tooling costs. The process is most commonly used for cylindrical components of which the most common in modern society is the aluminum beverage can. However, deep-drawn components are not limited to circular cross-sections and a wide range of open-top box shapes are to be found in products. These range in size from cases for electronic components to oil pans on combustion engines. Figure 9.19 shows a deep-drawn rectangular component which has been drawn from a flat rectangular blank. In this case, the blank has been drawn down partially into the draw die to leave a flange around the top of the component. A cross-sectional view of the tooling used to form this part is illustrated in Figure 9.20. This shows the three elements of a sheet metal draw die; namely a matching punch and die together with a third tooling element

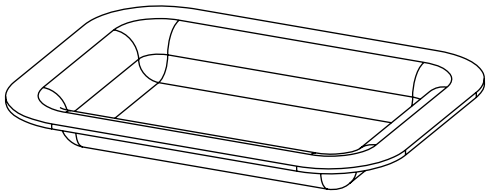

FIGURE 9.19
Deep drawn rectangular component.

called a blank holder. The blank holder exerts pressure on the outer part of the blank as it is drawn inwards by the downward force of the punch. As the blank is drawn inwards, its outer perimeter decreases resulting in large induced compressive stresses in the plane of the sheet. Without the pressure of the blank holder, these induced compressive stresses generally result in wrinkling of the flange and unacceptable components. The blank holder is often held down by hydraulic or pneumatic cushions built into the die set. However, in some cases, it is necessary to use special double-action hydraulic presses in order to exert sufficient blank holder pressure to prevent wrinkling.

It is obvious from examination of the tooling arrangement in Figure 9.20 that further travel of the punch would produce a narrower flange and finally a box shape with just straight vertical walls. Because of slight differences in the properties of rolled sheet metal from the rolling to the transverse direction, deep drawing can never produce a perfect profile around the outside of the flange, or around the top of a fully drawn component. They require a secondary trimming operation, using tooling similar to a blanking die to remove the slight edge waviness.

It should be noted that drawn parts may be redrawn with increasingly smaller punch and die sets to produce deeper and, if desired, stepped components. Figure 9.21 illustrates the component shape produced by an initial full drawing operation of a circular blank, followed by two partial redrawing operations. If in each of the drawing operations, the component had been pushed fully through the draw die, then the final drawn cylindrical component would be approximately half the diameter and three times as tall as the first drawn "cup" on the left.

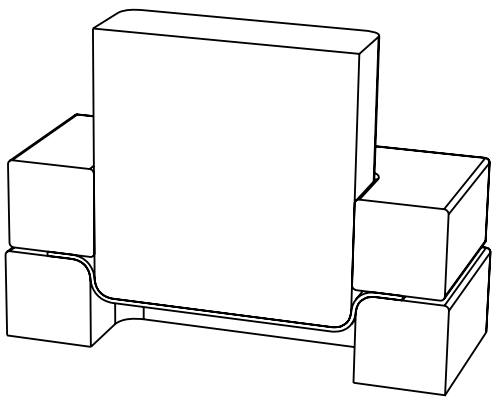

FIGURE 9.20
Tooling elements for deep drawn rectangular component.

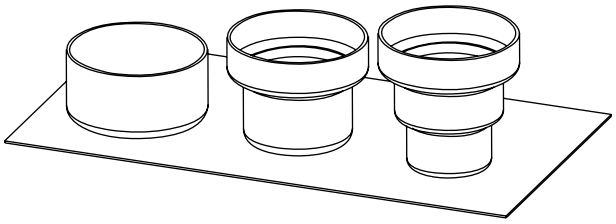

FIGURE 9.21
Part produced by deep drawing and two redrawing operations.

Because the principal deformation in deep drawing results from compressive strains outside the dies (in the inward flowing flange), large ratios of part depth to diameter are possible without exceeding the material ductility. Extreme examples are the cylindrical metal refills used in ball-point pens, many of which are made by deep drawing sequences, followed by a final tapered forming of the ends down to the ball socket.

The base of a deep drawn part is essentially the same thickness as the original blank, since a negligible amount of stretching occurs over the punch face. Because of the circumferential compression of the flange as it travels towards the opening of the die, the wall thickness of a deep-drawn part increases slightly towards the top. This thickening can be removed in a subsequent 'ironing' operation, or ironing can be carried out more aggressively to substantially reduce the wall thickness. Figure 9.22 shows a section across the diameter of an ironing operation, showing the punch pushing a previously drawn cup through an ironing die. Repeated ironing operations are used in beverage can manufacture to reduce the material in the wall. No successful method has been found,

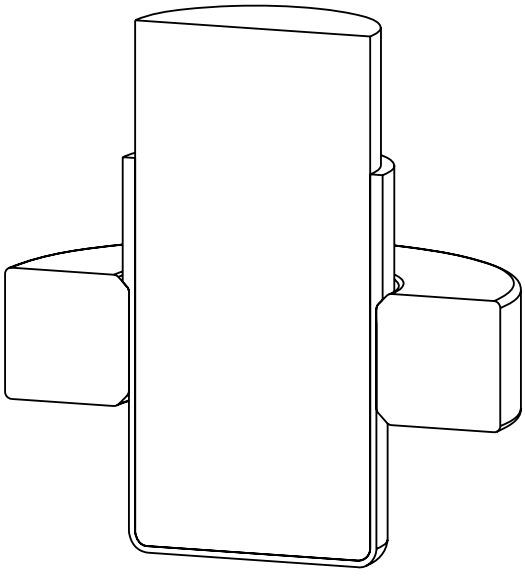

FIGURE 9.22
Section view of ironing operation.

however, to further reduce cost by reducing the base thickness from its initial blank thickness.

From the above discussion, it is clear that the manufacturing process steps for a deep drawn component may include the following:

Die cut blanks; deep draw initial form; redraw multiple times if necessary for extra deep parts; iron if required to reduce wall thickness; trim flange or top of part to eliminate waviness; carry out additional die operations to produce holes or miscellaneous features (see Section 9.2.6).

The reason why multiple re-drawing operations are often required is that a limit exists on the reduction in cross-section which can be achieved in a single operation. If the limit is exceeded then the force required on the punch to produce the drawing action overstresses the blank around the edges of the punch face with resulting tearing of the sheet metal. The limit, which varies with different materials, is called the limiting drawing ratio (β) and is represented for cylindrical deep drawn components as

$$\beta = \frac{D_0}{D_1} \tag{9.16}$$

where D_0 and D_1 are the outer part diameter before and after drawing, respectively. Values of β for initial draw and first redraw, for a number of the materials in Table 9.2, are given in Table 9.3 below.

Investigations by Panknin and Dutschke [11] show that these limiting drawing ratio values can be applied to rectangular box-type parts if β is redefined as

$$\beta = \left(\frac{A_0}{A_1}\right)^{1/2} \tag{9.17}$$

where A_0 and A_1 are the part cross-sectional areas before and after drawing, respectively. Industry practice follows a constant reduction of 4% in the maximum drawing ratio for further redrawing operations. For example, a second redrawing operation using commercial quality low-carbon steel would be limited to a maximum drawing ratio of (1.3)(0.96) = 1.248.

With respect to the cost of dies for deep drawing, guidelines established by Harig [10] and extensive costing analyses carried out by Hardro [12] will be followed. Deep drawn parts usually have a simple contour with substantial radii in any corner to facilitate the

TABLE 9.3

Material Properties for Deep Drawing

Alloy	Yield Strength Y_1 at 1% Strain (MN/m²)	β_0 Initial Draw	β_1 First Redraw
Steel, low-carbon commercial quality	235	2.00	1.30
Steel, low-carbon, drawing quality	236	2.10	1.35
Stainless steel T304	326	2.18	1.30
Aluminum, 1100	43	2.10	1.35
Aluminum, 3003	53	1.80	1.30

blank "flow" into the draw die. For this reason, the profile grinding of profile radii around the edges of the punch and draw die, or of the chamfer on the edges of ironing dies represent only small additional costs. The costs of die sets for ironing or trimming can be estimated exactly as for blanking in Section 9.2.2. For a drawing operation, requiring a blankholder, Harig suggests that an additional 30% should be added to the basic tooling cost estimate; that is, $f_d = 1.3$ in Equation 9.8.

EXAMPLE

The cup shown in Figure 9.23 is 10 cm diameter by 20 cm tall and is to be manufactured from 18 gage deep drawing quality low-carbon steel. Determine the number of drawing operations required and estimate the tooling cost for the first two operations.

The surface area of the part is

$$\text{Area} = \pi(5)^2 + \pi(5)(20) = 392.7 \text{ cm}^2$$

The diameter of the required circular blanks is thus

$$D_0 = \left(\frac{(4)(392.7)}{\pi} \right)^{1/2} = 22.4 \text{ cm}$$

From Table 9.3, the minimum diameter after the first drawing operation is

$$D_1 = \frac{22.4}{2.1} = 10.65 \text{ cm}$$

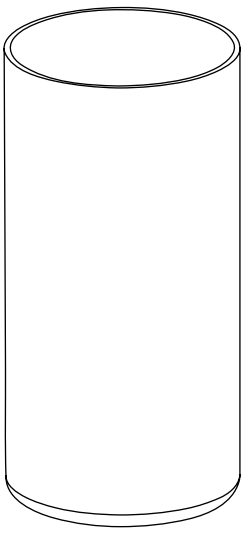

FIGURE 9.23
Deep cylindrical drawn part.

and so two drawing operations are required. If we use the same factor, λ, of the maximum allowable drawing ratio, then from Table 9.3 we obtain

$$\frac{22.4/(2.10\lambda)}{(1.35\lambda)} = 10.0 \quad \text{or} \quad \lambda = 0.888$$

Hence, the tooling would be designed to produce initial drawing ratio 1.865 and redraw ratio 1.20. The diameter after the first draw would then be 22.4/1.865 = 12.0 cm.

For circular die profiles, the perimeter complexity value from Equation 9.3 is

$$X_p = \pi$$

and so the basic die-manufacturing points are

$$M_{p0} = 28 + 1.03(\pi) = 31.2$$

The plan area of the blank is $(22.4)^2 = 501.8$ cm^2, and so from Figure 9.9 the area correction factor is $f_{lw} = 3.6$ and so the total manufacturing hours for the die elements is estimated to be

$$M_p = (3.6)(31.2) \simeq 112 \text{ h}$$

Using useable die set area $A_u = (22.4 + 10)^2 = 1050$ cm^2, the equivalent manufacturing hours for the die set are

$$M_{ds} = 3 + 0.009(1050) \simeq 12.5 \text{ h}$$

Finally, assuming a tool-manufacturing rate of \$40/h, the estimated cost of the blanking die is

$$\text{Blanking die cost} = (112 + 12.5)(40) \simeq \$5000$$

For the first draw die the plan area is $(12)^2 = 144$ cm^2, and so from Figure 9.9 the area correction factor is now $f_{lw} \simeq 1.5$ and so the total manufacturing hours for the die elements is estimated to be

$$M_p = (1.5)(31.2)(1.3) \simeq 61 \text{ h}$$

Note that the final factor of 1.3 in this calculation is to allow the added cost of a pressure blank holder in the tooling.

Using useable die set area $A_u = (12 + 10)^2 = 484$ cm^2 the equivalent manufacturing hours for the die set are

$$M_{ds} = 3 + 0.009(484) \simeq 7.4 \text{ h}$$

Finally assuming a tool-manufacturing rate of \$40/h, the estimated cost of the initial draw die is

$$\text{Initial draw die cost} = (61 + 7.4)(40) \simeq \$2750$$

Similar calculations based on the final diameter of 10.00 cm are used to determine the costs of the redraw die and the final trim die.

9.2.6 Miscellaneous Features

Other features commonly produced in sheet metal parts by regular punching operations are lances, depressions, hole flanges, and embossed areas.

A lance is a cut in a sheet metal part that is required for an internal forming operation. This may be for the bending of tabs or for the forming of bridges or louver openings. In producing a lance the cutting edges of the punch are pressed only partway through the material thickness, sufficient to produce the required shear fracture.

Depressions are localized shallow-formed regions produced by pressing the sheet downward into a depression in the die plate with a matching profile punch. The punch and die surfaces in this case are analogous to the cavity and core in injection molding, and the "cavity" is filled by localized stretching of the sheet metal. Patterns of long, narrow depressions, called beads, are often formed onto the open surfaces of sheet metal parts, in order to increase bending stiffness. Unlike deep drawing, where the material flows into the die without thinning, in a depression the sheet material reduces in thickness as a result of being stretched around the punch profile. For example, in the depression shown on the left side of the part in Figure 9.24, assume the material is stretched by approximately 15% in every direction. Because the volume of metal stays constant after forming, the thickness will have been reduced by approximately 30%. In contrast, the embossed region shown on the right side of the part in Figure 9.24 is reduced in thickness by a direct compression between punch and die. In this case, the required punch pressures are much larger than for the material stretching involved in depression forming. For this reason, embossed areas are usually small, with only modest reductions in thickness.

Finally, hole flanges are produced by pressing a taper or bullet-nosed cylindrical punch into a smaller punched hole. The material is thus stretched by an entry of the larger punch and displaced in the direction of punch travel. Because of ductility limitations of sheet metals, typically hole flanges can only be formed to a height of two or three times the sheet metal thickness.

The cost of dies for these miscellaneous operations can be determined from the equations for the costs of piercing dies given in Section 9.2.3. Equation 9.9 is used to determine the base cost of the die plates, punch blocks, and so on. The additional cost of punch and die machining is then obtained from Equation 9.10. In this case, parameter P_p is the perimeter of the forming or cutting punches to be used. With the appropriate rate for tool

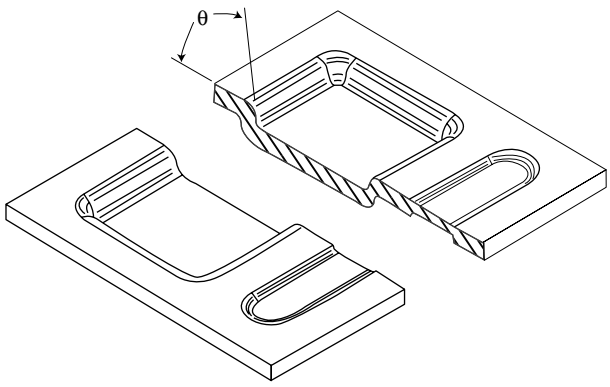

FIGURE 9.24
Shallow formed and embossed regions of sheet metal part.

making and an appropriate die set cost, these Equations can provide an approximate estimate of die cost for lancing, hole swaging, or the forming of simple depressions or embossed areas. However, if the required formed areas of a part have surface details or patterns, then the cost of machining appropriate die surfaces should be added. Empirical equations given in Chapter 8, for the machining of geometrical details in matching cavities and cores, can be used for this purpose. Combining appropriate equations from Chapter 8, the number M_{px} of additional hours of punch and die machining is given by

$$M_{px} = 0.313 N_{sp}^{1.27} \text{ h} \tag{9.18}$$

where

N_{sp} = total number of separate surface patches to be machined on punch faces and matching die surfaces.

9.2.7 Progressive Dies

For the manufacture of sheet metal parts in very large quantities, the hand-loading of parts into individual dies at different presses is unnecessarily inefficient. If the quantities to be produced can justify the additional tooling expense, then it is usual practice to use a multistation die on a single press. Stations within the die carry out the different piercing, forming, and shearing operations as the sheet metal is transported incrementally through the die. To carry out this incremental movement, the sheet metal is supplied from coil, which has to be purchased in the required width, and which is fed through the die automatically by coil feeding equipment mounted at the side of the press. An example of multistation operation is illustrated in Figure 9.25. It can be seen that the technique is to produce features on the part at the different stations and then to separate the part from

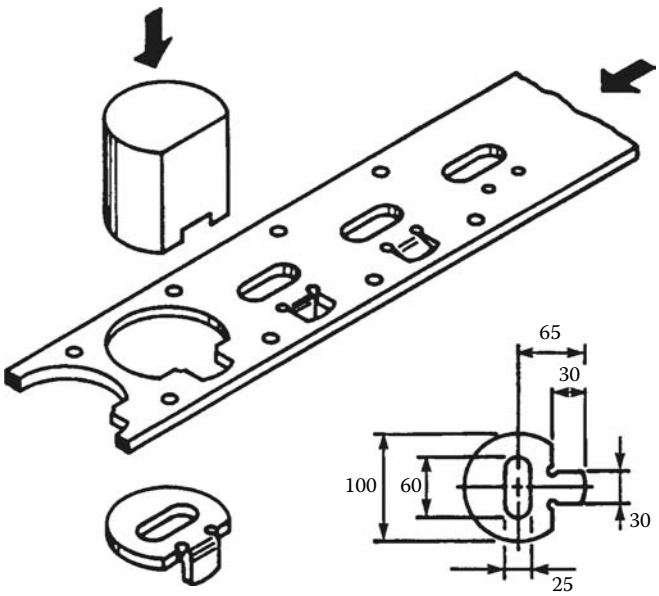

FIGURE 9.25
Multistation die operation with strip feed.

the strip at the last one. The illustration in Figure 9.25 shows the last station as a blanking operation. However, as described in Section 9.2.1, if the part can be designed appropriately, then the separation from the strip can take place with a part-off or cut-off operation with reduced scrap and lower die cost. It should be noted that for complex-shaped parts, the perimeter is usually sheared in increments at the different stations with only the final parts of the profile being sheared at the last station. This allows a more uniform distribution of shearing forces among the different stations, resulting in balanced loads on the die. It also enables bending operations to be performed with wiper dies when portions of the perimeter around the bend have been removed. The two additional holes in the strip skeleton shown in Figure 9.25 are punched at the first station and then engaged with taper-nosed punches at the second station. This pulls the strip into a more precise registration between the stations so that part accuracy does not depend on the accuracy of the strip feeding mechanism.

The design of progressive dies is an art form with only basic principles of alignment, required clearances, material ductility, and loading distribution to guide the tool engineer. Die casting or injection-molding designs for the same part produced by different designers are almost identical. In contrast, progressive dies for the same sheet metal part may be entirely different, with different numbers of stations and different combinations of shearing and forming punches. Under these circumstances, early cost estimating of progressive dies can only be approximate. For such estimates, at the sketch stage of part design, a rule of thumb quoted in the literature [13] is used. This can be stated as

$$C_{pd} = 2C_{id} \tag{9.19}$$

where

C_{pd} = cost of single progressive die

C_{id} = cost of individual dies for blanking, cut-off or part-off, piercing, and forming operations for the same part.

As reported by Zenger [8] the factor 2 seems to agree with tool cost quotes for other than very simple or very complex parts. For the latter, the appropriate factor can be as high as 3, whereas for very simple parts a factor of 1.5 may be more appropriate.

9.3 Press Selection

A selection of typical presses used for sheet metal stamping operations is given in Table 9.4. These are referred to as "single-action" presses, since they consist of a single slide or ram which closes and opens the dies. For deep drawing, double-action presses are sometimes required. These have an inner ram which closes the die, and an outer ram which holds the blank down to prevent wrinkling as the material is drawn inwards. The conditions which require the use of a double-action press are discussed later in this section. When a double-action press is required, the press operating costs given in Table 9.4 should be increased by 20% [12]. In choosing the appropriate press for a given part, the main considerations will be the press bed size and the required press force. For shearing operations, the required force is simply determined from the shear length, gage thickness, and material shear

TABLE 9.4

Single-Action Presses

Bed Size		Press Force	Operating Cost[a]	Maximum Press Stroke	Strokes
Width (cm)	Depth (cm)	(kN)	($/h)	(cm)	(per min)
50	30	200	55	15	100
80	50	500	76	25	90
150	85	1750	105	36	35
180	120	3000	120	40	30
210	140	4500	130	46	15
240	175	6000	140	54	8

[a] Machine rates will vary by country, region, and year–text values are intended for design comparisons only. If a double-action press is required for a deep drawing operation, then 20% increase should be made to the above operating costs.

strength. For metals, the material strength in shear, S, is approximately half of the strength in simple tension. Moreover, during shearing, the strains build up rapidly in the narrow shear zone extending between the punch and die edges; see Figure 9.26. This means that strain hardening must be taken into account and that the tensile strength at failure, denoted by U (ultimate tensile strength), is more appropriate than the initial yield strength. Accordingly, the required force f for such operations as blanking, piercing, lancing, and so on, is given by

$$f = 0.5Uhl_s \text{ kN} \tag{9.20}$$

where

U = ultimate tensile strength, kN/m^2
h = gage thickness, m
l_s = length to be sheared, m.

As an example, circular disks 50 cm in diameter are to be blanked from No. 6 gage commercial-quality, low-carbon steel. From Tables 9.1 and 9.2 the thickness of 6 gage steel

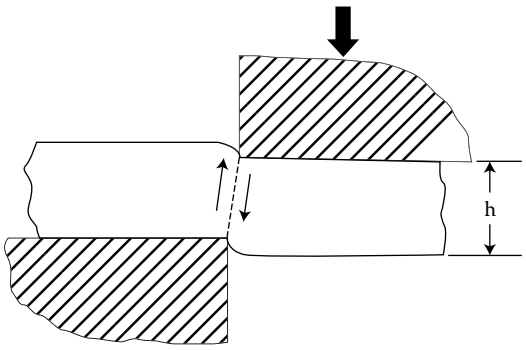

FIGURE 9.26
Shearing operation.

is 5.08×10^{-3} m and the ultimate tensile strength U is 330×10^3 kN/m^2. The required blanking force is thus given by

$$\begin{aligned} f &= 0.5 \times (330 \times 10^3) \times (5.08 \times 10^{-3}) \times (\pi \times 50 \times 10^{-2}) \\ &= 1316.6 \text{ kN} \end{aligned}$$

Thus, the 1750 kN press in Table 9.4, which can be seen to have sufficient bed size, would be the appropriate choice.

For bending operations, the required forces are usually much less than for shearing. For example, for the bending operation illustrated in Figure 9.27, assume that the inside bend radius, r, equals twice the gage thickness, h. Under these conditions, as the material is bent around the die profile, through increasing angle θ, the length of the outer surface increases to $3h\theta$. The length of the centerline of the material (the neutral axis in simple bending) remains approximately constant at $2.5h\theta$. The strain in the outer fibers of the material is thus

$$e = \frac{(3h\theta - 2.5h\theta)}{2.5h\theta} = 0.2 \tag{9.21}$$

The strain decreases to zero from the outer fibers to the centerline, and then becomes compressive, increasing to approximately −0.2 on the inside surface. The average magnitude of strain in the bent material is thus $0.5e$ under these conditions. To obtain an approximate value of the required force we can consider the energy balance in the process. The work done per unit volume on the material as it forms around the die is the product of stress and strain. If we assume that the punch radius also equals twice the thickness, then the 90 bend would be completed when the punch moves down, while in contact with the part, through a distance of approximately $5h$. At this point, the volume of material subjected to bending is

$$V = \frac{\pi((3h)^2 - (2h)^2)L_b}{4} = \frac{5\pi h^2 L_b}{4} \tag{9.22}$$

where L_b is the bend length.

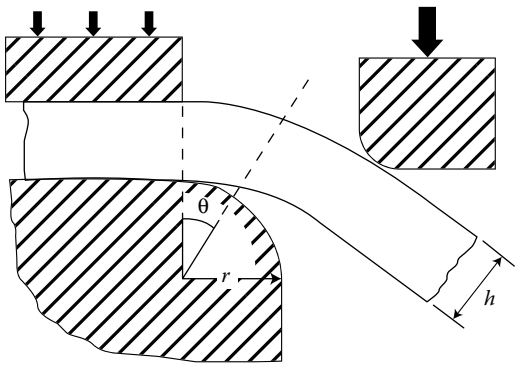

FIGURE 9.27
Wiper die bending operation.

The energy balance can thus be represented approximately by

$$0.5e \times U \times \frac{5\pi h^2 L_b}{4} = f \times 5h \tag{9.23}$$

where f is the average press force that moves through distance $5h$. Thus, under these conditions, the press force f is given by

$$f = 0.08UhL_b \text{ kN} \tag{9.24}$$

Comparing Equation 9.24 with Equation 9.20 shows that under typical bending conditions the required force is only about 15% of the force required for shearing of the same length and gage thickness. Eary and Reed [6] give an empirical relationship for wiper die bending as

$$f = \frac{0.333UL_b h^2}{(r_1 + r_2)} \text{ kN} \tag{9.25}$$

where r_1, is the profile radius of the punch and r_2 is the profile radius of the die. This agrees almost precisely with Equation 9.18 for the condition $r_1 = r_2 = 2h$.

For deep drawing of a cylindrical component, the forces are largest near the beginning of the operation when the largest flange diameter is being drawn inwards to the die. The radial drawing stress induced in the material leading down into the die, at the very start of drawing, is given by [14]

$$\sigma_d = Y \log_e\left(\frac{D_0}{D_1}\right) \tag{9.26}$$

where Y is the yield stress of the material, and D_0, D_1 are the outer blank and die diameters, respectively. Since this draw stress acts around the entire perimeter of the punch, the required punch force can be represented by

$$f = \lambda PhY \log_e\left(\frac{D_0}{D_1}\right) \tag{9.27}$$

where P = perimeter length of punch, h = gage thickness, and λ is a factor which allows for blank holder friction, bending around the die profile, and the effect of operation and shape type. For cylindrical parts, the appropriate value of λ is 1.3. The formula can also be applied to rectangular box-type parts. However, for these cases the drawing effect is into the curved corners, while around the sides the material merely bends over the die radius. This results in a reduction of drawing force by typically 50%, and so a value of 0.65 should be used for factor λ.

The yield stress value in Equation 9.26 rises during the early part of the operation, because the effect of strain hardening which increases the material yield stress and so f directly, outweighs the reduction in the diameter ratio which decreases f, but less significantly through the logarithmic term. For initial drawing operations, a value of Y resulting

from 1% strain hardening may be used; that is, Y_1 from Table 9.3. For redrawing operations it may be assumed that the material has been full hardened in the initial drawing operations, and the ultimate tensile stress, *U*, from Table 9.2 should be substituted for *Y*.

An additional consideration for press selection for deep-drawing is the potential for wrinkling of the blank as it is drawn radially inwards. Eary and Reed [6] have shown that a propensity for the blank to wrinkle, which can only be avoided by using a double-action press, exists when $D_0/h \geq 200$. In this case, as discussed at the beginning of this section, the press operating costs in Table 9.4 should be increased by 20%. If $D_0/h < 200$, cushions or springs incorporated into the die can be used to prevent wrinkling.

For the deep drawing example at the end of Section 9.2.5, the appropriate values are $h = 1.22$ mm, $D_0 = 22.4$ cm, $D_1 = 12.0$ cm, and from Table 9.3 the appropriate value for Y_1 is 236 MN/m². Hence, the required press force from Equation 9.27 is

$$f = (1.3)\left(\frac{22.4\pi}{10^2}\right)\left(\frac{1.22}{10^3}\right)(236\times10^3)\log_e\left(\frac{22.4}{12.0}\right) = 164.4 \text{ kN} \tag{9.28}$$

Also for this example $D_0/h = 18.4$ and so the single-action 200 kN press in Table 9.4 may be used.

For shallow forming, as illustrated on the left side of the part in Figure 9.24, the material being displaced downward into the die form is subjected to stretching in every direction. During this process, the tensile stresses in the stretching material are transmitted from the perimeter of the depression in toward its center. If the walls of the depression make angle θ with the part surface (Figure 9.24), and the stress is assumed to be approximately equal to the ultimate tensile stress, then the vertical resisting force from the walls can be given as

$$f = Uh\sin\theta L \text{ kN} \tag{9.29}$$

where *L* is the perimeter of the depression. This is equal to the required punch force. Thus, for a depression with almost vertical walls ($\sin\theta = 1$) the required punch force can approach twice the force required to shear the material around the same perimeter.

Finally, the region on the right side of the part in Figure 9.24, which has been reduced in thickness, is referred to as having been embossed or coined. This type of bulk forming of sheet metal between punch and die surfaces involves very high compressive stresses. Because the displaced material must flow sideways across the face of the die, this introduces constraints that make the process much less efficient than pure compression. The required force for an embossing operation is thus

$$f = \phi UA \text{ kN} \tag{9.30}$$

where

A = area to be embossed
ϕ = constraint factor > 1.

As the size of the embossed region increases, factor ϕ increases exponentially. Because of this, extensive embossing should be avoided whenever possible. The alternative is to produce required surface patterns through shallow forming, although much less precise pattern details are possible with this form-stretching process.

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9.3.1 Cycle Times

When using individual dies for sheet metalworking, the presses must be manually operated. This involves hand loading of parts into the dies. In the case of shearing (blanking, part-off, cut-off, or piercing), the part can be automatically ejected from the die after the press operation. However, for a bending or forming operation, the press operator must also remove the parts from the die, which increases the cycle time further.

Ostwald [15] has shown that the time to load a blank or part into a mechanical press, operate the press, and then remove the part following the press operation is proportional to the perimeter of the rectangle that surrounds the part. This time can be given by

$$t = 3.8 + 0.11(L + W)\,\text{s} \tag{9.31}$$

where

L, W = rectangular envelope length and width, cm.

For shearing or piercing of flat parts, for which automatic press ejection would be appropriate, two-third of the time given by Equation 9.31 should be used. Also, for the first press operation, the material may be supplied in strips that have been power sheared from large sheets into the appropriate width. These strips are then loaded individually into the die and manually indexed forward after each press operation. The power shearing time per part is typically small, since the strip for several parts is produced by each shear. It is assumed that this time is balanced by the reduced press time per part from strip loading of the first die.

For press working with progressive dies, the cycle time is governed by the size of the press and its reciprocating speed when operated continuously. Typical operation speeds for a variety of press sizes are given in Table 9.4.

EXAMPLE

For the part shown in Figure 9.25 compare the cycle times and processing costs for using individual dies to those for progressive die working. The part is to be made from No. 8 gage stainless steel for which the ultimate tensile stress is 515 MN/m^2.

The outer perimeter of the part equals 370 mm and the thickness of No. 8 gage steel is 4.17 mm. From Equation 9.20 the required shear force for blanking the outer perimeter is

$$f_1 = 0.5 \times (515 \times 10^3) \times (4.17 \times 370 \times 10^{-6})$$
$$= 397\ \text{kN}$$

For piercing the obround cutout with perimeter 149 mm, the required force is

$$f_2 = 160\ \text{kN}$$

Finally, the force required for bending the tab across an approximate 25 mm bend line, with assumed 6 mm tool profile radii, is given from Equation 9.24 as

$$f_3 = 0.333 \times 515 \times 10^3 \times (25 \times 10^{-3}) \times (4.172 \times 10^{-6}) / ((6 + 6) \times 10^{-3})$$
$$= 6.2\ \text{kN}$$

Referring to Table 9.4, it can now be seen that the blanking operation would require the 500 kN press, and the piercing and bending operations could be carried out on the smallest 200 kN press.

Using Individual Dies

For the blanking and piercing operations, we can assume automatic ejection of the blanks and scrap. The cycle time for these two operations will thus be approximated as two-third of the time for loading and unloading given by Equation 9.22:

$$t_1 = 0.67 \times (3.8 + 0.11(10 + 11.5)) = 0.67 \times 5.4$$
$$= 3.6 \text{ s}$$

For the bending operation, part unloading is required and thus

$$t_2 = 5.4 \text{ s}$$

Finally, applying the press hourly rates from Table 9.3 gives the processing cost per part as

$$C_p = \left[\left(\frac{3.6}{3600}\right) \times 76 + \left(\frac{3.6}{3600}\right) \times 55 + \left(\frac{5.4}{3600}\right) \times 55\right] \times 100 \text{ cents}$$
$$= 21.4 \text{ cents}$$

Using Progressive Die

Using a progressive die, the required press force would be approximately

$$f = f_1 + f_2 + f_3 = 563 \text{ kN}$$

The space required for the four die stations is

$$4 \times 100 + 3(2 \times 4.17) = 418.5 \text{ mm}$$

From Table 9.4 the appropriate press has 1750 kN press force, an operating cost of 105 $/h, and a press speed of 35 strokes/min.
The estimated cycle time per part is thus

$$t = \frac{60}{35} = 1.7 \text{ s}$$

and the processing cost per part is

$$C_p = \left(\frac{1.7}{3600}\right) \times 105 \times 100$$
$$= 5.0 \text{ cents}$$

9.4 Turret Pressworking

An alternative to the use of dedicated dies for the manufacture of sheet metal parts is the numerically controlled turret press. This is a machine, as illustrated in Figure 9.28, which contains punches and matching dies in two rotary magazines or turrets. Depending upon the machine size, turrets may contain as many as 72 different dies for a variety of punching operations.

The lower turret rests in the center of the press bed, the surface of which is covered with steel balls that freely rotate in spherical sockets and that project just above the bed surface. For this reason, the press bed is sometimes referred to as a ball table. A large metal sheet placed onto the press bed can thus slide easily to different positions between the two turret faces. This sliding is accomplished by gripping an edge of the sheet in two clamps attached to linear (X, Y) slideways. The slideways are under numerical control, which allows precise positioning of the sheet under the active punch in the machine turret. The turret is also controlled numerically so that while the sheet is moving to the next punching position, the turrets can be rotated to bring the desired punch and die into play.

The advantage of the turret press is that it uses general-purpose punches and dies, which can be used to manufacture a wide range of different parts. Changing from the manufacture of one part to another usually involves changing only one or two of the punches and dies. This is accomplished in a matter of a few minutes. Moreover, the punches and dies fit into standard holders and can be purchased from tool suppliers in a large variety of standard or custom-ordered profiles. In either case, punches and dies typically range from less than $150 for simple cutting punches and dies up to about $750 for punches and dies for cutting complex shapes or doing localized forming operations. The disadvantages of turret press working are that any forming operation must be shallow enough for the part to pass between the two turret faces. Moreover, any forming of depressions, or of lanced areas to produce projections or louvers, must be made in an upward direction. That is, the forming punch must be in the lower turret and the corresponding die in the upper one. This is necessary so that the sheet can continue to slide smoothly over the ball table. Also, formed areas must be limited in height so that they can still pass between the turret faces.

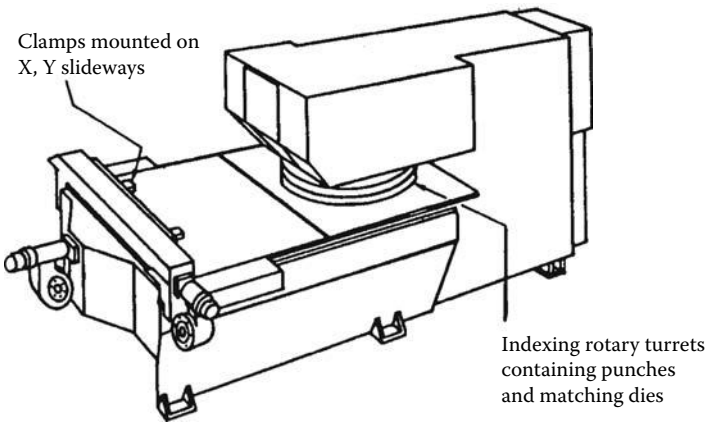

FIGURE 9.28
Turret press.

The limitation depends upon the particular machine but may be of the order of 15 mm. This height limitation also applies to bends; if the parts require bending, this must usually be carried out as a separate operation after the turret press operations are completed. Such bending operations are usually carried out on a special press called a press brake, which will be described later.

The other disadvantage of turret press working is that punching operations are carried out sequentially, and in consequence the cycle time per part may be much longer than with dedicated die sets.

Because of these disadvantages, turret presses are most often used when parts are required in relatively small quantities. In this case, the insignificant cost of the tools easily outweighs the disadvantage of longer cycle times. However, there is no simple rule for choosing the appropriate process, since the changeover point from one process to the other depends on the number of features, the type of features, and the likely cost of dedicated tooling.

A typical turret press manufactured part is shown in Figure 9.29. The part is laid out to cover the sheet, usually in a regular array pattern as shown. The turret press is programmed to punch one of the two hole types first in every row and column position on the sheet. The turret then rotates to the punch for the other hole and punches that one in the appropriate position for every part. Finally, cut-off punches are used to shear the outer part perimeters. For straight edges, narrow cutting punches typically about 6 mm thick are used to separate parts. As shown in Figure 9.29, the punching positions are programmed to leave small regions, called microtabs, still connecting all adjacent parts. This allows the punching to continue without frequent stoppages for part removal. The sheet can then be removed at the end of the machine cycle with all of the parts attached. Parts can then be knocked out of the sheet, or with thin-gauge material separated by simply shaking the sheet. In industrial jargon, the parts are referred to as shaker parts. External radii such as the two lower corners of the parts shown in Figure 9.29 are produced with a radius tool of the types shown in Figure 9.30. It should also be noted that the punching of the external profile requires a cut-off punch in two different orientations for the vertical and horizontal edges, respectively. For most turret presses this will be accomplished by having two different cut-off punches at different turret positions. However, some turret

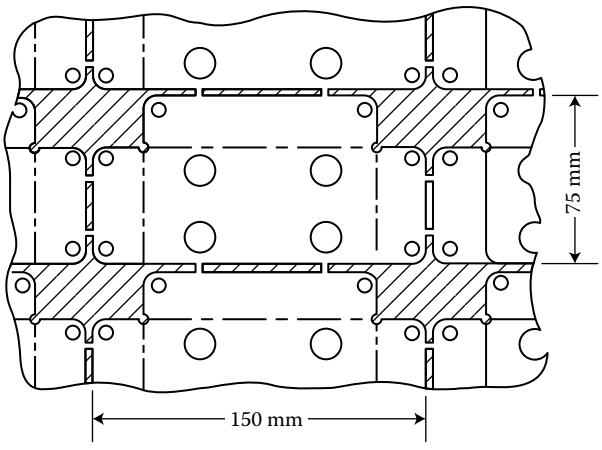

FIGURE 9.29
Layout of parts produced by turret press; (– —— –) Subsequent bend lines.

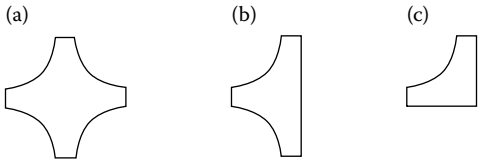

FIGURE 9.30
Turret press radius tools.

presses have so-called indexers, or tool holders which can be rotated under numerical control. These offer the possibility of efficient turret press manufacture of a much wider variety of part geometries.

Turret presses are less efficient when required to produce more complex curved edges. In this case, one method is to use a circular punch to create the curved edge through successive closely spaced hits. This procedure, known as nibbling, produces a scalloped edge, as shown on the lower-right corner profile in Figure 9.31. The height of the scallops can be reduced by using a larger punch or reducing the pitch between hits. For the internal curved cutout in Figure 9.31 the size of the circular punch is determined by the width of the slot, and both slot edges are produced simultaneously during the nibbling operation. Most turret presses have a nibble mode in which the press cycles continuously at high speeds. This allows rapid incremental moves of the sheet to be used for efficient nibbling. The characteristics of a typical turret press are given in Table 9.5.

An alternative to nibbling for curved edges is the use of turret presses equipped with profile-cutting attachments. Machines are available with either plasma or laser cutting devices. These are typically affixed to the machine structure at a precise distance from the center of the active turret punch. This distance is simply placed in the numerical control file as a coordinate offset prior to the commencement of profile cutting. The sheet is moved to the appropriate start point, the cutting torch is switched on, and movement is then continued around the required profile path. The cutting speed for either laser or plasma cutting varies with the thickness of material and the curvature of the path being followed; tighter curves require a slower speed to maintain a given tolerance level. Table 9.6 gives typical average cutting speeds for 3 mm gage thickness of different metals. Plasma cutting is generally faster than laser cutting, but the former process produces a somewhat less precise and heat-affected edge. For thicker gages the speed difference becomes more

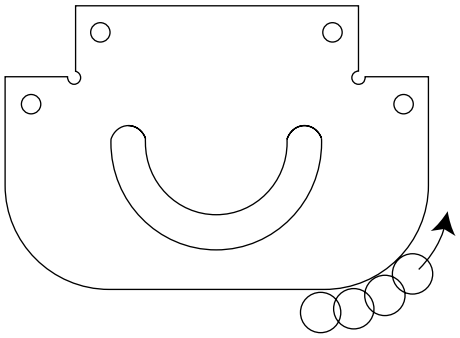

FIGURE 9.31
Part geometry that requires nibbling or profile cutting.

TABLE 9.5

Typical Turret Press Manufacturing Characteristics

Machine setup time	20 min
Loading plus unloading time per sheet	
One 750 × 750 mm sheet	24 s
One 1200 × 3600 mm sheet	72 s
Average speed between punching	0.5 m/s
Time to punch one hole	0.5 s
Nibbling speed	360 strokes/min
Maximum form height	6 mm
Machine rate, including programming costs	72 $/h

pronounced, and from cutting speed data in the literature [16], it appears that the effect of thickness on cutting speed S can be given by

$$S = S_p \times \left(\frac{3}{h}\right)^{0.5} \text{ mm/s for plasma cutting} \tag{9.32}$$

and

$$S = S_c \times \left(\frac{3}{h}\right) \text{mm/s for laser cutting} \tag{9.33}$$

where

S_p, S_e = plasma and laser cutting speed values, respectively, from Table 9.6 for 3 mm thick material

h = material gage thickness, mm.

9.5 Press Brake Operations

A press brake is a mechanical press with a bed several feet wide and only a few inches deep. General-purpose bending tools, usually v-blocks or wiper-die blocks and matching punches, are mounted at positions along the bed. At each punch position, a back stop is mounted on the rear of the bed in order for the part to be positioned correctly with respect

TABLE 9.6

Plasma and Laser Cutting Speeds for 3 mm Thick Material

	Typical Speed (mm/s)	
Material Class	**Plasma, S_p**	**Laser, S_c**
Carbon steel	60	40
Stainless steel	60	35
Aluminum alloy	75	15
Copper alloy	75	20
Titanium alloy	50	20

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TABLE 9.7

Typical Press Brake Manufacturing Characteristics

Machine setup time	20 min
Time to load, position, brake, and stack	
One 200 mm × 300 mm part	8.50 s
One 400 mm × 600 mm part	13.00 s
Time to position and brake for each additional bend	
One 200 mm × 300 mm part	4.25 s
One 400 mm × 600 mm part	6.50 s
Machine rate	$28/h

to the bending tool. The method of operation is for the press operator to pick up the flat sheet metal part, turn it to the correct orientation, push it against the back stop at the first tool position, and then operate the press by pressing a foot pedal. If more bends are required, then the part is turned and moved to the next punching position and the operation repeated. After the last bend the part is stacked on a pallet beside the press. The manufacturing characteristics of a typical press brake are given in Table 9.7.

Applying linear interpolation to the press brake data in Table 9.7 gives the following empirical relationship for brake bending:

$$t = 2(1 + N_b) + 0.05(2 + N_b)(L + W) \tag{9.34}$$

where

N_b = number of required bending operations

L, W = length and width of part, cm.

EXAMPLE

The part shown in Figure 9.29 is to be manufactured from 16 gage (1.52 mm thick), commercial-quality, low-carbon steel in standard sheet size 48 in. (1219.2 mm) by 60 in. (1524 mm).

The maximum number of parts which can be made from each sheet is 135, from a pattern of 15 rows with 9 parts in each row and 6 mm separation between each part. The area of each part is 94.6 cm^2. The volume of each part is given by

$$94.6 \times 0.152 = 14.38\,\text{cm}^3\ \text{s}$$

and the volume of material used for each part is

$$(121.92 \times 152.4) \times \frac{0.152}{135} = 20.92\ \text{cm}^3$$

Using data from Table 9.2, the cost of material per part is

$$20.92 \times 7.90 \times 10^{-3} \times 80 = 13.2\ \text{cents}$$

and the resale value of scrap per part is

$$(20.92 - 14.38) \times 7.90 \times 10^{-3} \times 6 = 0.3\ \text{cents}$$

The number of hits required to produce each part can be estimated as follows:

Internal holes	10 hits
Outside radii	8 hits
Outside edges	11 hits

In estimating the 11 hits for the outside straight edges, account is taken of the simultaneous generation of adjacent part edges around portions of the perimeter.

A typical sheet movement speed for a modern CNC turret press is 0.5 m/s, so the time for sheet movement between punching is of the order of 0.1 s. However, this time does not include the dwell time for punching, the acceleration and deceleration between stops, and the periodic delays for turret rotation to change tools. Time studies carried out on a variety of turret press parts [17] suggest that an average of 0.5 s per hit is appropriate for early cost estimating (Table 9.5) where hole spacing is of the order of 50 mm or less. For large parts with significantly greater distances between holes, extra sheet movement times of 0.1 s for each additional 50 mm can be added.

For the example part, the punching time per part is estimated to be

$$t_1 = N_h \times 0.5 \tag{9.35}$$

where

N_h = number of hits

Thus, for the present example

$$t_1 = 29 \times 0.5 = 14.5 \text{ s}$$

From the data in Table 9.5, if the time for sheet loading plus unloading is assumed to be proportional to the sheet perimeter, it can be expressed as

$$t_2 = 2.0 + 0.15(L + W) \text{ s} \tag{9.36}$$

where

L, W = sheet length and width, cm.

For the sheet size used for the example part, the loading plus unloading time is given by

$$t_2 = 2.0 + 0.15(121.92 + 152.4) = 43 \text{ s}$$

Note that separation of the 135 parts from the sheet can be carried out during the total machine cycle time of 135×14.5 s or 32.6 min. During this time previously punched parts may also be passed between an automatic belt deburring machine to remove sharp punched edges.

The turret press cycle time per part is thus

$$t = 14.5 + \frac{43}{135} = 14.8 \text{ s}$$

The cost of turret press operations per part, using the machine rate of \$72/h from Table 9.5, is estimated to be

$$C_1 = 14.8 \times \frac{(72 \times 100)}{3600} = 29.6 \text{ cents}$$

For the example part, $N_b = 3$, $L = 15$, and $W = 7.5$ and Equation 9.36 predicts a press brake cycle time per part of

$$t = 8 + 0.05 \times 5 \times 22.5 = 13.6 \text{ s}$$

The cost for press brake operations per part is thus

$$C_2 = 13.6 \times \frac{(28 \times 100)}{3600} = 10.6 \text{ cents}$$

Finally, the estimated sum of material plus the processing cost per part is

$$C_{\text{part}} = (13.2 - 0.3) + (29.6 + 10.6) = 53 \text{ cents}$$

9.6 Design Rules

In the design of sheet metal stampings, the first consideration is the shape of the external perimeter. As discussed in Section 9.2.1, for parts that are to be manufactured with dedicated dies, it is advantageous to design the outer profile with parallel straight edges defining the part width. To allow satisfactory shearing in cut-off or part-off operations, the end profiles should meet the straight edges at angles no less than 15°. Whether this is possible or not, the profile shape should not contain narrow projections or notches that require narrow weak sections in either punches or die plates; see dimensions marked "a" in Figure 9.32.

Similar considerations for the avoidance of weak tool sections apply to internal punched holes. That is, small holes or narrow cut-outs that require fragile punches should be avoided. In addition, internal punched holes should be separated from each other, and from the outside edge, with sufficient clearance to avoid distortion of narrow sections of the workpiece material during punching. The accepted rule of thumb is that both feature dimensions and feature spacings should be at least twice the material thickness. With reference to the part shown in Figure 9.32, satisfactory blanking and punching require that dimensions labeled "a" through "d" should all be greater than or equal to twice the gage thickness. Note that all profile radii, such as dimension "e," are subjected to the same rule of thumb. In this case, the concern is the associated corner radii in the die plate. Radii equal to at least twice the gage thickness will minimize the corner stress concentrations in the die plate, which may lead to crack formation and failure. Finally, it is a good practice to incorporate relief cut-outs dimensioned as "d," at the ends of proposed bend lines that terminate at internal corners in the outer profile. These circular relief cut-outs would be part of the die profile for blanking or would be punched before the adjacent outer profile in turret press working. However, if for any reason holes that intersect the outer profile must be punched later, then the diameter should be at least three times the gage thickness to accommodate the offset loading to which the punch would be subjected.

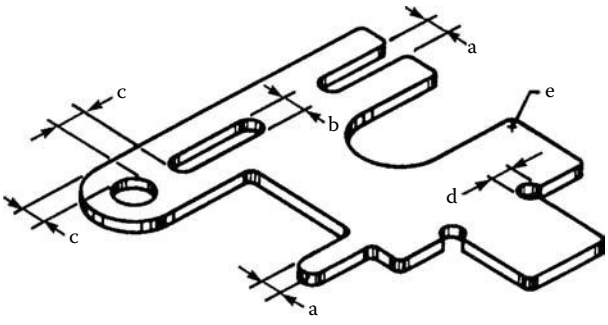

FIGURE 9.32
Critical dimensions in the design of a sheet metal blank.

When formed features are being considered, the principal design constraint is the maximum tensile strain the material can withstand; this is usually called the material ductility. Typical ductility values are given in Table 9.2. Thus, if a lanced and formed bridge as shown in Figure 9.33 is to be incorporated into a component made from low-carbon, commercial-quality steel, the ratio of L to H can be calculated as follows. Assume that the transition or ramp from the surface to the top of the bridge is 45°. The length along the bridge from end to end can easily be calculated as

$$\text{Bridge length} = L + 0.82H \tag{9.37}$$

Assuming uniform stretching of the bridge, the tensile strain along the bridge is thus

$$e = \frac{0.82H}{L} \tag{9.38}$$

Thus, if the maximum permissible strain in tension is 0.22 (as given in Table 9.2), then from Equation 9.29 successful forming is assured if

$$L > 3.7H \tag{9.39}$$

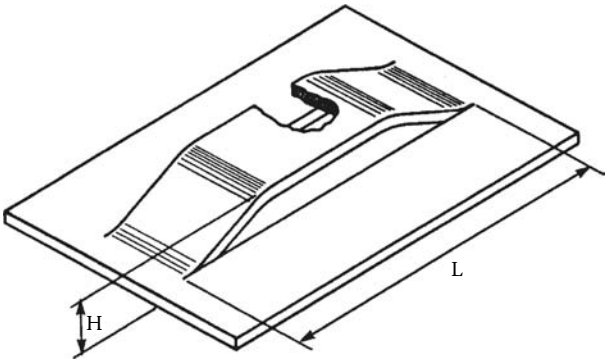

FIGURE 9.33
Lanced and formed bridge.

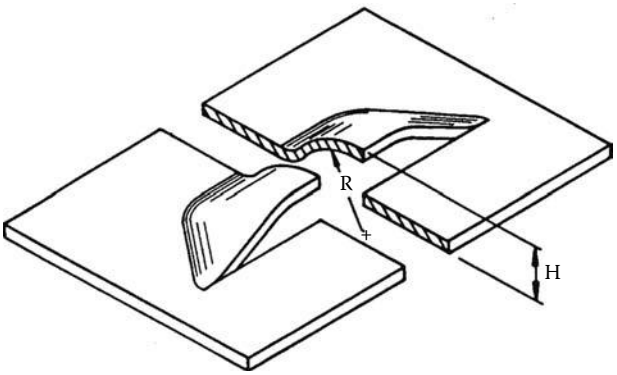

FIGURE 9.34
Lanced and formed louver.

This corresponds approximately to a rule of thumb quoted in the literature that the length of bridges should be greater than 4 times their height. However, such rules are frequently based on the experience with press working of annealed low-carbon steel. For different materials or varying geometries, such as changing the ramp angles in the preceding example, the tensile strains must be estimated and compared to the permissible maximum value.

A common example of a lanced and formed feature in sheet metal parts is the louver. Louvers are often formed as groups of parallel slots in the sides of sheet metal enclosures for air circulation and cooling purposes. Figure 9.34 shows a section through a louver. The length of the front edge of the louver must be greater than a certain multiple of the louver opening height H, determined by the material ductility and the end ramp angles exactly as in the bridge calculation. However, stretching also occurs at right angles to the louver edge where the material is stretched upward into a circular arc as shown. This would not cause material failure, since the front edge of the louver would be pulled backward as the tensile stress develops in the surface. The consideration here, and the choice of radius R in Figure 9.34, is more one of appearance and the amount of space taken up by a single louver.

Another type of feature, which involves stretching along a sheared edge, is the hole flange. Figure 9.35 shows a sectional view of this feature type. Hole flanging is often carried

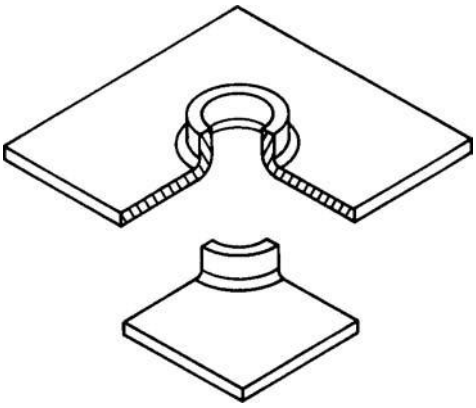

FIGURE 9.35
Formed hole flange.

out to provide increased local thickness for tapping of screw threads or for assembly with machine screws. The hole flange is formed by pressing a taper-nosed punch of diameter D into a smaller punched hole of diameter d. The tensile strain around the top edge of the formed flange is thus

$$e = \frac{(D-d)}{D} \tag{9.40}$$

and this value must be less than the permissible material ductility. The limit of the ratio D/d, due to limited ductility, limits the amount of material displaced and in turn the height of hole flanges that can be produced. Typical values of flange height in sheet steel components, for example, range between 2 and 3 times the material gage thickness.

In the design of beads or ribs used to stiffen open surfaces of sheet metal parts, the cross-sectional geometry as shown in Figure 9.36 is important. Ribs may be circular in section as shown, or are sometimes V-shaped. In any case, for a required height, H, the width and shape of the rib must be chosen so that the required amount of stretching across the rib does not exceed the material ductility. The radius at the base of the rib, in Figure 9.36, must also be greater than a certain value to prevent overstraining the material on the underside of the part. This may result from the bending effect along the sides of the rib and will be considered next.

As discussed in Section 9.3, the maximum tensile strain in bending is in the outer fibers of the sheet on the outside of the bend and is governed by the ratio of inside bend radius, r, to sheet gage thickness, h. For a bend through any angle θ, the length of the outer surface is

$$L_s = (r+h)\theta \tag{9.41}$$

and the length of the surface in the center of the sheet, on which lies the neutral axis of bending, is

$$L_o = \left(r + \frac{h}{2}\right)\theta \tag{9.42}$$

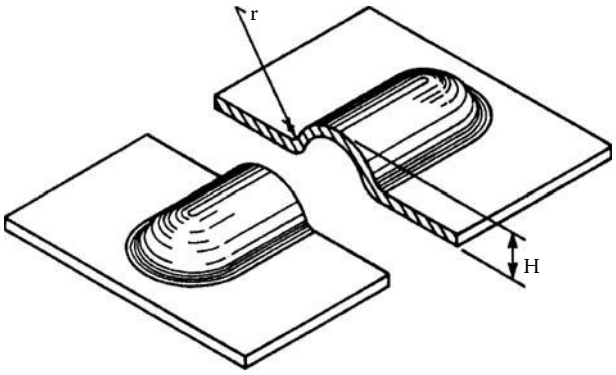

FIGURE 9.36
Cross section of rib.

Hence, the strain on the outer surface is

$$e = \frac{(L_s - L_o)}{L_o} = \frac{1}{(1 + 2r/h)} \tag{9.43}$$

Radius r is defined precisely by the profile radius of the bending tool: either the convex radius of the die block for a wiper die or the convex radius of the punch in a v-die.

In any case, the minimum acceptable radius value can be obtained from Equation 9.43 and the ductility of the material to be bent. For example, for low-carbon, commercial-quality steel with ductility 0.22, Equation 9.43 gives

$$e = 0.22 = \frac{1}{(1 + 2r/h)}$$

or

$$r = 1.77h$$

A rule of thumb often quoted in the literature is that the inside bend radius should be greater than or equal to twice the sheet thickness. This is, in fact, the limiting value for a material with 20% ductility.

An additional consideration with respect to bending is the placing of other features next to bend lines. For the part shown in Figure 9.37 the slots would almost certainly have to be punched after the bending operation. This is because the small separation, l, of the edges of the slots from the bend line would result in distortion of the slots during bending if they were punched first. This would give rise to the need for a more expensive piercing die, since a die block would have to be machined with a matching step to support the nonflat part. Even worse, if the part contains other holes or slots that are now on nonparallel surfaces to the one shown, then two separate dies and operations are needed for punching where one would otherwise have been sufficient. The rule of thumb in stamping is that the edge of circular holes should preferably be 2 times the sheet thickness from the beginning of a bend. For slots parallel to a bend this clearance should increase to 4 times sheet thickness.

The manufacture of small flat sheet metal parts can be performed with a high degree of precision. Blanked parts or punched holes with maximum dimensions up to 10 cm can be

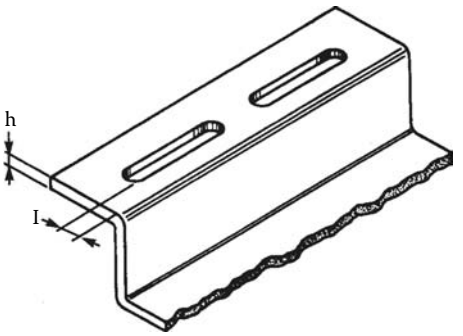

FIGURE 9.37
Punched slots adjacent to a bend.

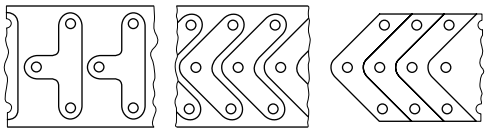

FIGURE 9.38
Design changes of a three-hole bracket for minimization of manufactured scrap.

held to tolerances of approximately ±0.05 mm However, as part size increases, precision is more difficult to control, and for a part with dimensions as large as 50 cm permissible tolerances are in the range of ±0.5 mm. The requirement for tolerances much tighter than these guideline values may call for features to be machined at greatly increased cost. For formed parts, or formed features, variation tends to be larger and minimum tolerances attainable are in the range of ±0.25 mm for small parts. This includes bending when dedicated bending dies are used. Thus, a tight tolerance between punched holes, which are on parallel surfaces separated by bends, would require the holes to be punched after bending at greater expense. If the holes are on nonparallel surfaces, then machining may be necessary to obtain the required accuracy. Finally, in the design of turret press parts to be bent on press brakes, it should be noted that the inaccuracies of this bending process are substantially worse than with dedicated dies. Attainable tolerances between bent surfaces and other surfaces, or features on other surfaces, range from ±0.75 mm for small parts up to ±1.5 mm for large ones.

Finally, an important consideration in the design of any sheet metal part should be the minimization of manufactured scrap. This is accomplished by designing part profiles so that they can be nested together as closely as possible on the strip or sheet. Also, if individual dies are to be used, then the part should be designed if possible for cut-off or part-off operations. Figure 9.38 illustrates the type of design changes that should always be considered. The cut-off design lacks the elegance of the rounded end profiles. Nevertheless, the acute sharp corner is removed during deburring, and for many applications this type of design may be perfectly functional.

PROBLEMS

In all of the questions below use the data from the Tables for material costs, material properties, machine performance, and machine hourly rates. Assume a rate of $40/h for all die-making cost estimates.

1. For the part shown in Figure 9.25, whose dimensions are given in mm, and which is made from 12 gage commercial quality low-carbon steel, determine the following:
   a. The likely cost of a progressive die assuming a total production volume of 150,000 parts;
   b. The required press force for the external shearing, internal hole punching and the bending operation;
   c. The press cycle time and the processing cost per part assuming 15% down-time for batch setup and miscellaneous stoppages;
   d. The manufactured cost per part, including material cost, but neglecting the small return on manufactured scrap for the low-carbon steel. Assume the die is amortized over the total production volume.
2. The part illustrated in Figure 9.39 is the tool part of a barbeque spatula which is to be assembled to a wooden handle. The head is 15 cm long, and has a width of 9 cm

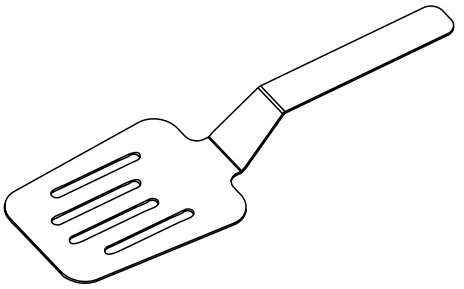

FIGURE 9.39
Stainless steel barbeque spatula blade.

across the front and 12 cm across the back. The shaft is 20 cm long × 3 cm wide, and increases to 4 cm wide over the angled portion. The two bends are parallel and separated by a distance of 6 cm. To reduce material scrap, the parts are to be blanked in pairs from strip as shown in Figure 9.40. The distance between the center of each spatula blank along the strip is 7.0 cm, and the strip width is 36.0 cm.

a. Estimate the total manufacturing hours for the die elements for a blanking die for one of the spatula blanks.
b. Assuming an 85% learning curve, estimate the total manufacturing hours for the die elements for a blanking die for a pair of the spatula blanks.
c. Including a die set with useable area large enough for the nested pair of blanked shapes, estimate the likely cost of the blanking die.
d. If the spatula is to be made from 16 gage T304 stainless steel, estimate the material cost per part using the cost and scrap value given in Table 9.2. How much greater would be the material cost per part be if the parts where blanked out individually with a spacing of 12.75 cm?
e. Using the material values estimated in part (d), how many spatulas would need to be produced to justify the additional investment in a blanking tool for blanking of pairs?

3. The machine support bracket illustrated in Figure 9.41 is to be manufactured from 6 gage low-carbon, commercial quality steel using turret press with plasma profile cutting capability, followed by press brake operations. The dimensions of the blank prior to bending are 20 × 15 cm. After bending the horizontal base is nominally 5 cm wide and the vertical wall is 10 cm high, tapering down over a horizontal length of 8 cm to a height of 4 cm. The vertical slots are 6 cm long and the horizontal ones 7.5 cm long. All four slots have a width of 1.25 cm wide. Punches are available on the turret press for both slot sizes.

   Estimate the following elements of the manufacturing process steps:
   a. The plasma profile cutting time per bracket.
   b. The turret press punching time per bracket.

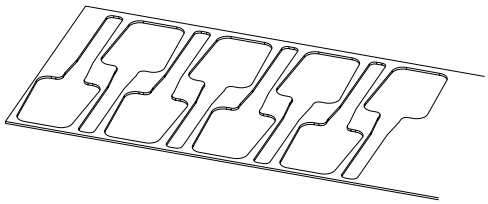

FIGURE 9.40
Layout of spatula blades to minimize manufacturing scrap.

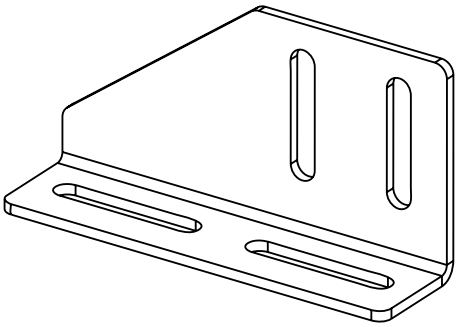

FIGURE 9.41
Machine support bracket.

c. The processing cost per part prior to the bending operation, assuming sets of 20 are made from custom-sized sheets measuring 800 × 840 mm.
d. The press force required for the bending operation.
e. The cycle time and operation cost per bracket for the press brake operation.

4. If the machine support bracket illustrated in Figure 9.41 is to be made from annealed low-carbon commercial quality steel with properties as in Table 9.2, what is the smallest inside bend radius you would recommend? If for the structural requirements of the design, you wish to use half-hard commercial quality steel (not annealed after the finish rolling passes of the strip) for which the maximum allowable strain is reduced to 0.10, to what value would you need to increase the inside bend radius?
5. The body of a rotor component shown in Figure 9.42 Is to be made by deep drawing from 2.03 mm thick Al 3003 aluminum alloy sheet. The part is 13 cm high. The large diameter is 20 cm which steps down to 17.5 cm, at distance 6.5 cm from the base.
   a. Estimate the required blank diameter to produce this part and determine that it is possible to produce the initial 20 cm diameter cup in a single drawing operation, so that only one redraw operation would be needed.
   b. The set of operations required to make the rotor includes: blank, draw, redraw, and trim. Estimate the costs of the dies for each of these operations.

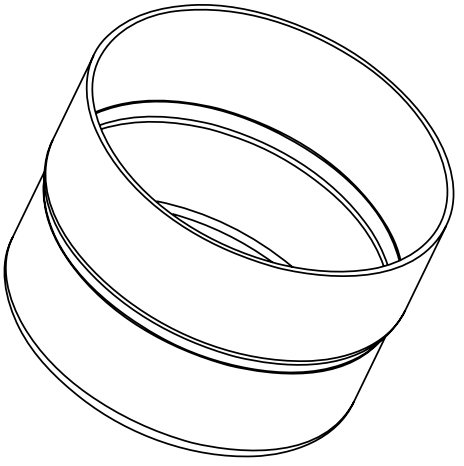

FIGURE 9.42
Deep drawn aluminum rotor–primary shape.

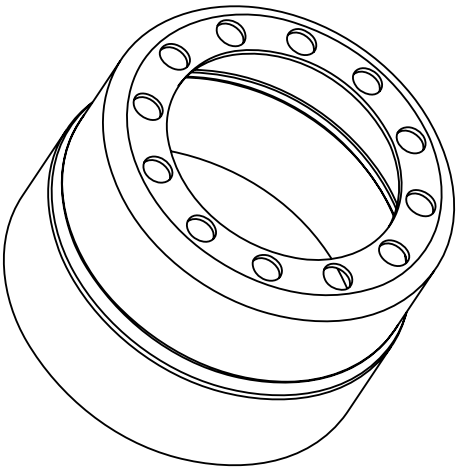

FIGURE 9.43
Deep drawn aluminum rotor–finished part.

c. Estimate the press forces required for each of the operations.
d. Estimate the cycle times for each of the operations. Assume that hand loading and unloading are required for each operation except blanking.
e. Using rates for the appropriate machines from the Table 9.4, estimate the processing cost for the set of four primary operations.

6. The completed rotor component involves the production of the body, as described in problem 5, with the addition of a centered 12.5 cm diameter hole, surrounded by twelve 1.5 cm diameter holes as shown in Figure 9.43.
   a. Estimate the press force required to punch these 13 holes simultaneously, and select an appropriate press from Table 9.4.
   b. Estimate the cost of the required die.
   c. Estimate the cycle time and process cost for this piercing operation.

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10

Design for Die Casting

10.1 Introduction

The die-casting process, also called pressure die casting, is a molding process in which molten metal is injected under high pressure into cavities in reusable steel molds, called dies, and held under pressure during solidification. In principle, the process is identical to injection molding with a different class of materials. Die casting can, in fact, produce parts that have identical geometries to injection-molded ones. The reverse is also true, and much of the increase in the use of injection molding since the mid-1980s has been a substitute for part types that were previously die cast. In many cases, this has been a wise substitution, resulting in decreased parts costs. However, for structural parts, particularly those for which thick-wall injection moldings are required, die casting can often be the better selection. The analysis of die-casting costs in this chapter closely parallels the early costing procedure for injection molding given in Chapter 8. This is intended to allow comparisons of the two processes to be made with a minimum of redundant effort. The chapter includes information on the die-casting process, casting materials, equipment performance, and die construction sufficient to understand the factors that influence material and manufacturing cost. The chapter ends with basic design principles that naturally follow from the evaluations of cost drivers in the process. Readers wishing to study the die-casting process further may begin with suggested further reading [1–3] under the reference section.

10.2 Die-Casting Alloys

The four major types of alloys that are die cast are zinc, aluminum, magnesium, and copper-based alloys. The die-casting process was developed in the nineteenth century for the manufacture of lead/tin alloy parts. However, lead and tin are now very rarely die cast because of their poor mechanical properties. A tabulation of the specific gravity, mechanical properties, and cost of commonly used examples of the four principal alloy groups is given in Table 10.1.

The most common die-casting alloys are the aluminum alloys. They have low density, have good corrosion resistance, are relatively easy to cast, and have good mechanical properties and dimensional stability. Aluminum alloys have the disadvantage of requiring the use of cold-chamber machines, which usually have longer cycle times than hot-chamber machines, used for zinc alloys, owing to the need for a separate molten metal

TABLE 10.1

Commonly Used Die-Casting Alloys

Alloy[a]	Specific Gravity (g/cm^3)	Yield Strength (MN/m^2)	Elastic Modulus (GN/m^2)	Cost[b] ($/kg)
Zamak[(1)]	6.60	220	66	1.78
Zamak 5[(1)]	6.60	270	73	1.74
A13[(2)]	2.66	130	130	1.65
A360[(2)]	2.74	170	120	1.67
ZA8[(3)]	6.30	290	86	1.78
ZA27[(3)]	5.00	370	78	1.94
Silicon brass 879[(4)]	8.50	240	100	6.60
Manganese bronze 865[(4)]	8.30	190	100	6.60
AZ91B[(5)]	1.80	150	45	2.93

[a] Alloy types: (1) zinc, (2) aluminum, (3) zinc–aluminum, (4) copper, and (5) magnesium.

[b] Material costs are subjected to constant change and are influenced strongly by the quantity of purchase—text values are intended for design comparison exercises only.

ladling operation. The distinction between hot- and cold-chamber machines will be discussed in some detail later in this chapter.

Zinc-based alloys are the easiest to cast. They also have high ductility and good impact strength, and therefore can be used for a wide range of products. Castings can be made with very thin walls, as well as with excellent surface smoothness, leading to ease of preparation for plating and painting. Zinc alloy castings, however, are very susceptible to corrosion and must usually be coated, adding significantly to the total cost of the component. Also, the high specific gravity of zinc alloys leads to a much higher cost per unit volume than for aluminum die-casting alloys, as can be deduced from the data in Table 10.1.

Zinc–aluminum (ZA) alloys contain a higher aluminum content (8–27%) than the standard zinc alloys. Thin walls and long die life can be obtained, similar to standard zinc alloys, but as with aluminum alloys, cold-chamber machines, which require pouring of the molten metal for each cycle, must usually be used. The single exception to this rule is ZA8 (8% Al), which has the lowest aluminum content of the ZA family, and can be used in hot-chamber machines.

Magnesium alloys have very low density, a high strength-to-weight ratio, exceptional damping capacity, and excellent machinability properties.

Copper-based alloys, brass and bronze, provide the best mechanical properties of any of the die-casting alloys, but are much more expensive. Brasses have high strength and toughness, good wear resistance, and excellent corrosion resistance. One major disadvantage of copper-based alloy casting is the short die life caused by thermal fatigue of the dies at the higher casting temperatures. For complex parts with consequently high die cost, this can add substantially to the cost of manufacture.

Die life is influenced most strongly by the casting temperature of the alloys, and for this reason is highest for zinc and lowest for copper alloys. The typical number of castings per die cavity is given in Table 10.2. However, this is only an approximation since casting size, wall thickness, and geometrical complexity also influence the wear and eventual breakdown of the die surface. Associated trim dies are usually sound for more than a one million parts because of the relatively low strength and thin sections to be trimmed.

TABLE 10.2

Typical Die Life Values per Cavity

Alloy	Die Life
Zinc	500,000
Zinc-aluminum	500,000
Aluminum	100,000
Magnesium	180,000
Copper	15,000

10.3 Die-Casting Cycle

In the casting cycle, first the die is closed and locked. The molten metal, which is maintained by a furnace at a specified temperature, then enters the injection cylinder. Depending on the type of alloy, either a hot-chamber or a cold-chamber metal-pumping system is used. These will be described later. During the injection stage of the die-casting process, pressure is applied to the molten metal, which is then driven quickly through the feed system of the die while air escapes from the die vents. The volume of metal must be large enough to overflow the die cavities and fill overflow wells. These overflow wells are designed to receive the lead portion of the molten metal, which tends to oxidize from contact with air in the cavity and also cools too rapidly from initial die contact to produce sound castings. Once the cavities are filled, pressure on the metal is increased and held for a specified dwell time during which solidification takes place. The dies are then opened, and the part extracted, often by means of automatic pick and place devices. The open dies are then cleaned and lubricated as needed, and the casting cycle is repeated.

Following extraction from the die, parts are often quenched to improve metallurgical properties, and then trimmed in a separate press operation. Trimming is necessary to remove the runners and the overflow wells, as well as any parting-line flash that is produced. Subsequently, secondary machining and surface finishing operations may be performed.

10.4 Die-Casting Machines

Die-casting machines consist of several elements: the die mounting and clamping system, the die, the metal-pumping and injection system, the metal-melting and storing system, and any auxiliary equipment for mechanization of such operations as part extraction and die lubrication.

10.4.1 Die-Mounting and Clamping Systems

The die-casting machine must be able to open and close the die and lock it closed with enough force to overcome the pressure of the molten metal in the cavity. The mechanical or hydraulic systems needed to do this are identical to those found on injection-molding machines and described in Chapter 8. This fact should not be surprising, since injection-molding machines were developed from die-casting technology.

10.4.2 Metal-Pumping and Injection Systems

The two basic types of injection systems are hot-chamber and cold-chamber. Hot-chamber systems, in which the pump is placed in the container of molten metal, are used with alloys having low melting temperatures, such as zinc. Cold-chamber machines must be used for high melting temperature alloys such as aluminum, copper-based alloys, and the ZA zinc alloys, which contain large amounts of aluminum. High melting temperature alloys used in a hot-chamber machine would erode the ferrous injection pump components, thereby degrading the pump and contaminating the alloy. Magnesium alloys, although they are cast at high temperatures, can be cast in hot-chamber machines as well as in cold-chamber machines, because they are inert to the ferrous machine components.

10.4.3 Hot-Chamber Machines

A typical hot-chamber injection or shot system, as shown in Figure 10.1, consists of a cylinder, a plunger, a gooseneck, and a nozzle. The injection cycle begins with the plunger in the up position. The molten metal flows from the metal-holding pot in the furnace, through the intake ports, and into the pressure cylinder. Then, with the dies closed and locked, hydraulic pressure moves the plunger down into the pressure cylinder and seals off the intake ports. The molten metal is forced through the gooseneck channel and the nozzle and into the sprue, feed system, and die cavities. The sprue is a conically expanding flow channel that passes through the cover die half from the nozzle into the feed system. The conical shape provides a smooth transition from the injection point to the feed channels and allows easy extraction from the die after solidification. After a preset dwell time for metal solidification, the hydraulic system is reversed and the plunger is pulled up. The die is then opened for part extraction, the die is spray lubricated if necessary, and the cycle then repeats. Cycle times range from several seconds for castings weighing a few grams to 30 s or more for large, thick-walled castings weighing over a kilogram [4]. Specifications for a range of hot-chamber machines are given in Table 10.3.

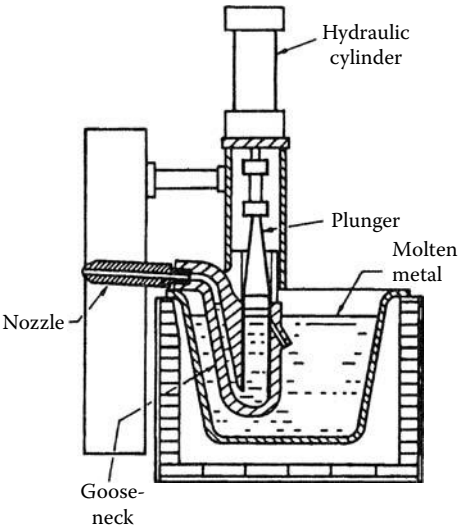

FIGURE 10.1
Hot-chamber injection system.

TABLE 10.3

Hot-Chamber Die-Casting Machines

Clamping Force (kN)	Shot Size (cm^3)	Operating Cost[a] ($/h)	Dry Cycle Time (s)	Max. Die Opening (cm)	Platen Size (cm)
900	750	58	2.3	20.0	48 × 56
1150	900	60	2.5	23.0	56 × 64
1650	1050	62	2.9	25.0	66 × 70
2200	1300	64	3.3	31.0	70 × 78
4000	1600	70	4.6	38.0	78 × 98
5500	3600	73	5.6	45.7	100 × 120
6000	4000	76	6.2	48.0	120 × 150
8000	4000	86	7.5	53.0	120 × 150

[a] Machine rates will vary by country, region, and year—text values are intended for design comparisons only.

10.4.4 Cold-Chamber Machines

A typical cold-chamber machine, as shown in Figure 10.2, consists of a horizontal shot chamber with a pouring hole on the top, a water-cooled plunger, and a pressurized injection cylinder. The sequence of operations is as follows: when the die is closed and locked and the cylinder plunger is retracted, the molten metal is ladled into the shot chamber through the pouring hole. In order to tightly pack the metal in the cavity, the volume of metal poured into the chamber is greater than the combined volume of the cavity, the feed system, and the overflow wells. The injection cylinder is then energized, moving the plunger through the chamber, thereby forcing the molten metal into the die cavity. After the metal has solidified, the die opens and the plunger moves back to its original position. As the die opens, the excess metal at the end of the injection cylinder, called the biscuit, is forced out of the cylinder, because it is attached to the casting. Material in the biscuit is required during the die-casting cycle in order to maintain liquid metal pressure on the casting while it solidifies and shrinks.

Specifications for a number of cold-chamber machines are given in Table 10.4.

Low tonnage mechanical presses are used for the trimming operations to remove the runner systems, overflow wells and flash. Consistent with the machine hourly rates in Tables 10.3 and 10.4, a trim press rate of $40 per hour should be used.

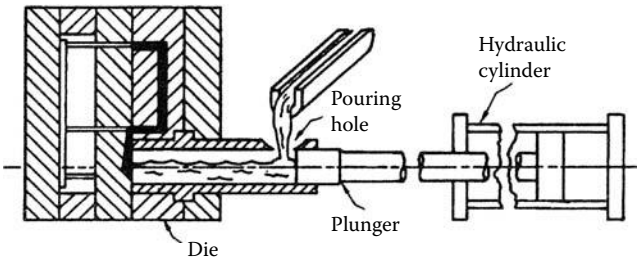

FIGURE 10.2
Cold-chamber die-casting machine elements.

TABLE 10.4

Cold-Chamber Die-Casting Machines

Clamping Force (kN)	Shot Size (cm^3)	Operating Cost[a] ($/h)	Dry Cycle Time (s)	Max. Die Opening (cm)	Platen Size (cm)
900	305	66	2.2	24.4	48 × 64
1800	672	73	2.8	36.0	86 × 90
3500	1176	81	3.9	38.0	100 × 108
6000	1932	94	5.8	46.0	100 × 120
10,000	5397	116	8.6	76.0	160 × 160
15,000	11,256	132	10.2	81.0	210 × 240
25,000	11,634	196	19.9	109.0	240 × 240
30,000	13,110	218	23.3	119.0	240 × 240

[a] Machine rates will vary by country, region and year—text values are intended for design comparisons only.

10.5 Die-Casting Dies

Die-casting dies consist of two major sections—the ejector die half and the cover die half—that meet at the parting line; see Figure 10.3. The cavities and cores are usually machined into inserts that are fitted into each of these halves. The cover die half is secured to the stationary platen, while the ejector die half is fastened to the movable platen. The cavities and matching cores must be designed so that the die halves can be pulled away from the solidified casting.

The construction of die casting dies is almost identical to that of molds for injection molding. In injection molding terminology, the ejector die half comprises the core plate and ejector housing, and the cover die half comprises the cavity plate and backing support plate.

Side-pull mechanisms for casting parts with external cross-features can be found in exactly the same form in die-casting dies as in plastic injection molds, as described in

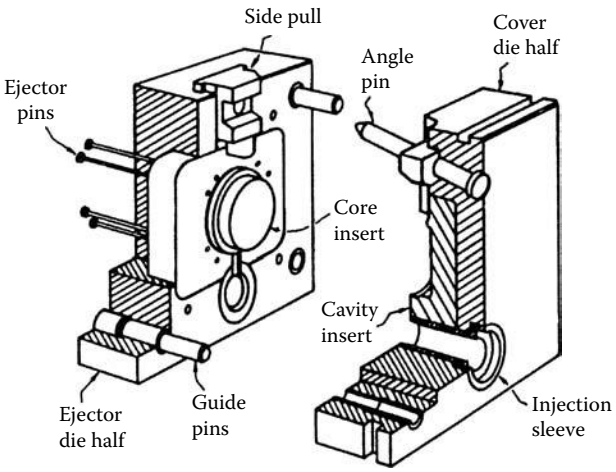

FIGURE 10.3
Die for cold-chamber die-casting machine.

Chapter 8. However, molten die-casting alloys are much less viscous than the polymer melt in injection molding and have a great tendency to flow between the contacting surfaces of the die. This phenomenon, referred to as "flashing," tends to jam mold mechanisms, which must, for this reason, be robust. The combination of flashing with the high core retraction forces due to part shrinkage makes it extremely difficult to produce satisfactory internal core mechanisms. Thus, internal screw threads or other internal undercuts cannot usually be cast and must be produced by expensive secondary machining operations. Ejection systems found in die-casting dies are identical to the ones found in injection molds.

"Flashing" always occurs between the cover die and ejector die halves, leading to a thin, irregular band of metal around the parting line. Occasionally, this parting line flash may escape between the die faces. For this reason, full safety doors must always be fitted to die-casting machines to contain any such escaping flash material.

One main difference in the die-casting process, as compared to injection molding, is that overflow wells are usually designed around the perimeter of die-casting cavities. As mentioned earlier, they reduce the amount of oxides in the casting, by allowing the first part of the shot, which displaces the air through the escape vents, to pass completely through the cavity. The remaining portion of the shot and die are then at a higher temperature, thereby reducing the chance of the metal freezing prematurely. Such premature freezing leads to the formation of surface defects called cold shuts, in which streams of metal do not weld together properly, because they are partially solidified by the time they meet. Overflow wells are also needed to maintain a more uniform die temperature on small castings, by adding to the mass of molten metal.

10.5.1 Trimming Dies

After extraction from the die-casting machines, the sprue or biscuit, runners, gates, overflow wells, and parting-line flash must be removed from the casting. This is done either manually or, if production quantities are larger, with trimming presses. The dies used for trimming operations are similar to blanking and piercing dies used for sheet metal press-working. They are mounted on mechanical or hydraulic presses, and because the required forces are low, the bed area to tonnage rating ratio is relatively large. The thickness of the metal to be trimmed is usually in the range of 0.75–1.5 mm.

It is desirable, when designing a casting, to locate the main gates from the feed channels as well as the gates to the overflow wells around the parting line of the cavity and to design a parting line that is not stepped. This simplifies both the casting die and the trimming die.

10.6 Finishing

Following trimming, castings are often polished and/or coated to provide corrosion resistance and wear resistance, and to improve aesthetic appearance. Polishing is sometimes the only surface treatment for aluminum castings. However, for aluminum as well as the other casting alloys, a variety of plating or painting processes are commonly used. Before any coating process, parts are put through a series of cleaning operations to remove any contamination that could prevent the adhesion of these applied coatings. The cleaning operations usually performed are degreasing, alkaline cleaning, and acid dipping.

Commonly used coatings may be separated into three groups: electroplating, anodizing, and painting. Electroplating is used mainly for zinc alloy castings, because aluminum and magnesium alloys oxidize quickly, which prevents the electroplate layers from adhering properly. Brass castings, although they may be electroplated after removal of oxides, are often used unfinished.

The most common type of electroplating is a decorative chrome finish on zinc die castings, which consists of several layers of applied metal. First, a very thin layer of copper (0.008 mm) is applied to aid in the adhesion of the subsequent layers. A second layer of copper is then sometimes added to improve the final surface finish. Two layers of nickel, 0.025 mm thick, are then applied. These layers aid in corrosion resistance by diverting the corrosion to the outer layer of nickel because of the difference in electrical potential between the two layers. The final layer is a thin coat of chromium (0.003 mm), which also helps to prevent corrosion by serving as a barrier.

Anodizing, used on aluminum, zinc, and magnesium alloy castings, provides corrosion resistance and wear resistance, and it may also serve as a base for painting. Anodizing of aluminum is the formation of a layer, 0.005–0.030 mm thick, of stable oxides on the surface of the base metal by making the casting the anode in an electrolytic cell, with separate cathodes of lead, aluminum, or stainless steel. This surface is usually a dull gray and therefore not ordinarily applied for decorative purposes.

The most common form of applied coating for aesthetic appearance and protection is painting. Paint may be applied to bare metal, primed metal, or surfaces that have additional protective coatings. Paint is often applied by electrostatic painting, which uses powdered paint sprayed through a nozzle having an electric potential opposite to that of the castings.

The process of impregnation, while not a surface-finishing process, is sometimes performed after any required polishing processes have been completed. Impregnation is used on castings where porosity may produce structural problems, as when castings are to be used to hold fluids or to contain fluid pressure. The process of impregnation consists of placing the castings in a vacuum chamber to evacuate the pores, and immersing the castings in a sealant. The sealant is then forced into the pores once the casting is in atmospheric pressure.

The cost of surface treatments is often represented as a simple cost per square area of the casting surface. Typical costs for the more common surface treatments and for sealant impregnation are given in Table 10.5.

TABLE 10.5

Costs of Common Finishing Processes

Finishing Process	Cost[a] per 50 cm^2 of Surface Area (cents)
Sealant impregnation	1.8
$Cu/N_i/Cr$ plate	4.5
Polish	1.3
Anodize	1.6
Prime cost	2.1
Finish paint coat	2.4

[a] Costs will vary by country, region and year—text values are intended for design comparisons only.

10.7 Auxiliary Equipment for Automation

Several operations in die casting may be automated in order to reduce cycle times and to produce more consistent quality. These operations, which may utilize mechanized equipment or simple programmable manipulators, are the removal of the casting from the die, transfer of castings to subsequent operations such as trimming, application of die lubricants, and transfer of molten metal to the shot chamber of cold-chamber machines.

Automatic extraction involves the use of a pick and place device to remove the part from the die. The fingers of the device are open upon entry into the die opening; they then close on the casting, which is usually suspended on the ends of the ejector pins, pull it out of the die opening, and drop it onto a conveyor belt or into a trim die. These devices range from simple two-degree-of-freedom mechanisms to programmable robots that are capable of multiple-axis motions. Small nonprecision die castings may simply be dropped from the die in the same manner as small injection moldings.

Die lubricants may be applied automatically by stationary spray heads located near the die, or by reciprocating spray heads located near the die, or by reciprocating spray heads that enter the die opening after the casting has been extracted. These are sometimes mounted on the back of the extractor arm and are sprayed as the arm is retracting from the die.

Automatic metal transfer systems are used to transfer molten metal from the holding furnace to the shot chamber of cold-chamber die-casting machines. These systems may be simple mechanical ladles as shown in Figure 10.4 or a variety of more complex systems, some of which fill at the bottom in order to reduce the transfer of oxides.

10.8 Determination of the Optimum Number of Cavities

Die-casting processing cost is the product of the die-casting cycle time and the operating rate of the die-casting machine and its operator. In order to determine the operating rate, the machine size must be known. This, in turn, can only be determined if the number of die cavities is known. Since the procedures being developed in this work are to be used in early design, the number of cavities that may be used in later manufacturing cannot be determined with certainty. It can only be assumed that the part would be manufactured in

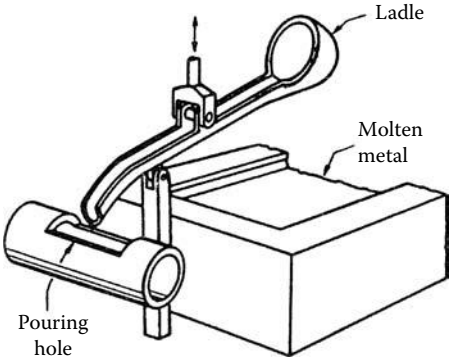

FIGURE 10.4
Simple mechanical ladle for cold-chamber machine.

an efficient manner. Thus, a value for what is likely to be an optimum number of cavities must be used. The determination of this value is the subject of this section, which follows the procedure introduced for injection molding.

The optimum number of die cavities to be used in the die-casting die, equal to the number of apertures in the trim die, can be determined for a particular die-casting task by first calculating the most economical number of cavities, and then analyzing the physical constraints of the equipment to ensure that the economical number of cavities is practical. The most economical number of cavities can be determined by the following analysis, which is almost identical to the one for injection molding:

$$C_t = C_{dc} + C_{tr} + C_{dn} + C_{tn} + C_{ta}, \$ \tag{10.1}$$

where

C_t = total cost for all the components
C_{dc} = die-casting processing cost, $
C_{tr} = trimming processing cost, $
C_{dn} = multicavity die casting die cost, $
C_{tn} = multiaperture trim die cost, $
C_{ta} = total alloy cost, $.

The die-casting processing cost, C_{dc}, is the cost of operating the appropriate size die-casting machine, and it can be represented by the following equation:

$$C_{dc} = \left(N_t/n\right)C_{rd}t_d, \$ \tag{10.2}$$

where

N_t = total number of components to be cast over the die payback period
n = number of cavities
C_{rd} = die-casting machine and operator rate, $ per hour
t_d = die-casting machine cycle time, hour.

The hourly operating rate of a die-casting machine, including the operator rate, can be approximated by the following linear relationship:

$$C_{rd} = k_1 + m_1F, \$ \quad \text{per hour} \tag{10.3}$$

where

F = die casting machine clamp force, kN
k_1, m_1 = machine rate coefficients.

This relationship, which is identical in form to the one for injection molding, was arrived at through examination of machine hourly rate data. Linear regression analysis of the data in Tables 10.2 and 10.3 gives the following values:

$$\text{Hot chamber} : k_1 = 55.4,\ m_1 = 0.0036$$

$$\text{Cold chamber} : k_1 = 62.0,\ m_1 = 0.0052.$$

The form of the relationship is supported by the nature of the variation of die-casting machine capital costs with rated clamp force values as shown in Figure 10.5. This machine cost data, obtained from five machine makers, shows a linear relationship between clamp

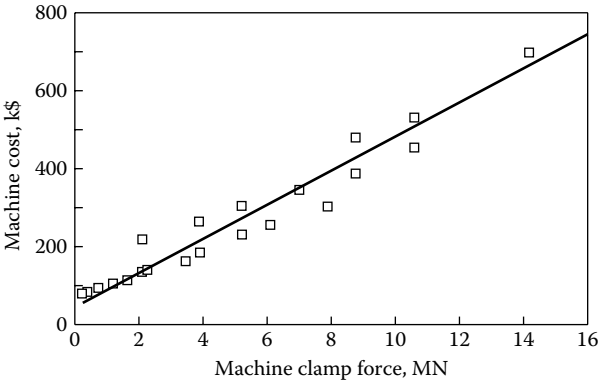

FIGURE 10.5
Capital costs of die-casting machines.

force and machine costs for hot- or cold-chamber machines up to 15 MN. However, it should be noted that very large cold-chamber machines in the range of 15–30 MN are associated with greatly increased cost. For these machines, the smooth relationship results obtained in this section should be applied with caution.

The cost of trimming, C_{tr}, can be represented by the following equation:

$$C_{tr} = (N_t/n)\, C_{rt} t_p, \ \$ \tag{10.4}$$

where

C_{rt} = trim press and operator rate, \$/hour
t_p = trimming cycle time, hour.

In the present analysis, the hourly rate for trimming is approximated by a constant value for trim presses of all sizes. This is done because the cost of trim presses is relatively low due to the small forces required, and therefore only small-capacity presses are necessary in the trimming of die-casting alloys. For this reason, C_{rt} is dominated by the hourly rate of the trim press operator rather than by the cost of the press itself.

The trimming cycle time may be represented by the following equation:

$$t_p = t_{p0} + n\Delta t_p, \text{h} \tag{10.5}$$

where

t_{p0} = trimming cycle time for a single-aperture trimming operation for a single part
$n\Delta t_p$ = additional trimming cycle time for each aperture in a multiaperture trimming die, mainly due to increased loading time of the multicavity casting into the press.

The cost of a multicavity die-casting die, C_{dn} relative to the cost of a single-cavity die, C_{dl}, follows a relationship similar to that of injection molding dies. Based on data from Reinbacker [5], this relationship can be represented as the following power law:

$$C_{dn} = C_{dl} n^m, \ \$ \tag{10.6}$$

where
C_{dl} = cost of a single-cavity die-casting die, $
m = multicavity die cost exponent
n = number of cavities.

The decreased cost per cavity resulting from the manufacture of multiple identical cavities follows the same trend as for the manufacture of injection molds. Also, the plate area per cavity and hence the die set cost per cavity follows a similar trend as shown in Chapter 8 for injection mold bases. Thus, as discussed in Chapter 8, a reasonable and justifiable value for m is 0.766, associated with an 85% learning curve.

The cost of a multiaperture trim die, C_{tn}, relative to the cost of a single-aperture trim die, C_{t1}, will clearly follow a similar relationship, namely

$$C_{tn} = C_{t1} n^m, \$ \tag{10.7}$$

where
C_{t1} = cost of a single-aperture trim die, $
m = multiaperture trim die cost exponent.

The equation for the total alloy cost, C_{ta}, is

$$C_{ta} = N_t C_a, \$ \tag{10.8}$$

where
C_a = alloy cost for each casting, $.

Compiling the previous equations gives

$$C_t = (N_t/n)(k_1 + m_1 F)t_d + (N_t/n)(t_{p0} + n\Delta t_p)C_{rt} + (C_{d1} + C_{t1})n^m + N_t C_a \tag{10.9}$$

If full die-casting machine clamp force utilization is assumed, then

$$F = nf \; kN$$

or

$$n = F/f \tag{10.10}$$

where
F = die-casting machine clamp force, kN
f = separating force on one cavity, kN.

Substituting Equation 10.10 into Equation 10.9 gives

$$C_t = N_t(k_1 f/F + m_1 f)t_d + N_t C_{rt} t_{p0} f/F + N_t C_{rt}\Delta t_p + (C_{d1} + C_{t1})(F/f)^m + N_t C_a \tag{10.11}$$

In order to find the number of cavities that gives the lowest cost for any given die-casting machine size, the derivative of Equation 10.11 with respect to the clamp force, F, is equated to zero. This gives

$$dC_t/dF = -N_t f\left(k_1 t_d + C_{rt} t_{p0}\right)/F^2 + mF^{(m-1)}\left(C_d + C_t\right)/f^m = 0 \tag{10.12}$$

Finally, rearranging Equation 10.12 gives

$$n = \left[\frac{N_t\left(k_1 t_d + C_{rt} t_{p0}\right)}{\left(m\left(C_{d1} + C_{t1}\right)\right)}\right]^{1/(1+m)} \tag{10.13}$$

as the equation for the most economical number of die cavities for any given die-casting task.

EXAMPLE

An aluminum die cast component has an estimated die-casting cycle time of 20 s for a single-cavity die and an estimated 7 s trimming cycle time for a single-aperture trim die. The cost of a single-cavity die for this part has been estimated to be \$10,000 and the trim die has been estimated to be \$2000. Determine the optimum number of cavities for production volumes of 100,000, 250,000 and 500,000 assuming k_1 = \$62/h, C_{rt} = \$40/h, and m = 0.766.

Using Equation 10.13, when N_t = 100,000 components, gives

$$n = \left[\frac{100{,}000\left(62 \times 20 + 40 \times 7\right)}{\left(3600 \times 0.766 \times 12{,}000\right)}\right]^{1/1.766}$$

$$= 2.4$$

Similarly, for 250,000 components, n_c = 3.9, and for 500,000 components, n_c = 5.8. These numbers indicate that for production volumes of 100,000, 250,000, and 500,000 dies with cavity numbers of 2, 4, and 6, respectively, would lead to most efficient manufacture.

Once the most economical number of cavities has been determined for a particular die-casting task, the physical constraints of the equipment must be examined. The first consideration is the number and position of sliding cores in the die.

As with injection molds, sliding cores must be located in the die such that they may be retracted, and such that there is space for their driving mechanisms. Also, as with injection molds, cavities that require sliding cores on four sides are limited to single-cavity dies, while cavities with cores on three sides are limited to two-cavity dies. Cavities containing core slides on two sides are restricted to either a single row of cavities or four cavities in a 2×2 configuration die, depending on the angle between slides; see Figure 10.6.

The remaining constraints are on the die-casting machine and trim press to be used for the task. The die-casting machine must be large enough to provide the required clamp force, as well as to provide a platen area, shot volume, and die opening large enough for the specified casting arrangement. Similarly, the bed area of the trim press must be large enough to accommodate the area of the shot. If the available machines and presses cannot meet all these constraints, then the number of cavities must be lowered until the required machine size falls within the range of available machines. The process of determining the appropriate machine size will be covered in detail in the next section.

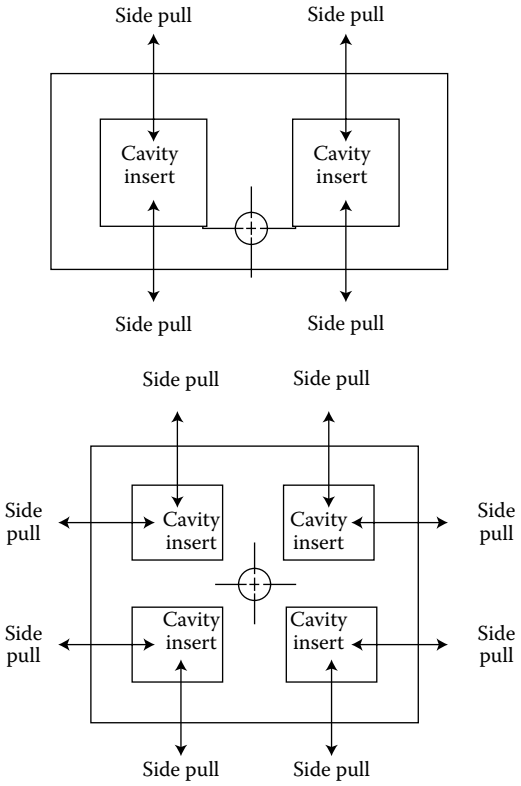

FIGURE 10.6
Restricted layout of cavities with two side-pulls.

10.9 Determination of Appropriate Machine Size

Several factors must be considered when choosing the appropriate machine size with which to cast a particular die-cast component. These factors include the machine performance, as well as the dimensional constraints imposed by the machine. The most important machine performance capability to be considered is the machine clamping force. Dimensional factors that must be considered include the available shot volume capacity, the die opening stroke length (also called clamp stroke), and the platen area.

10.9.1 Required Machine Clamp Force

Die-casting machines are primarily specified on the basis of machine clamping force. In order to prevent the die halves from separating, the clamp force, F, exerted by the machine on the die must be greater than the separating force, f, of the molten metal on the die during injection:

$$F > f \tag{10.14}$$

For a given die-casting task, the force exerted by the molten metal may be represented as follows:

$$f = p_m A_{pt} / 10, \text{ kN} \tag{10.15}$$

where
f = force of molten metal on die, kN
p_m = molten metal pressure in the die, MN/m^2
A_{pt} = total projected area of molten metal within the die, cm^2.

The total projected area, A_{pt}, is the area of the cavities, feed system, and overflow wells, taken normal to the direction of die opening, and can be represented by the following equation:

$$A_{pt} = A_{pc} + A_{po} + A_{pf} \tag{10.16}$$

where
A_{pc} = projected area of cavities
A_{po} = projected area of overflow wells
A_{pf} = projected area of feed system.

Figure 10.7 shows the relative size of a typical casting before and after trimming. The proportions of A_{pf} and A_{po} to the cavity area, A_{pc}, vary with the size of the casting, the wall thickness, and the number of cavities. However, the analysis of a wide variety of different castings has failed to establish any logical relationships between the geometry of the cavity and the area of the feed and overflow system. One reason for this situation may be, as stated by Herman [6], that the relationships between casting geometry and overflow size are not well understood. The size of overflow wells is thus a matter of individual diemaker judgment coupled with trial and error modifications during die tryout. The range of variation of $(A_{po} + A_{pf})$, from the examination of actual castings, appears to be from 50% of A_{pc} to 100% of A_{pc}. The mean value of the total casting projected area can thus be represented approximately by

$$A_{pt} \approx 1.75 A_{pc} \tag{10.17}$$

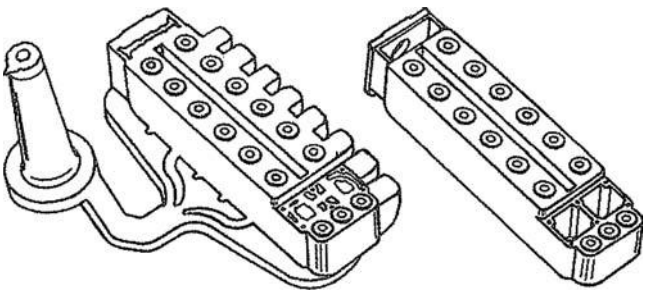

FIGURE 10.7
Hot-chamber die casting before and after trimming.

TABLE 10.6

Typical Cavity Pressures in Die Casting

Alloys	Cavity Pressure (MN/m²)
Zinc	21
Aluminum	48
ZA	35
Copper	40
Magnesium	48

Equation 10.17 is intended to be used at the early stage of design in order to obtain a first estimate of required clamp force from Equation 10.15. The pressure at which the molten metal is injected into the die depends primarily on the die-casting alloy being used. Typical pressures for the main classes of alloys are given in Table 10.6. It should be noted that the metal pressure is often increased from the instant that the die is filled in order to reduce metal porosity and surface defects that may result from metal shrinkage. However, this intensification of pressure occurs when a skin of solidified metal has already formed from contact with the die surface. This skin acts like a vessel that helps to contain the pressure increase, and for this reason machine builders suggest that the unintensified pressure should be used for clamp force calculations. Thus, the values for p_m in Equation 10.15 may be taken directly from Table 10.6. Note that, unlike the thermoplastics used in injection molding, molten metal has very low viscosity and allowance is not made for pressure losses through the die passages.

10.9.2 Shot Volume and Material Cost per Part

The shot volume required for a particular casting cycle may be represented by

$$V_s = V_c + V_o + V_f, \text{ cm}^3 \tag{10.18}$$

where
V_s = total shot volume, cm³
V_c = volume of cavities, cm³
V_o = volume of overflow wells, cm³
V_f = volume of feed system, cm³.

As with the projected area contributions, the volumes of the overflow wells and the feed system represent a significant portion of the shot volume. Also, the proportion of material in the overflow and runner system is considerably greater for the casting of parts with thinner main walls. Blum [7] analyzed a large number of different castings and suggested that the volumes of the overflow and feed systems can be represented by the approximate relationships

$$V_o = 0.8V_c/h^{1.25}, \text{ cm}^3 \tag{10.19}$$

$$V_f = V_c/h, \text{ cm}^3 \tag{10.20}$$

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where h is the average wall thickness of the part measured in millimeters. The trend of these relationships is supported in part by Herman [6], who recommends overflow volumes for die design, the average values of which fit almost precisely to the curve

$$V_o = V_c/h^{1.5},\ \text{cm}^3 \tag{10.21}$$

For the present early design assessment purposes, these tentative relationships are further reduced to the simple expression for shot size:

$$V_s = V_c\left(1 + 2/h\right),\ \text{cm}^3 \tag{10.22}$$

where again h is the average wall thickness in mm. The difference between Equation 10.22 and Equations 10.18 through 10.20 over the range h = 1–10 mm is only 4–7%. Note that the shot volume varies widely from $3V_s$ to $1.4V_s$ over the range of typical die-casting thicknesses from 1.0 to 5.0 mm.

It should be noted that the feed system and overflow wells, which are trimmed from the casting, cannot be reused immediately, as with injection moldings. The scrap material from die casting must be returned to the material supplier, where oxides are removed and the chemical composition is recertified. This "conditioning" process typically costs 15–20% of the material purchase cost. Material cost per part should, therefore, be estimated from the weight of the part, plus say 20% of the weight of overflow wells and feed system, using the costs per kilogram given in Table 10.1. Thus, the cost of material per part, C_p, can be represented as

$$C_p = (V_c + 0.2(V_s - V_c))\rho C_m \tag{10.23}$$

where

ρ = material density
C_m = material cost per unit weight.

10.9.3 Dimensional Machine Constraints

For a part to be die cast on a particular machine that has sufficient clamp force and shot volume, two further conditions must be satisfied. First, the maximum die opening or clamp stroke must be wide enough so that the part can be extracted without interference. Thus, the required clamp stroke, L_s, for a hollow part of depth D (cm), with a clearance of 12 cm for operator or mechanical extractor, is

$$L_s = (2D + 12),\ \text{cm} \tag{10.24}$$

Factor 2 is required to achieve separation from both the cavity and core.

The second requirement is that the area between the corner tie bars on the clamp unit, sometimes referred to as the platen area, must be sufficient to accommodate the required die. The size of the die can be calculated in the same way as the mold base for injection molding. Thus, the clearance between adjacent cavities or between cavities and plate edge should be a minimum of 7.5 cm with an increase of 0.5 cm for each 100 cm^2 of cavity area. Reasonable estimates of the required plate size are given by allowing a 20% increase of part width for overflow wells and 12.5 cm of added plate width for the sprue or biscuit, see Figure 10.8.

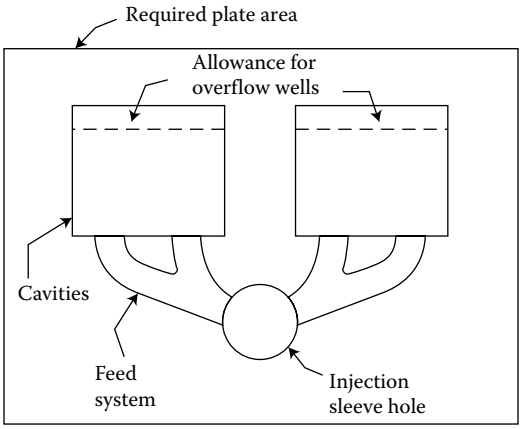

FIGURE 10.8
Layout of two-cavity die.

EXAMPLE

A 20 cm long by 15 cm wide by 10 cm deep box-shaped die casting is to be made from A360 aluminum alloy. The mean wall thickness of the part is 5 mm and the part volume is 500 cm^3. Determine the appropriate machine size if a two-cavity die is to be used, and estimate the material cost per part.

Projected area of cavities is given by

$$A_{pc} = 2 \times 20 \times 15 = 600 \text{ cm}^2$$

and thus the estimated shot area is

$$A_{pt} = 1.75 \times 600 = 1050 \text{ cm}^2$$

Thus, the die-separating force from Equation 10.15 and Table 10.6 is

$$F_m = \frac{48 \times 1050}{10}$$

$$= 5040 \text{ kN}$$

The shot size is given by Equation 10.22 to be

$$V_s = 2 \times 500(1 + 2/5) = 1400 \text{ cm}^3$$

The clamp stroke, L_s, must be at least

$$L_s = 2 \times 10 + 12 = 32 \text{ cm}$$

The clearance between the cavities and the plate edge is likely to be (allowing for an increase of 0.5 cm for every 100 cm^2 of cavity area)

$$\text{Clearance} = 7.5 + 0.5 \times (20 \times 15)/100$$

$$= 9.0 \text{ cm}$$

Thus, the two cavities may be arranged end to end with 9.0 cm spacing between them and around the edges, and with a 20% width increase to allow for the overflow wells. If an additional increase of 12.5 cm is then applied to the plate width for the biscuit, a final plate size of 67 × 42.5 cm is obtained. The layout within this plate is shown in Figure 10.8. The appropriate machine from Table 10.4 would thus be the one with 6000 kN clamp force, which can accommodate plate sizes up to 100 cm × 120 cm.

Using Equation 10.23 with material cost and density from Table 10.1 gives the estimated material cost per part as

$$C_p = [500 + 0.2 \times 200](2.74)(1.67)/1000 = \$2.47$$

10.10 Die Casting Cycle Time Estimation

A die-casting machine cycle consists of the following elements:

1. Ladling the molten shot into the shot sleeve (for cold-chamber machines only)
2. Injection of molten metal into the feed system, cavities, and overflow wells
3. Cooling of the metal in the feed system, cavities, and overflow wells
4. Opening of the die
5. Extraction of the die casting, which is usually held on the projecting ejector pins
6. Lubrication of the die surfaces (for some materials not every cycle)
7. Closing of the die for the next cycle

10.10.1 Ladling of Molten Metal

The time for manual ladling of the molten metal shot into a cold-chamber machine has been studied by Ostwald [8], who presents time standards for different shot volumes. This can be represented almost precisely by the linear relationship

$$t_{lm} = 0.0048V_s \tag{10.25}$$

where

t_{lm} = manual ladling time, s
V_s = total shot volume, cm^3.

This time does not include the transfer of the ladle to the machine pouring hole, which occurs while the die and safety door on the machine are closing.

10.10.2 Metal Injection

Metal injection and the resultant filling of feed system, cavities, and overflow wells occur extremely rapidly in die casting. This is essential to avoid premature solidification, which would prevent complete cavity filling or cause casting defects in which partially solidified streams of metal come together with incomplete bonding taking place. It is clear that the

TABLE 10.7

Typical Die Casting Thermal Properties

Alloy	Injection Temp. (°C)	Liquidus Temp. (°C)	Die Temp. (°C)	Ejection Temp. (°C)
Zinc	440	387	175	300
Aluminum	635	585	220	385
ZA	460	432	215	340
Copper	948	927	315	500
Magnesium	655	610	275	430

problem of premature solidification is greater for thinner wall die castings since, during filling, a thinner stream of molten metal, with less heat content, contacts the cooled die walls. The Society of Die Casting Engineers [9] has recommended that fill time should be directly proportional to the average casting wall thickness governed by the following equation:

$$t_f = 0.035h\left(T_i - T_l + 61\right) / \left(T_i - T_m\right), \text{ s} \tag{10.26}$$

where

t_f = fill time for feed system, cavities, and overflow wells, s
T_i = recommended melt injection temperature, °C
T_l = die-casting alloy liquidus temperature, °C
T_m = die temperature prior to shot, °C
h = average wall thickness of die casting, mm.

Typical values of T_i, T_l, and T_m, together with recommended ejection temperature, T_x, for the different families of die-casting alloys are given in Table 10.7. Substitution of these values into Equation 10.26 yields fill times ranging from 0.005 to 0.015 h. It can be seen that fill times in die casting rarely exceed 0.1 s and are usually represented in milliseconds. Thus, for the purposes of estimating cycle times, fill time can simply be neglected.

10.10.3 Metal Cooling

As described briefly above, the casting cycle proceeds when molten metal, at temperature T_i, is injected rapidly into the die, which is at initial temperature T_m. The casting is then allowed to cool to a recommended ejection temperature T_x, while the heat is being removed from the die through the circulation of cooling water.

During solidification of the metal, latent heat of fusion is released as the metal crystallizes. This additional heat can be represented by an equivalent increase in temperature, ΔT, given by the following equation:

$$\Delta T = H_f / H_s \tag{10.27}$$

where

H_f = latent heat of fusion coefficient, J/kg
H_s = specific heat, J/(kg°C).

The equivalent injection temperature, T_{ir}, then becomes

$$T_{ir} = T_i + \Delta T \tag{10.28}$$

This approach to the inclusion of heat of fusion in cooling calculations has been used extensively in the literature. The term ΔT is often referred to as "superheat."

It is accepted in the literature [10] that the main resistance to heat flow from the casting is the interface layer between the casting and the die. This is in direct contrast to injection molding, where the resistance to heat flow is provided by the polymer itself. This is because in injection molding, the thermal conductivity coefficient of the thermoplastics is of the order of 0.1 W/(m°C), whereas die-casting alloys have typical conductivity values of approximately 100 W/(m°C). This leads to a cooling problem in die casting, which is entirely opposite to that existing in injection molding. In injection molding, the goal is to cool the polymer as rapidly as possible in order to reduce the major component of cycle times. In die casting, "lubricants" are sprayed onto the die to protect the die surface, and also to provide a heat-resistant coating in order to slow cooling for satisfactory die filling.

The resistance of the die interface is represented by its heat-transfer coefficient, H_t, which has units kW/m²/°C. The rate of heat flow into the die surface is then given by

$$\dot{W} = H_t A(T - T_m) \tag{10.29}$$

where

T = alloy temperature adjacent to die face, °C
T_m = temperature of die adjacent to die face, °C
A = area of contact with die surface, m²
H_t = heat-transfer coefficient, kW/m²/°C
$\dot{W}$ = heat flow rate, kW.

Reynolds [11] has shown that for permanent mold (nonpressurized) casting of aluminum alloy, the heat transfer coefficient with a polished die surface is as high as 13 kW/(m² K). However, with a thin coat of amorphous carbon, the heat-transfer coefficient varies between 1 and 2 kW/(m² K). Sekhar et al. [12] confirmed the pronounced effects on heat transfer of the thin layers of carbon produced from the die lubricants by the hot metal contact. They also showed that the heat-transfer coefficient is increased by applied pressure on the metal. For typical die-casting pressures between 20 and 50 MN/M², and carbon layers between 0.05 and 0.2 mm thick, Sekhar's results show an average heat-transfer coefficient value of approximately 5 kW/(m² K). This value has been used to establish the cooling-time coefficients below.

Dewhurst and Blum [13] have shown that, based on the heat-transfer coefficient as the principal heat resistance mechanism, the cooling time may be represented by the simple equation

$$t_c = \frac{h_{max}}{2H_t/(\rho H_s)} \log_e \left[\frac{T_{ir} - T_m}{T_x - T_m} \right] \tag{10.30}$$

where
- ρ = density, Mg/m^3
- H_s = specific heat, J/(kg °C)
- T_{ir} = "superheat" injection temperature, °C
- T_m = mold temperature, °C
- T_x = casting ejection temperature, °C
- h_{max} = maximum casting wall thickness, mm
- H_t = heat-transfer coefficient, $W/(m^2\ °C)$.

The reader may note the major difference between this equation with the corresponding one for cooling of injection moldings, which has a similar form. In die casting, no great processing penalty must be paid for significant increases in wall thickness since the time is linearly related to the thickness rather than to the square of the thickness.

EXAMPLE

Determine typical cooling times for zinc die castings.

For a typical zinc die-casting alloy, the following parameter values can be used:

$\rho = 6.6\ Mg/m^3$
$H_s = 419\ J/(kg°C)$
$T_{i'} = 440°C$
$T_e = 300°C$
$T_m = 175°C$
$H_f = 112 \times 10^3\ J/kg$
$H_t = 5000\ W/(m^2°C)$.

Thus, from Equations 10.27 and 10.28

$$T_{ir} = \frac{440 + \left(112 \times 10^3\right)}{419} = 707.3°C$$

Substituting the preceding values into Equation 10.30 gives an estimate of the nominal cooling time as

$$t'_{cz} = 0.4h_{max}\ s$$

where
- t'_{cz} = nominal cooling time for zinc alloys
- h_{max} = maximum wall thickness, mm.

Similar substitutions into Equation 10.30 with appropriate parameter values for other die-casting alloys give the following simple expressions for cooling time:

$$t'_c = \beta h_{max}\ s \tag{10.31}$$

where
β = cooling factor
and
β = 0.4 for zinc alloys
= 0.47 for aluminum alloys
= 0.42 for ZA alloys
= 0.63 for copper alloys
= 0.31 for magnesium alloys.

Equation 10.31 is based on the assumption that there is negligible resistance to heat flow through the steel die and into the cooling channels. This is a good assumption for basically flat castings where cooling channels can be arranged through the cavity and core blocks to cover the casting surfaces. For complex casting shapes, however, cooling of the dies becomes less efficient and the cooling time increases. Herman [6] has suggested that the cooling time increases with casting complexity in proportion to the ratio of the cavity surface area, A_f, divided by the cavity projected area, A_p. However, comparisons with industrial case studies show that this tends to overestimate the cooling time for geometrically complex castings and that the trend represented by the square root of the ratio of surface to projected area is more reasonable. However, for thin-wall castings, the cooling time for the feed system may be longer than for the casting itself. A rule of thumb, obtained from industrial sources, is that the cooling time is never less than for a flat 3 mm thick casting. Thus, the cooling time estimate becomes

$$\begin{aligned} t_c &= \beta h_{max} \left(A_f/A_p\right)^{1/2} \\ &= 3\beta \quad \text{if } h_{max} \left(A_f/A_p\right)^{1/2} < 3 \end{aligned} \tag{10.32}$$

where
A_f = cavity surface area
A_p = cavity projected area; excluding the feed system and overflow wells.

EXAMPLE

Determine the cooling time for a 50 mm diameter by 100 mm deep plain cylindrical cup, with 3 mm wall thickness, which is to be die cast from aluminum alloy.

Cavity area, A_f = 17,671 mm^2
Cavity projected area, A_p = 1963 mm^2.

From Equation 10.32, with the appropriate β value of 0.47,

$$h_{max} \left(A_f/A_p\right)^{1/2} = 2\left(17{,}671/1963\right)^{1/2} = 6.0,$$

thus, $t_c = 6 \times 0.47 = 2.8$ s

10.10.4 Part Extraction and Die Lubrication

On die opening, the ejector pins protrude through the core and push the casting, with its feed and overflow system, into the gap between the cavity and core plates. Small nonprecision castings may then be dropped into the gap below the die, usually into a water tank where a conveyer belt transports the part into a bin. However, die castings always stick onto the ejector pins because of flashing around the pin ends in the die, and a secondary ejection mechanism must be employed to break the casting free. This usually involves putting small rack-and-pinion actuators behind a small proportion of the pins, which move these pins further forward at the end of the main ejector stroke.

For larger or precision parts, the casting must be removed from the ejector pins by the machine operator or by a pick-and-place device on an automatic machine. In this case, the time for casting removal depends principally on casting size. Discussions with die casters suggest that a typical time for unloading a 10 cm × 15 cm casting is 3 s, and that unloading a 20 cm × 30 cm casting will take 5 s. It is assumed, on the basis of manual handling time estimates by Ostwald [8], that the unloading time increases linearly with the casting envelope perimeter, and thus these values give the relationship

$$\begin{aligned} t_x &= 1 + 0.08(W + L) \quad \text{for } W + L > 25 \text{ cm} \\ &= 3.0 \text{ s otherwise} \end{aligned} \tag{10.33}$$

where

t_x = casting extraction time, s
W, L = width and length of the smallest rectangle that will enclose feed system, cavities, and overflow wells, cm.

EXAMPLE

A box-shaped aluminum alloy casting, 8 cm wide by 10 cm long by 2 cm deep, is to be cast in a six-cavity die. Estimate the time for extraction of the casting from the die-casting machine.

Using the guidelines for casting layout given in Section 10.8, the size of each cavity plus overflow wells is approximately (8 × 1.2) by 10 or 9.6 cm by 10 cm. Assuming a two-by-three pattern of castings with a separation of 8 cm (7.5 plus 0.5 cm for a cavity area of approximately 100 cm^2), gives a cavity array size equal to 28 cm × 44.8 cm. Finally, allowing a 12.5 cm width increase for the sprue or biscuit and runners gives a total casting size of 40.5 × 44.8 cm.

The time for part extraction, from Equation 10.33, is thus

$$t_x = 1 + 0.08(40.5 + 44.8) = 7.8 \text{ s}$$

The time for die opening and closing is estimated in the same way as for injection molding. The only difference is that in die casting, the full clamp stroke is commonly utilized to give adequate access for casting removal. As in injection molding, the die must be opened at less than full clamp speed to allow safe separation of casting from the cores. If 40% full speed is assumed, as discussed in Section 8.6.3, then the die opening plus closing time can be given by

$$t_{open} + t_{close} = 1.75 t_d \text{ s} \tag{10.34}$$

where t_d is the machine dry cycle time.

Thus, if the six-cavity die above is operated on the 6000 kN cold-chamber machine in Table 10.3, the die opening and closing time is given by

$$t_{open} + t_{close} = 1.75 \times 5.8 = 10.2 \text{ s}$$

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TABLE 10.8

Lubricant Application Times for Die Casting (Seconds) and Required Cycles per Lubrication

		Added Time	
Part Size	**Basic Time**	**Per Side-Pull**	**Per Extracavity**
Small (10 cm × 10 cm)	3	1	1
Medium (20 cm × 20 cm)	4.5	1	2
Large (30 cm × 30 cm)	6	1	3
Number of machine cycles per lubrication, n_l			
Aluminum	1		
Copper	1		
Zinc–aluminum	2		
Magnesium	2		
Zinc	3		

After part extraction, and before the die is closed, the die surfaces are sprayed with an appropriate lubricant. The resulting lubricant film serves two purposes. It forms a barrier to heat flow, as discussed in Section 10.10.3, to allow more time for satisfactory cavity filling. It also protects the die surface from erosion by the high-pressure wave of hot metal. The time for the application of die lubricant depends on the alloy being cast and on the number of cavities and cavity size. It also increases with the number of side-pulls, since the slideways require additional lubricant concentration. Typical times obtained from industrial contacts are given in Table 10.8. The basic time for this small amount of die lubrication data can be seen to be linearly related to the part envelope perimeter. With this linear assumption, the time for die lubrication can be written as

$$t_l = (1.5 + (0.075 + 0.05(n_c - 1))(L + W) + n_c n_s)/n_l \tag{10.35}$$

where

L,W = length and width of rectangular part envelope, cm
n_c = number of die cavities
n_s = total number of side-pulls
n_l = number of machine cycles per lubrication.

EXAMPLE

The box-shaped aluminum castings discussed above have a hole in the side wall that requires one side-pull for each of the six cavities. The average wall thickness is 4 mm and the maximum wall thickness is 10 mm. The projected area, A_p, of each cavity is 80 cm^2 and the cavity surface area, A_f, equals 280 cm^2. The volume of each casting is 85 cm^2. Thus, from Equation 10.22, the shot volume is given by

$$V_s = 6 \times 85 \times (1 + 2/4) = 765 \text{ cm}^3$$

Referring to Equation 10.35, the die lubrication time per machine cycle is given by

$$t_l = 1.5 + (0.075 + 0.05 \times 6)(8 + 10) + 6 \times 1 = 14.3\,\text{s}$$

Note that if the boxes were cast from zinc alloy, then lubrication would occur every three cycles, and so the value for t_l would be 4.8 s.

The cooling time for the box castings is given by Equation 10.34 as

$$t_c = (280/80)^{1/2} \times 0.47 \times 10$$
$$= 8.8\,\text{s}$$

The time for ladling of the molten aluminum shot into the cold-chamber machine is given from Equation 10.25 as

$$t_{lm} = 2 + 0.0048 \times 765 = 5.7\ \text{s}$$

Finally, from Section 10.10.2, it can be shown that the fill time is approximately 0.004 s, which can be neglected.

Thus, the complete cycle time for the six-cavity die casting operation is as follows:

Cooling time	= 8.8
Part extraction time	= 7.8
Die lubrication time	= 14.3
Die open/close time	= 10.2
Metal ladling time	= 5.7
Total	= 46.9 s.

10.10.5 Trimming Cycle Time

The need for the trimming operation in the die-casting process is an important factor distinguishing die-casting cost estimation from that of injection molding. The trimming processing cost is the product of the trimming time and the hourly operating rate of the machine and operator. As previously mentioned in the discussion on optimum number of cavities, the hourly trimming rate can be approximated by a constant value for all machine sizes because of the small tonnages of the machines as well as the relatively small range of machine sizes. This small press size requirement means that the hourly rate is dominated by the hourly labor rate of the trim press operator rather than by the cost of the press itself.

The trimming cycle time, including the time to load the shot into the press, is similar to punch press loading and cycle times for sheet metalworking, given by Ostwald [8]. These times vary linearly with the sum of the length and width of the part and can be represented by the following relationship developed from these data:

$$t_s = 3.6 + 0.12(L + W)\,\text{s} \tag{10.36}$$

where

t_s = sheet metal press cycle time, s
L = length of the rectangular envelope, cm
W = width of the rectangular envelope, cm.

Discussion with industrial sources indicates that press loading times of die-casting shots are generally longer than sheet metal loading times. One reason for this is that die-casting shots are oddly shaped and are, therefore, more difficult to align in the die. Additional time is also required for periodic cleaning of the trimming die, as flash and other scrap create a buildup of debris.

It appears from data on a limited number of castings that trim press cycle times are typically 50% higher than manual press operations for sheet metal. Thus, for early costing purposes, the trim press cycle time can be estimated by

$$t_p = 5.4 + 0.18(L + W)\,\text{s} \tag{10.37}$$

For consistency with the die-casting machine hourly rates in Tables 10.3 and 10.4, a trim press rate of $40 per hour should be used with Equation 10.37 to estimate trimming process cost.

Note that for castings with side holes produced by side-pulls, trimming is required in both the die opening and side-pull directions. In some cases, these separate trimming tasks will be carried out with separate trim tools on separate presses. In these cases, a multiple of the time estimate from Equation 10.37 would give the appropriate total trimming cycle time. The cost of trim dies and the effect on die cost of multiple trim directions are discussed in Section 10.11.3.

10.11 Die Cost Estimation

The tooling used for die casting is somewhat more expensive than for injection molding. There are three main reasons for this. First, because of the much greater thermal shocks to which a die-casting die is subjected, finer steels must be used for the die set and cavity and core inserts than are necessary for injection molding. This gives rise to increased costs for the die set even though it is identical in basic construction to an injection-molding mold base. It also results in greater costs for manufacturing the cavity and core inserts because of the more difficult-to-machine material. Second, the overflow wells and larger sprue or biscuit take up more plate area than in injection molding with the requirement for a larger die set than the corresponding mold base for an injection-molded part. Third, for other than the smallest production volumes, a separate trim tool must be manufactured to remove the flash, feed system, and overflow wells from the finished castings.

10.11.1 Die Set Costs

A major supplier of interchangeable die sets and mold bases offers them with three qualities of steel: No. 1 steel (SAE 1030), No. 2 steel (AISI4130), and No. 3 steel (P-20 AISI 4130). Steels No. 1 and No. 2 are recommended for injection molding, while steels No. 2 and No. 3 are recommended for die casting. For the same plate areas and thicknesses, the average cost of mold bases (steel No. 1 or 2) is compared with the average price of die sets (steel No. 2 or 3) in Figure 10.9. The line drawn on the graph has a slope equal to 1.25, which means that for the same plate sizes, a die-casting die set would typically be 25% more expensive than a mold base for injection molding. It will be assumed that, because of the more

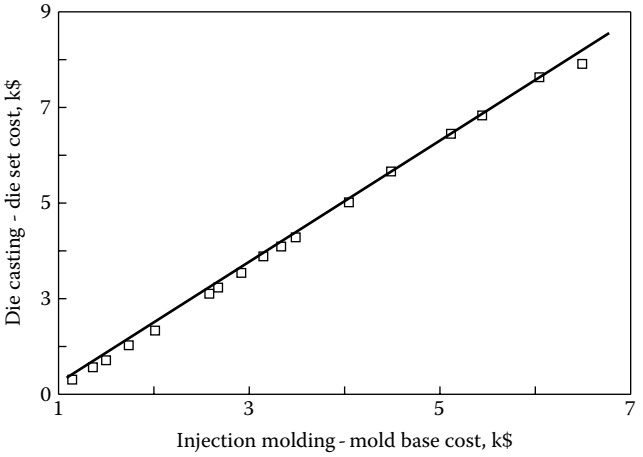

FIGURE 10.9
Relative cost of die-casting die sets.

difficult machinability of the steels, the custom machining work to be carried out on the die set is also 25% more expensive than for injection mold bases. Thus, from Equation 8.11 in Chapter 8, the cost of a completed die set can be represented as an equivalent number of manufacturing hours given by

$$M_d = 62.5 + 0.029 A_c h_p^{0.4} \text{ h} \tag{10.38}$$

where

A_c = area of die set cavity plate, cm^2 (which can be estimated from the casting layout rules given in Section 10.9.3)

h_p = combined thickness of cavity and core plates in die set, cm.

As with injection molding, typical plate thicknesses should be based on 7.5 cm of plate material separating the casting from the outer plate surfaces. Thus, a 10 cm plain cylindrical cup would typically have the main core mounted onto a 7.5 cm thick core plate and the cavity sunk into a 17.5 cm thick cavity plate.

Also, as for injection molding, the plate area should be increased to allow for any necessary side-pulls; see the description in Section 8.7.1.

10.11.2 Cavity and Core Costs

The equations developed for estimating the costs of cavities and cores for injection molding in Chapter 8 can be applied directly to die casting with only minor changes. The most important change is the use of a factor to allow for the more difficult-to-machine steels and the machining of overflow wells. A survey of die and mold makers found reasonable agreement that die-casting dies are in the range of 20–30% more expensive than equivalent molds for injection molding. This also agrees with the comparison of die set to mold base costs in the last section. It seems that typically the cavities and cores would be 25% more expensive for die casting. The equations in Section 8.8.2 of Chapter 8 should, therefore, be applied with a multiplying factor of 1.25. Also, for any required side-pull mechanisms in the die, a manufacturing time of 80 h should be assigned; that is, approximately 25% more than for injection

TABLE 10.9

Surface Finish Effect on Point Score

Appearance	Percentage Increase
Minimum finish	10
Medium finish	18
Highest quality	27

molds. As for mold cost estimating, an 85% learning curve should be allowed for repeated identical side pulls, and of course to allow for repeated identical features in the part geometry.

The range of tolerances that can be achieved with die casting is approximately the same as for injection molding, and the effect on cavity and core manufacturing time is as given in Section 8.9. However, as opposed to the six different surface finish and appearance factors applicable to injection molding, only three surface finish categories are typically used for die casting. These can be represented as

1. Minimum finish required to achieve clean separation from the die.
2. Medium finish that would allow parts to be buffed or polished.
3. Highest-quality finish, which is usually reserved for zinc alloy parts that are to be chrome-plated to mirror standard.

The percentage increases that should be used in the point cost system of Section 8.9 to account for cavity and core finishing are given in Table 10.9.

10.11.3 Trim Die Costs

The basic trim die performs essentially the same function as a sheet metal blanking die. However, the trim die construction is less expensive than for blanking dies because of the smaller forces that are encountered. Examination of a range of industrial trim dies indicates that the cost of a die to trim a casting with a flat parting plane and no internal holes is approximately half the cost of an equivalent sheet metal blanking die. Moreover, if additional punches are required to trim internal holes in a casting, then the cost is approximately the same as for the purchase and fitting of standard punches into a sheet metal die set.

Thus, from the equations developed in Chapter 9, the cost of a trim die can be estimated as follows. Complexity of the profile is defined as for sheet metal parts, but in this case the perimeter, P, is the sum of all the edges to be trimmed.

$$X_p = P/(LW)^{1/2} \tag{10.39}$$

where

P = total length of the edges to be trimmed, cm
L, W = length and width of the smallest rectangle that surrounds outer perimeter of one cast part, cm.

Taking 50% of the basic manufacturing points for blanking dies gives

$$M_{t0} = 14 + 0.52X_p \text{ h} \tag{10.40}$$

Using the average of the curves used in Chapter 9 for area correction of blanking dies gives

$$f_{lw} = 1 + 0.04(LW)^{0.7} \tag{10.41}$$

Using the sheet metal value of 2.0 equivalent manufacturing hours for the purchase and fitting of standard punches gives the estimated hours for a basic trim tool as

$$M_t = f_{lw}M_{t0} + 2N_h \tag{10.42}$$

where
M_t = tool manufacturing time, h
N_h = number of holes to be trimmed.

Two additional factors can substantially increase the cost of the basic trim tool. These are the complexity of the parting line and the existence of through holes, produced by side-pulls, which require trimming in a nonaxial direction. Data on trim tool costs obtained from die casters suggest the following approximate relationships for these added cost factors:

1. Each additional trim direction would require approximately 40 extra hours of tool making. This is the time to produce an extra trim tool with one or more shaving punches, or to incorporate a mechanism action into the main trim tool for angled punch action.
2. Approximately 17 h of additional tool making are associated with each unit of the parting line complexity factor, f_p, defined according to Table 8.8 of Chapter 8. Thus, a casting with parting line having a single step would require approximately $1.5 \times 17 = 25.5$ extra hours of manufacture for the trim tool. This time is required to produce a die with cutting edges on the different levels required to follow the stepped parting line. This same allowance of 25.5 h should be applied, for each level change, if holes or cutouts are to be trimmed at different levels than the casting perimeter.

EXAMPLE

A die casting has the following defining characteristics:

Outer perimeter, $P = 68.6$ cm
Envelope dimension, $L = 24.0$ cm
Envelope dimension, $W = 13.5$ cm
Number of holes to be trimmed, $N_h = 9$
Number of side-pulls per cavity, $n_s = 2$
Number of cavities, $n_c = 2$
Parting line factor = 2

Estimate the cost of the required trim tool.

$$\text{Outer profile complexity, } X_p = 68.62/(24 \times 13.5)^{1/2}$$

$$= 3.8$$

$$\text{Area correction factor, } f_{lw} = 1 + 0.04(24 \times 13.5)^{0.7}$$
$$= 3.3$$

$$\text{Basic manufacturing points, } M_{t0} = 14 + 0.52(3.8)$$
$$= 16$$

The base manufacturing hours for the trim tool for a single cast part is given by Equation 10.42 as

$$M_t = 3.3 \times 16 + 2 \times 9 = 70.8 \text{ h}$$

Two additional trim directions are required for the side-pull features, which would require 40 added hours of tool making. The parting line has several steps, giving a parting line factor of 2 and, thus, 34 added hours to achieve the stepped trim die surface.

If a typical tool making rate of $40/h is assumed, then the cost of the trim tool(s) for one cast part would be approximately

$$C_{tl} = (70.8 + 80 + 34) \times 40 = \$7392$$

In this case, a two-cavity die is used, so the trim tool must have two shaving dies and two sets of punches to accommodate the two-part casting. To allow for the manufacture of trim tools for multicavity castings, the multicavity cost index is used exactly as for the cost estimating of multicavity dies and molds. Thus, using a multicavity index value of 0.766 (as used in Section 10.8), the estimated total cost of the complete trim tool is

$$C_{tn} = 7392 \times 2^{0.766} = \$12{,}500$$

As carried out in Chapter 8 for injection molding, useful approximate die and trim tool cost estimators can be obtained by plotting the manufacturing hour equations, multiplied by the die-making hourly rate, for assumed typical casting geometries. For the approximate casting die costs given in Figure 10.10, the cavity was assumed to have a square envelope ($L = W$) and a depth of one quarter of that value ($D = L/4$). The typical tolerance was taken to be Level 3 in Table 8.7 of Chapter 8. The surface finish was assumed to be "medium" as in Table 10.9. Additional cost should be added, as described in Section 10.11.2, for any required side-pull mechanisms. Also Section 8.8 should be referred to for appropriate additional manufacturing cost for other than a flat parting surface between the die plates.

The approximate costs for trim dies, given in Figure 10.11, are for the trimming of the perimeter of casting where necessary for the removal of overflow wells, runners, and flash. An additional $80 should be added for each separate standard hole to be trimmed, and appropriate further additions should be made, as described above, for any required side action, or for trimming at different levels. The costs in Figures 10.10 and 10.11 are based on a die-making rate of $40/h, costs for other die-making rates can be changed in proportion.

10.12 Assembly Techniques

Die castings can be produced with a variety of features that assist with assembly. Alignment features such as chamfered pins, holes, slots, projecting alignment edges, and so forth have insignificant cost and yet can ensure frustration-free quality assembly

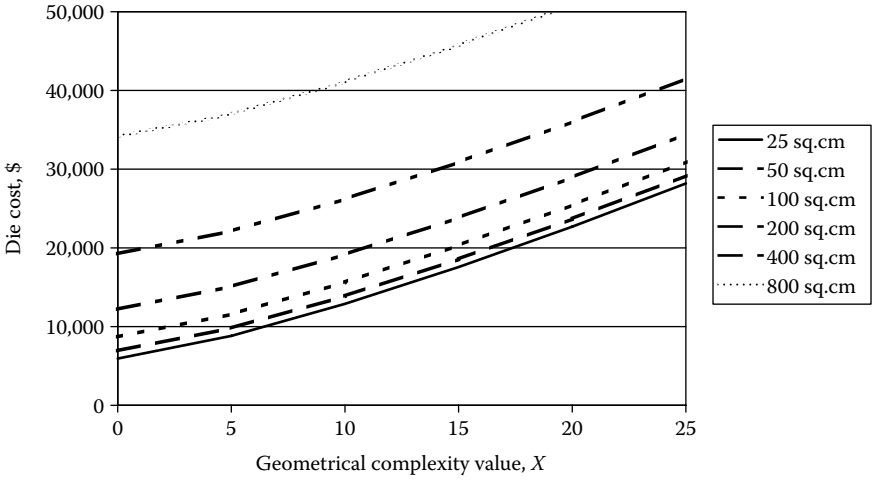

FIGURE 10.10
Approximate casting die cost curves for increasing projected area, A_p. (Costs for class of typical parts as described in the text with $40/h die making rate.)

work. Unfortunately, there is no equivalent in die casting to injection-molded snap fit elements. The only integral fastening method available seems to be the cold forming of cast projections to achieve permanent fastening. The cast alloy must, of course, possess sufficient ductility, and this limits the assembly method to zinc and ZA alloys. With these alloys, projecting rivet posts, tabs, or projecting edges can be upset or bent after assembly to achieve strong attachment.

As with injection molding, the die-casting process lends itself to the use of inserts, which are simply loaded into the die before injection. This practice is used widely to produce

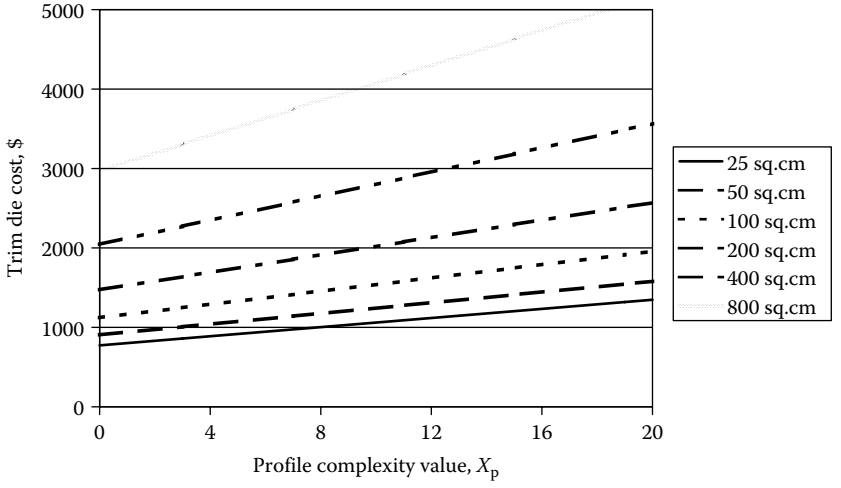

FIGURE 10.11
Approximate trim die cost curves for increasing plan area, *LW*. (Costs are for single trim plane with $40/h die making rate; additional costs must be added for standard holes, different trim levels or side action.)

castings with screw studs projections for assembly purposes. However, unlike injection molding, screw thread bushings are not used since cored holes in the casting can be tapped to produce high-strength attachment.

Examples can be found of die castings with spring steel inserts where the spring satisfies a functional requirement in the assembly. This suggests the possible use of spring steel inserts to produce snap fit die cast parts. However, the authors are unaware of any such application.

10.13 Design Principles

Die casting and injection molding are closely competing processes, and the detail design principles to ensure efficient manufacture are similar for both. Generally accepted guidelines for die-casting design are listed below.

1. Die castings should be thin-walled structures. To ensure smooth metal flow during filling and minimize distortion from cooling and shrinkage, the wall should be uniform. Zinc die castings should typically have wall thicknesses between 1 and 1.5 mm. Similar size castings of aluminum or magnesium should be 30–50% thicker than zinc, and copper die castings are usually 2–3 mm thick. These thickness ranges result in a fine-grained structure with a minimum amount of porosity and good mechanical properties. Thicker sections in a casting has an outer skin of fine metal, with thicknesses about half of the preceding values, with a center section that has a coarser grain structure, some amount of porosity, and poorer mechanical properties. The designer should, therefore, be aware that mechanical strength does not increase in proportion to wall thickness. However, large die castings are often designed with walls as thick as 5 mm and sections up to 10 mm thick. An important consideration in these cases is that, compared to injection molding, little cost penalty is associated with the casting of thick sections. Recall that the cooling time for die castings is proportional to thickness, while cooling time for injection molding is proportional to thickness squared. Thus, a 5 mm thick injection-molded part would typically take about 60 s to cool, while a 5 mm thick die casting may take only about 5 s. Perhaps of greater significance, a 2 mm thick die casting, which may have the same stiffness as the 5 mm injection-molded part, would only take 3 s to cool. This comparison suggests an economic advantage for die casting where good mechanical properties or heavy walls are required.
2. Features projecting from the main wall of a die casting should not add significantly to the bulk of the wall at the connection point. As with injection molding, this would produce delayed cooling of the localized thickened section of the main wall, resulting in contraction of the surface (sink marks) or internal cavitation. A general rule is that the thickness of projections, where they meet the main wall, should not exceed 80% of the main wall thickness.
3. Features projecting from the side walls of castings should not, if possible, lie behind one another when viewed in the direction of the die opening. In this way, die locking depressions between the features are avoided, which would otherwise require side-pulls in the die. Projections that are isolated when viewed in the

direction of the die opening can often be produced by making a step in the parting line to pass over the center of the projection.

4. Internal wall depressions or internal undercuts should be avoided in casting design, since moving internal core mechanisms are virtually impossible to operate with die casting. Such features must invariably be produced by subsequent machining operations at significant extra cost.

Notwithstanding the preceding guidelines, the power of die casting lies in its ability to produce complex parts with a multitude of features to tight tolerances and with good surface finish. Thus, having made the decision to design for die casting, the most important rule is to obtain as much from the process as is economically possible. In this way, the structure of the assembly is simplified with all the resulting cost and quality benefits. The main purpose of the procedures established in this chapter is to help the designer to identify economic applications of the die-casting process and to quantify, if necessary, the cost of alternative designs.

PROBLEMS

In all of the questions below use the data from Tables 10.1 through 10.7 for material costs, material properties, cycle time calculations, and machine hourly rates. Where needed assume a die-making rate of $40/h.

1. The rotor assembly housing shown in Figure 10.12 is to be die cast using Aluminum Alloy A360. The part is 13 cm high. The large diameter is 20 cm, which steps down to 17.5 cm at the midpoint. The bottom of the housing is open and the top has a large hole of 12.5 cm diameter in the center surrounded by 1.5-cm diameter holes.

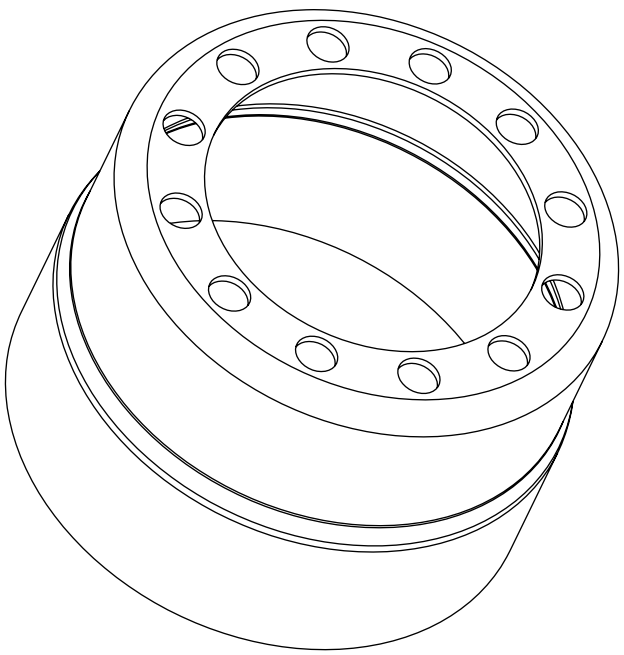

FIGURE 10.12
Rotor assembly housing.

The part has a uniform wall thickness value of 2.50 mm. It has an estimated weight of 584 g. Taking account of the through holes, it has a projected, A_p, of 170.3 cm^2.

a. Determine the appropriate cold chamber machine, from Table 10.4, on which to cast the part using a single-cavity die.
b. Estimate the die-casting cycle time and use it to obtain the estimated die-casting process cost.
c. Estimate the time and process cost for trimming.
d. Estimate the material cost.

2. For the rotor assembly housing described in Problem 1, estimate the cost of:
   a. A single-cavity die; assuming tolerance level 2 (Table 8.8, Chapter 8) and medium surface finish (Table 10.9).
   b. A corresponding trim die. Note that trimming is required on two levels—the bottom edge of the part, and the holes at the top. Make appropriate cost allowance for this step in the trim die construction.
3. Figure 10.13 shows a support platform for a precision electrical instrument. The platform is 100 mm high, and the platform base and top have outer dimensions 75 × 60 mm. The cutout in the top plate has dimensions 45 × 30 mm. The platform is to be diecast with Zamak 5 Zinc alloy with eight through holes as shown.

   Section thicknesses are 5 mm everywhere, with the exception of the stiffening ribs along the length and both sides of the legs. These are 3 mm thick.
   From the solid model of the part, the part volume, V_p, is 42.0 cm^3. The projected area for machine size selection, A_p, equals the top plate area of 31 cm^2.
   a. Determine the appropriate hot chamber machine, from Table 10.3, on which to cast the part using a single-cavity die.
   b. Estimate the die-casting cycle time and use it to obtain the estimated die-casting process cost.
   c. Estimate the time and process cost for trimming.
   d. Estimate the material cost.
4. For the support platform shown in Figure 10.13, and described in Problem 3, estimate the likely cost of a single-cavity casting die and a trim die. Die opening will be in the vertical direction so that the top and bottom surfaces can be flat and parallel as required. The die will have two opposing side-pull mechanisms to form the T-shaped legs and the opening between them. Assume a single trim die is to be used, which has mechanisms to allow edges of the feet to be shaved from the front and rear at the same time as the vertical trimming action. A total length, *P*, of 82 cm is to be trimmed as well as the eight standard through holes.

   For a geometry such as this one, there is no simple breakdown into inner and outer surfaces. In this case, it is easier to use a breakdown of the main features. The total complexity, *X*, has been calculated in this way in the table below.

Name of Feature	Surface Patches (N_s)	Repeats (r)	Complexity X ($0.1N_s * r^{0.766}$)
Top plate	6	1	0.60
Leg	12	4	3.47
Feet	5	4	1.45
Holes	1	8	0.49
			$X = 6.0$

5. Assume that the production of the rotor housing (Figure 10.12) has started using a single-cavity mold and trim tool. The actual cycle times have been measured as

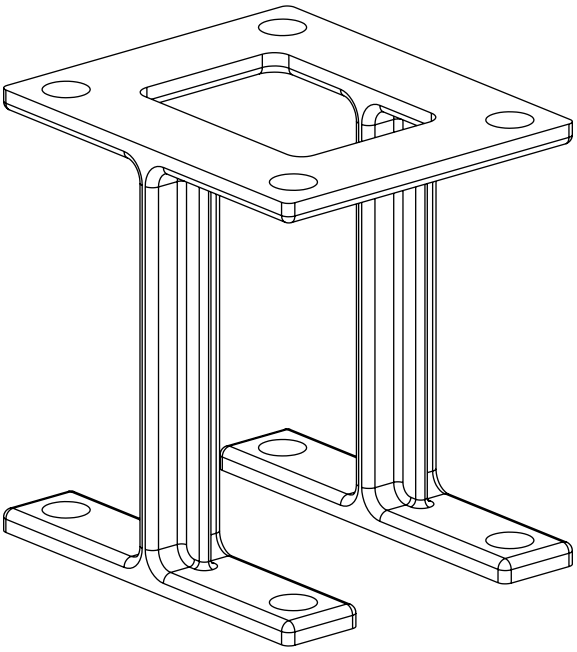

FIGURE 10.13
Support platform.

22 s for die casting and 14 s for trimming. In addition, the actual casting die cost was $16,000 and trim die cost was $5000. Your company has now been asked to quote for 450,000 housings.

a. Estimate the likely optimum numbers of cavities to use for this order, using the 85% learning curve.
b. Select the appropriate machine from Table 10.4, for use with your selected number of cavities.
c. Make a quick estimate of the likely cost of the multicavity mold and the multiaperture trim tool.
d. Is your multicavity die capable of making the entire order?
(Use coefficients $k_1 = 62.0$ and $m_1 = 0.0036$ for cold-chamber machine hourly rates (see Section 10.8) and assume a trim press rate of $40/h).

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11

Design for Powder Metal Processing

11.1 Introduction

A variety of structural parts, bearings, gears, and so on are produced from raw materials in the form of powders. This area of processing is generally called powder metallurgy, although parts can also be made from nonmetallic powders, such as ceramics, by these methods. In the main processing sequence used, raw material powders are mixed and then compressed into the required shape. The compact is then heated in a controlled atmosphere (sintered) to bond the particles together and produce the required properties of the part. A variation of the process, powder injection molding, has recently become more widely used and particularly has advantages for small complex parts. This process will be discussed later in the chapter (Section 11.14).

The powder metallurgy processes have a number of features that are not found in other metalworking processes, including [1–4]:

1. Precise control of material and product properties. Through careful control of the constituent powder materials, compaction levels, and so on, precise control of the final product properties can be achieved.
2. Unique material compositions. Although most powder metallurgy parts are produced with standard material compositions [5,6], a wide range of compositions can be produced by the powder metallurgy process, including combinations impossible by other means. For example, metals and ceramics can be combined by compaction and sintering.
3. Unusual physical properties. Physical properties can be readily varied by powder metallurgy from low-density, highly porous filters to high-density parts with low porosity. Tensile strengths can also be varied from low to very high. It is possible to compact dissimilar materials in layers to obtain different properties at various places in the part. The porosity can be controlled so that impregnation with oil or other lubricants can lead to self-lubricating properties for bearings.
4. Net-shape manufacturing. Complex-shaped parts that require no further processing can be produced by the powder metallurgy process. Many gears, cams, and so forth, which may require expensive machining to produce from wrought material stock, can be readily produced from metal powders. Counter bores, holes, flanges, and similar features can be formed when the parts are compacted.
5. Little material wastage and loss. Material wastage from the powder metal process is very low, as illustrated in Figure 11.1, which compares the overall material wastage for a range of processes [7].

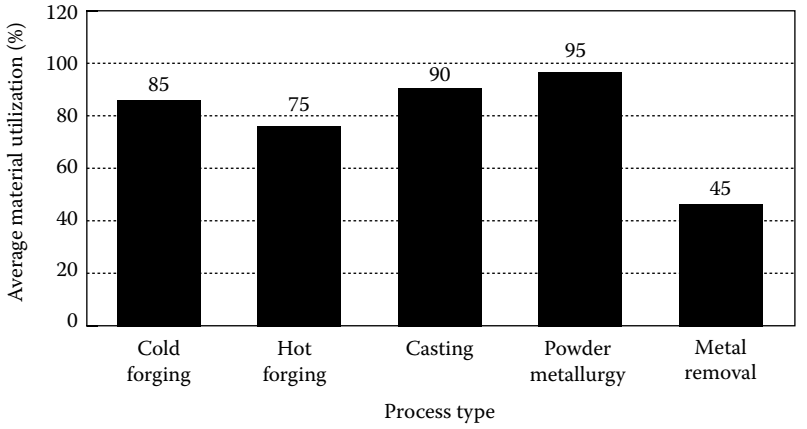

FIGURE 11.1
Material utilization for basic shape-producing processes. (Adapted from Kloos, K.H., VDI Berichte, No. 77, p. 193, 1977.)

6. High accuracy and repeatability. Close tolerances and a high degree of repeatability, particularly in the transverse direction, can be readily obtained.
7. Low overall energy utilization. The total energy usage by the process is low compared to other forming and shaping processes (Figure 11.2) [7].

11.2 Main Stages in the Powder Metallurgy Process

Unlike some other material shaping processes, such as injection molding or casting, the powder metallurgy process consists of several independent stages involving different equipments. The basic processing stages are shown in Figure 11.3.

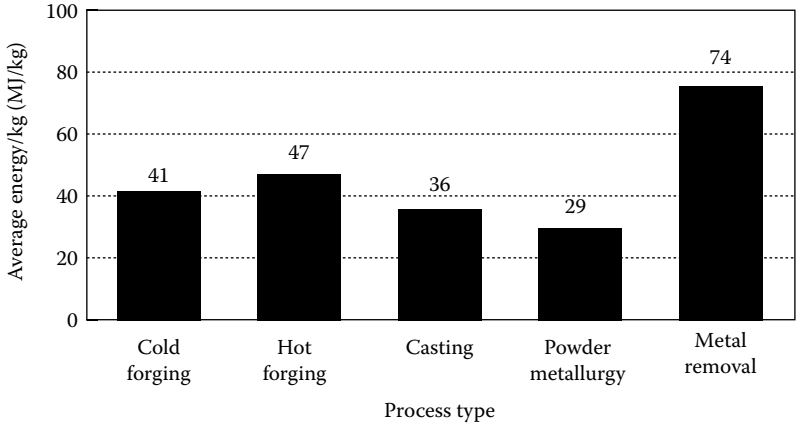

FIGURE 11.2
Energy utilization per unit part weight for basic shape-producing processes. (Adapted from Kloos, K.H., VDI Berichte, No. 77, p. 193, 1977.)

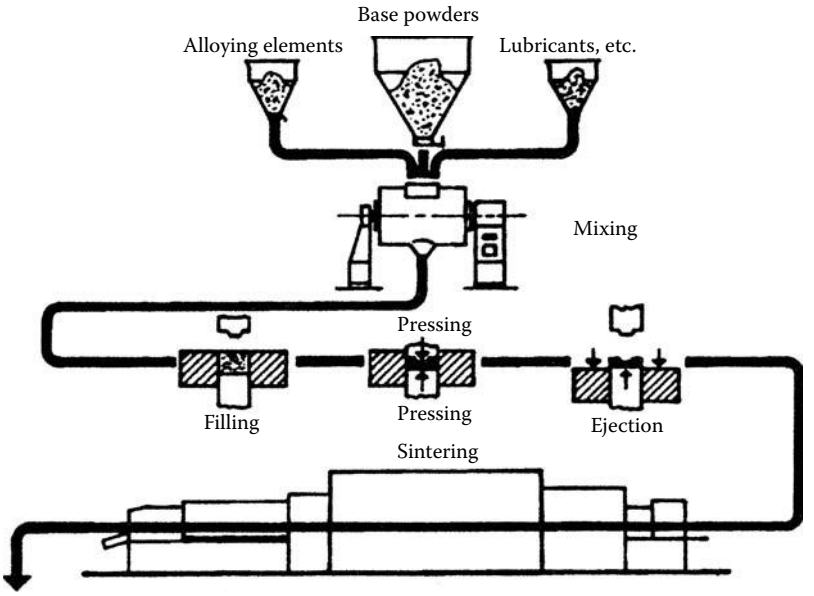

FIGURE 11.3
Main processing stages for sintered powder parts. (Adapted from Mosca, E., *Powder Metallurgy: Criteria for Design and Inspection*, Associozone Industriali Metallugici Meccanici Affini, Turin, 1984.)

11.2.1 Mixing

The initial stage in the powder metallurgy process is blending and mixing of the powder materials, together with additives such as lubricants, which are included to aid the compaction process. Metallic stearates, such as zinc stearate, are commonly used as lubricants for compaction and usually form 0.5–1.5% of the mixture. Premixed powders are available directly from suppliers for some standard materials; however, in general, mixing from constituent elemental or prealloyed powders within the plant is necessary. A variety of mixers are available with different configurations and capacities. The overall purpose of mixing is to obtain a mixture of powders and lubricants as homogeneous as possible.

11.2.2 Compaction

For the majority of engineering powder metallurgy parts, the next stage is cold compaction of the mixed powders. This is most often achieved by die pressing, but other methods are available. Hot compaction, which eliminates the subsequent sintering stage, is used for some specialized applications. In this chapter, mainly cold die pressing is considered in detail as this is the most commonly used method of compaction. A wide variety of different densities, porosities, and tensile strengths can be obtained by using different degrees of compaction or compaction pressures. Powder injection molding is discussed at the end of the chapter.

During the compaction process, the mixed powders are pressed, usually from both sides, by a number of separately moving punch elements, depending on the complexity of the part. The output of the process is a "green" compact, which has sufficient "green strength" properties to allow handling without damage prior to sintering. The final material properties are directly related to the compaction density achieved, as discussed in more detail in Section 11.4.

11.2.3 Sintering

During sintering, the compacted parts are passed through a controlled atmosphere furnace and heated to a temperature below the melting point of the constituent powders. The individual particles become bonded together by diffusion bonding. A variety of different furnace types are available. Most commonly, continuous flow furnaces are used for high productivity, but batch furnaces are also used, particularly if special atmosphere conditions or high temperatures are required.

11.3 Secondary Manufacturing Stages

A number of secondary manufacturing processes can be used in conjunction with the main processing steps, usually to refine material properties and produce features not obtainable from the basic processes. The commonly utilized secondary processes are shown schematically in Figure 11.4.

11.3.1 Repressing and Resintering

In order to achieve high component densities, partial sintering, followed by repressing and a further sintering stage, is usually necessary. The part is compacted to a moderate density and then presintered. Subsequently, the part is returned to a die set, usually different from the initial compaction die set, and pressed again. A further final sintering stage follows to achieve the required material properties. This combination of processes should be used only when density is critical, because the extra processing stages increase part costs considerably.

11.3.2 Sizing and Coining

Secondary pressing operations (sizing) are used to refine dimensional accuracy or compensate for warpage, and so forth, in the sintered part, with little increase in density occurring. Coining may also be used to engrave or emboss small features in the faces of the part. In each case, a suitable die set must be designed and manufactured, in addition to the compaction tools.

11.3.3 Infiltration

For some structural applications, it is necessary to eliminate any residual porosity from the powder metallurgy part and to increase strength properties. This can be achieved by infiltrating the sintered part with a lower melting point metal, such as copper, with metal being taken up into the part by capillary action. Infiltration is often carried out by placing a suitable slug of the lower melting point material on the base material compact and then heating to a temperature above the melting point of the infiltrant material. Infiltration can be carried out during the initial sintering process, but is most often done in a second pass through the furnace. In both cases, a compact of the infiltrant material must be prepared, in addition to the main part compact, which requires an additional compaction process and a corresponding die set. A range of standard copper-infiltrated steels can be produced

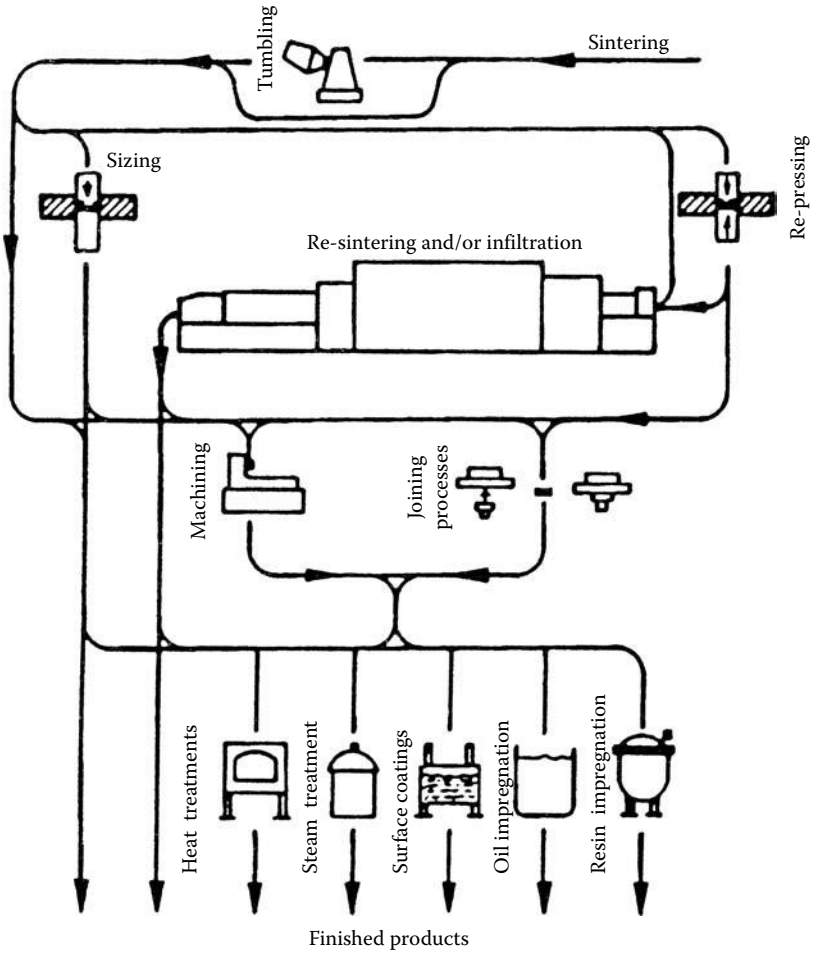

FIGURE 11.4
Secondary processing stages for sintered powder parts. (Adapted from Mosca, E., *Powder Metallurgy: Criteria for Design and Inspection*, Associozone Industriali Metallugici Meccanici Affini, Turin, 1984.)

by this process [5]. These materials can only be produced by the powder metal process in combination with infiltration.

11.3.4 Impregnation

Self-lubricating properties can be achieved by impregnating the porous sintered parts with oil. The sintered parts are usually submerged in a bath of oil for several hours, but for the best results vacuum impregnation should be used. A range of standard self-lubricating bearing materials are used [6], but most moderate density parts can be given self-lubricating properties by impregnation if required.

11.3.5 Resin Impregnation

Parts can also be impregnated with plastics, such as polyester resins, either to improve machinability or to remove porosity, which could adversely affect such finishing

operations as plating or interfere with a requirement for gas tightness. The process is similar to oil impregnation, with the interconnected porosity filled with resin by capillary action.

11.3.6 Heat Treatment

Sintered parts may require heat treatment, particularly ferrous-based powder metal parts and some aluminum alloy parts. The heat treatment processes are generally the same as those used for wrought parts.

11.3.7 Machining

Machining may be required, in particular, to produce features that cannot be produced, or may be uneconomical to produce, by sintering. However, because powder metallurgy is a net shape process, the amount of machining required is generally small. Such machining is usually restricted to undercuts or threaded holes, for example. The machining properties of sintered materials are similar to the equivalent wrought materials and can be enhanced sometimes by resin impregnation.

11.3.8 Tumbling and Deburring

Burrs produced during the compaction process can be removed by tumbling in a barrel or by vibratory deburring. In this process, the parts, after sintering, are loaded into a container, together with some abrasive particles, and then tumbled or vibrated together sufficiently to remove burrs and sharp edges.

11.3.9 Plating and Other Surface Treatments

All the common plating processes and other surface protection treatments, such as painting, can be used for powder metal parts. Residual porosity can cause plating solution entrapment; consequently, plating is often preceded by resin impregnation.

11.3.10 Steam Treating

Steam oxidizing can be used to increase surface wear and corrosion resistance of iron-based parts. Strength properties and density are also improved. Surfaces are coated with a hard black magnetic iron oxide (Fe_3O_4). The process closes some of the interconnected porosity and all surface porosity. Parts are heated to 480–600°C and exposed to superheated steam under pressure. Heat-treated parts cannot be steam-treated since the properties obtained by heat treatment would be altered.

11.3.11 Assembly Processes

Joining powder metal parts is not commonly required, because complex shapes can be achieved relative to other forming processes. Should joining of powder metal parts be required, many of the commonly used welding processes for wrought parts can be used. As a result of the residual porosity in powder metal parts, a unique joining process is possible. Parts are assembled and then infiltrated with a lower melting point metal to effect a bond similar to brazing and soldering.

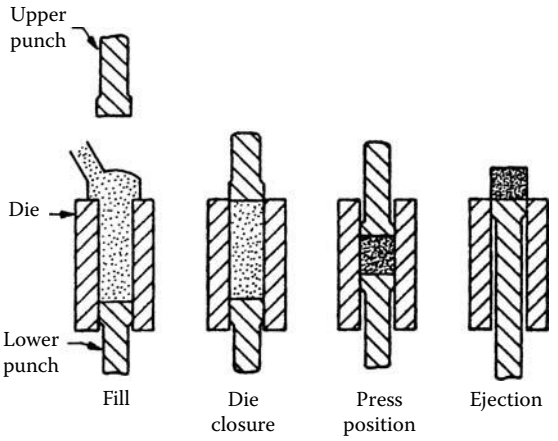

FIGURE 11.5
Basic compaction sequence for powder metal parts. (Adapted from MPIF, *Powder Metallurgy Design Manual*, 3rd ed., Metal Powder Industries Federation, Princeton, NJ, 2007.)

11.4 Compaction Characteristics of Powders

During compaction loose powders are poured into a die cavity with the compaction punches retracted (Figure 11.5). Then the punches are moved relative to the die to compact the powder and increase the density. Subsequently, the "green" compact is ejected from the tooling, prior to transfer to the sintering process.

The final material properties of the part are largely determined by the compaction density achieved. For example, Table 11.1 shows an extract from the data in the Metal Powder Industries Federation (MPIF) standard on materials [5] and shows the designation and material properties of some standard powder metal carbon steels. As can be seen, the composition of some of these standard materials is the same, but an increased strength and a modification of other properties are achieved by compaction to increased densities. For example, see the group of materials designated F-0005-15, F-0005-20, and F-0005-25, which are all low-carbon steel with a 0.05% carbon content; the different properties are achieved by the final density to which the material is compacted. The consequence of this is that for

TABLE 11.1
Extract from Data on Standard Iron-Based Materials

Material Designation or Name	Material Condition (AS or HT)	Yield Stress (N/mm^2)	Ultimate Tensile (N/mm^2)	Part Density (g/cc)
F-0000-10	AS	89.6	124.1	6.10
F-0000-15	AS	124.1	172.4	6.70
F-0000-20	AS	172.4	262.0	7.30
F-0005-15	AS	124.1	165.5	6.10
F-0005-20	AS	158.6	220.6	6.60
F-0005-25	AS	193.1	262.0	6.90

reasonably uniform properties in powder metal parts, it is necessary to achieve relatively uniform density in the "green" compacts. The basic mechanics of the powder compaction process influence the ways in which this can be done.

11.4.1 Powder Compaction Mechanics

The mechanics of powder compaction is governed by friction between the die and the powder and between the individual powder particles. Friction losses cause localized reductions in compaction pressure, and as a result, stresses are not distributed uniformly throughout the compact. First, for all but very thin parts (<6 mm), it is necessary to compact the powder from both sides. Figure 11.6 [8] shows the density distribution in a nickel powder compact that has been pressed only from one side. The highest densities are found in the upper outer circumference, where the wall friction causes the maximum relative motion of the particles. The lowest densities occur in the bottom of the compact remote from the moving punch. Thus, in order to achieve a more uniform density, it is necessary to press from both sides with independently moving punches. However, in this case, the lowest densities are in the middle of the part due to the effects of container wall friction (Figure 11.7). Even with double compaction, the density gradients impose a limit on the total length of the compact. Successful compaction becomes difficult to achieve when the length-to-diameter ratio of the compact exceeds 5 to 1 [1].

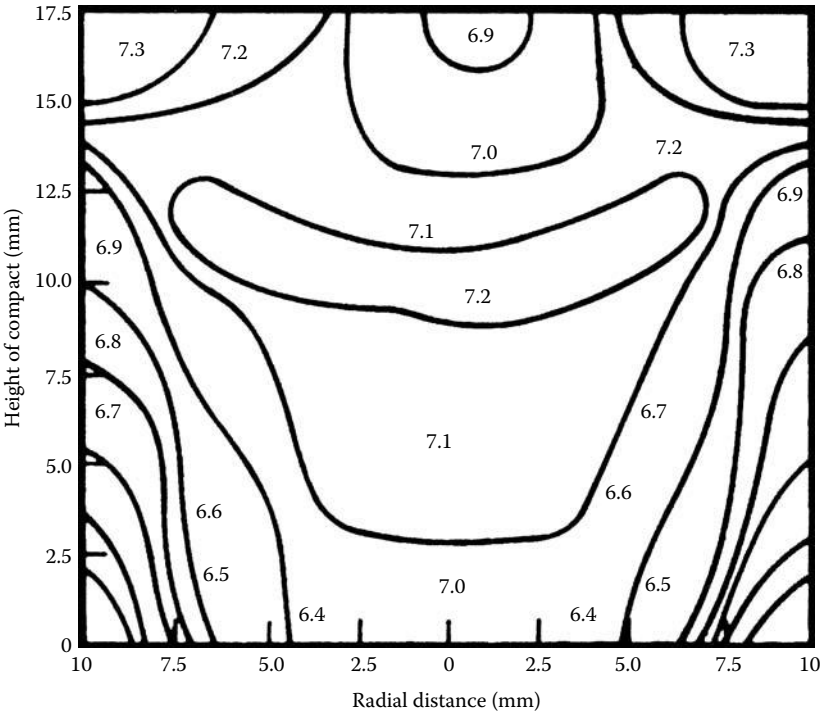

FIGURE 11.6
Density distribution in a nickel powder specimen compacted from one side only (densities in gm/cc). (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

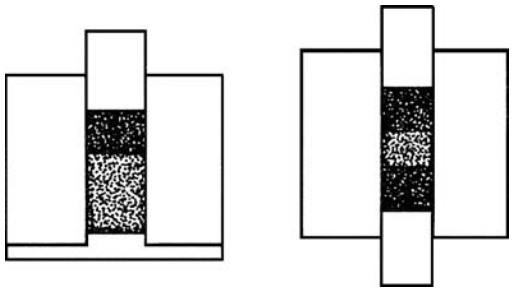

FIGURE 11.7
Density variations during two-sided compaction.

Many powder metal parts consist of a number of levels of different thicknesses in the compaction direction. In order to achieve uniform density in the compact, and hence uniform properties, these different levels must be compacted by separately moving punches. For example, Figure 11.8 shows a cross-section through a part with two levels [8]. If this is compacted with only one lower punch, with a step machined in the upper face, different compression ratios are achieved in the columns of powder associated with each level, resulting in higher densities in the thinner portion of the compact. In order to achieve more uniform density, it is necessary to use separate independently moving lower punches, with the relative movements controlled, to obtain the same compression ratio within each level.

From this it can be seen that to achieve uniform properties in a part, the overall complexity of the tooling must increase with the number of different thicknesses or levels in the parts produced.

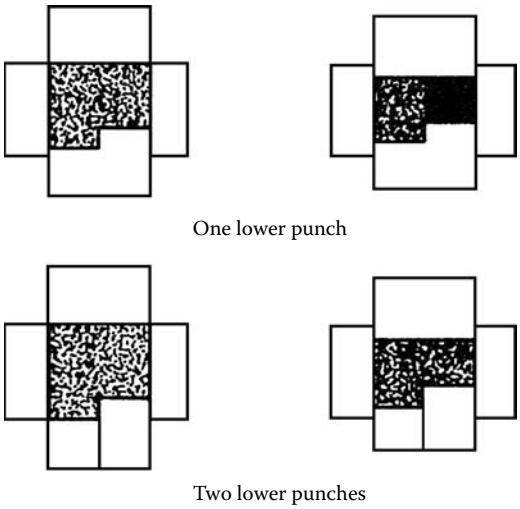

FIGURE 11.8
Density variations in a two-level part. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

11.4.2 Compression Characteristics of Metal Powders

The loads required during compaction are determined from the pressures required to achieve a certain density in the parts. Figure 11.9 shows some typical compaction curves for different materials [8]. Such curves are usually obtained from standard tests using short, cylindrical specimens. As can be seen, as the compaction pressure is increased, the density increases rapidly at first and then slows down, so that the curve eventually becomes asymptotic to a density somewhat below the wrought density of the material. It is difficult to obtain high-density parts, because at higher densities the applied loads must be increased by large amounts to obtain even small increases in the part density. For this reason, the maximum density obtained using a single compaction operation and sintering is usually around 90% of the equivalent wrought density of the material. Typical compaction pressures for a range of materials are given in Table 11.2.

In order to achieve near full density parts, it is necessary to use additional processing steps. In particular, repressing and resintering can be used. This is illustrated in Figure 11.10, which shows compaction curves for iron powders for single pressing and repressing. It can seen that to achieve a part density of, say, 7.3 g/cc by single pressing, it is necessary to use compaction pressures of 65 tons/in.^{2} (896 MPa), which produce high loads and require tooling of increased strength. By repressing and resintering, the initial compaction can be reduced to 6.85 g/cc, with moderate pressures of around 35 ton/in.^{2} (483 MPa). Repressing is then carried out at the same compaction pressure to achieve the required density. The total costs of the part, however, are increased considerably because of the extra processing stages required and a second set of compaction tooling for repressing.

Compaction curves for most materials follow the basic configuration shown in Figure 11.8, with the precise shape of the curve dependent on the material and shape of the raw

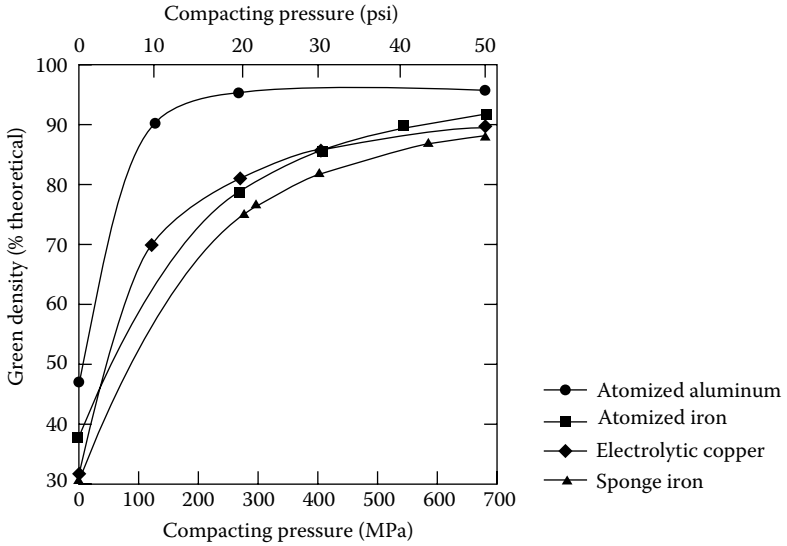

FIGURE 11.9
Typical compression curves for metal powders. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

TABLE 11.2

Typical Compaction Pressures for Powder Materials

Material	Tons (in.^{2})	MPa
Aluminum	5–20	69–276
Brass	30–50	414–687
Bronze	15–20	207–276
Carbon	10–12	138–165
Carbides	10–30	138–414
Alumina	8–10	110–138
Steatites	3–5	41–69
Ferrites	8–12	110–165
Iron (low density)	25–30	345–414
Iron (medium density)	30–40	414–552
Iron (high density)	35–60	483–827
Tungsten	5–10	69–138
Tantalum	5–10	69–138

Source: Adapted from American Society of Metals, *Metals Handbook*, Vol. 7, 2nd Ed., Powder Metal Technologies and Applications, ASM, Metals Park, OH, 1998.

powder particles among other things. Compaction curves can be approximated by a power law relationship such that

$$P = A\rho^b \tag{11.1}$$

where P is the compaction pressure and ρ is the part density. The constants A and b can be determined from two values of P and ρ obtained from suitable tests (Figure 11.11).

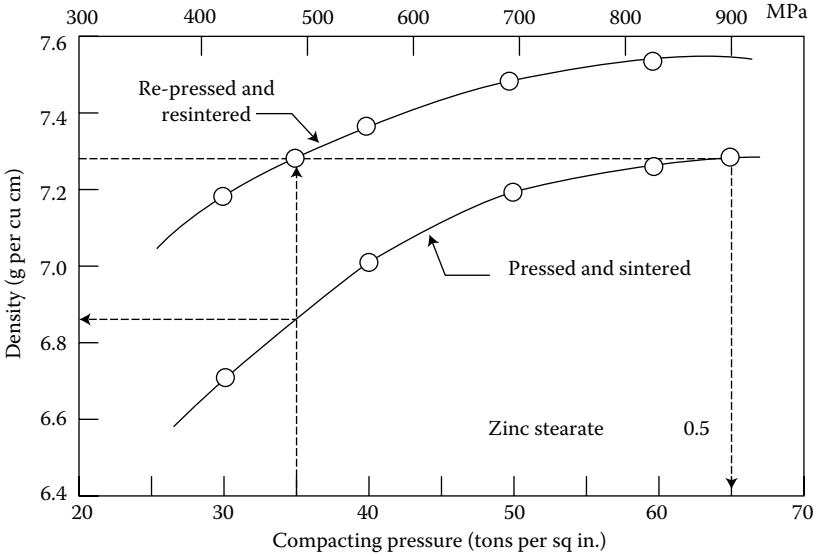

FIGURE 11.10
Compression curves for single compaction and repressing of iron powder.

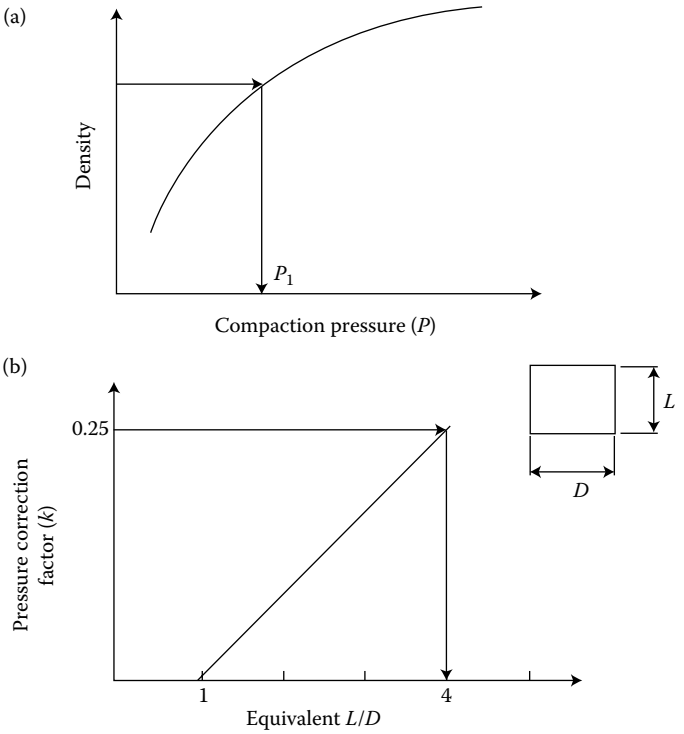

FIGURE 11.11
Correction of compaction pressures for increased part thickness.

Compaction curves are usually obtained from tests on cylindrical shapes with the height equal to the diameter. Consequently, for thicker parts the load must be increased for the required density to compensate for the increased container wall friction. This correction should be around 25% for a part length-to-diameter ratio of 4 to 1. Thus, the required compacting pressure can be obtained by increasing the value P_1 (Figure 11.11a), obtained from the basic compaction curve, by a factor K, obtained as illustrated in Figure 11.11b; that is,

$$K = \frac{0.25}{3}(L/D - 1) \quad \text{for} \quad L/D > 1$$
$$K = 0 \quad \text{for} \quad L/D < 1 \tag{11.2}$$

Therefore, the total pressure required is given by

$$P = P_1(1 + K) \tag{11.3}$$

For parts that are not cylindrical, an equivalent L/D ratio can be used given by

$$L_e/D_e = \frac{V}{2}\sqrt{\frac{\pi}{A^2}} \tag{11.4}$$

where V is the part volume and A is the projected area in the compaction direction.

11.4.3 Powder Compression Ratio

The depth of loose powder (fill height) required to give the final thickness of the compacted part is determined from the powder compression ratio at the required density (Figure 11.12). The compression ratio of the powder is given by

$$k_r = \frac{\rho}{\rho_a} \tag{11.5}$$

where ρ_a is the apparent density of the loose powder, which is dependent on the size and shape of the powder particles in the mixture. The compression ratio determines the fill height of powder required for any thickness variations in the final part.

11.5 Tooling for Powder Compaction

The requirement of maintaining relatively uniform densities means that each separate thickness in powder metal parts must usually be compacted by separately moving punch elements. Small thickness changes (<15% of the part thickness) can be accommodated by steps in the punch faces with little loss of density uniformity. Various mechanisms are used for achieving the necessary relative motions in tooling for successful compaction. The main elements for a typical tool set for a multilevel part are shown in Figure 11.13. The tool set consists of a die, inside which the relative movement of the punch elements to compact the powders takes place. Any through holes in the part are formed by core rods which remain at the same relative position to the upper die surface during the compaction

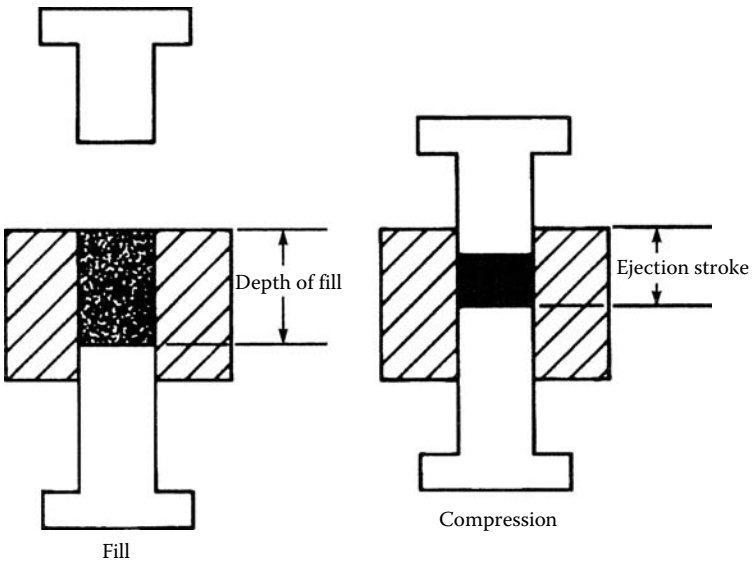

FIGURE 11.12
Fill height and ejection stroke during powder compaction. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

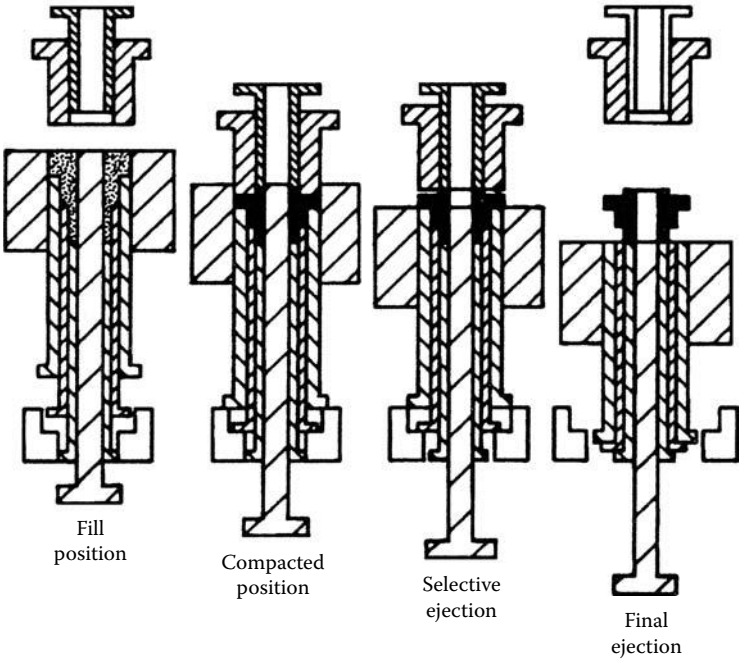

FIGURE 11.13
Typical compaction tool elements for a multilevel part. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

cycle. Other ancillary elements such as punch holder rings, core rod holders, stops, and so on, are required to complete the tool set.

During the compaction cycle, the punches are initially retracted to positions to accommodate the fill of loose powder. The retracted positions of the lower punches during filling are determined by the product of the corresponding part thicknesses and the powder compression ratio, k_r. Following filling, the compaction is achieved with the various punches moving relative to each other to give similar compaction densities in the various thicknesses in the part. Finally, after compaction, the "green" compact is ejected and the compression cycle is repeated for the next part.

The complexity and cost of compaction tooling increase as the number of levels or thickness changes in the part increases, since each separate level must be compacted by separately moving punch elements. Many presses utilize standard die sets, with an inserted die held by a suitable tool steel clamping ring. These die sets may be removable or nonremovable. In either case, the die sets must be well guided because of the small clearances between tooling elements required. Removable die sets are normally used for press capacities up to around 300 tons, after which the die sets become too large to be readily handled into and out of the press, but occasionally larger removable die sets are used.

11.5.1 Compaction Dies

The die controls the outer peripheral shape of the part, which can contain intricate detail of almost any shape. Compaction dies are usually cylindrical, with the overall thickness dependent on the part thickness and the fill height of powder required. Die surfaces must

be highly wear resistant, and the preferred material is tungsten carbide. However, because the cost of carbide is over 10 times that of tool steel, dies are usually constructed with inner carbide inserts, which are shrink-fitted into a tool steel ring. This tool steel ring has a standard outside diameter to suit the recess in the die set or press bed being used. The die insert size that can be accommodated on a particular press is limited.

The required die insert size for a specific part is dependent on the shape being compacted. Preferably, any core rod should be as near to the center of the press as possible, and for parts with multiple through holes, positioning the centroid of the projected area of the part at the die center is usually appropriate. A basic rule for determining the carbide insert size required is the diameter of the circle enclosing the part, centered on the centroid, plus an extra amount of material (Figure 11.14), which is usually not less than 10 mm. The outer die ring, as a practical rule, has a diameter at least three times that of the carbide insert.

11.5.2 Punches for Compaction

Separate punches are required for each level or thickness of the part. These punches move relative to each other during compaction, with the longer punches passing through the shorter punches. Punches must be carefully lapped to ensure close fitting with each other and with the die inner profile. Punches are usually manufactured from cylindrical tool steel stock, by combinations of turning, milling, profile grinding, and lapping.

11.5.3 Core Rods for Through Holes

Through holes of almost any profile can be achieved in powder metal parts, which allows features very difficult or costly to produce by other processes to be readily obtained.

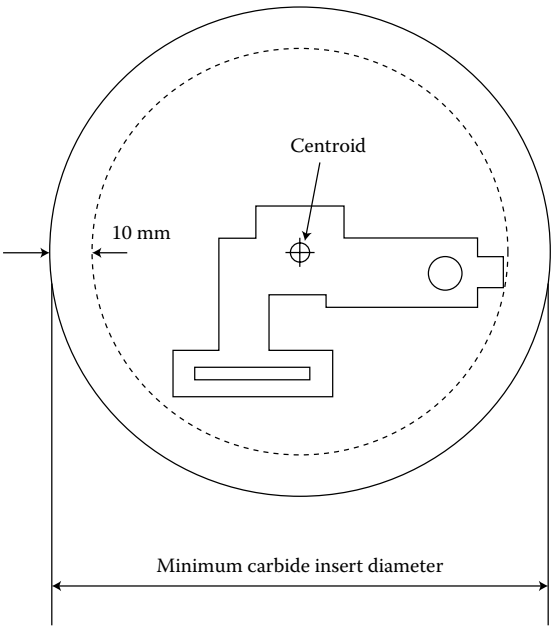

FIGURE 11.14
Compaction die insert dimensions.

Through holes are produced in the part by core rods of the appropriate cross-section. Core rods are the longest elements in the tool set. They may have very small cross-sections, but such small cross-section rods are relatively difficult and expensive to manufacture. In addition, since core rods are subjected to a cycle of compressive stresses during compaction and tensile stresses during part ejection, the fatigue life of small cross-section rods may be severely reduced. Core rods are produced from tool steel and carbide by similar methods to those used for punches. In all cases, holes of the appropriate shape must be machined in the punches through which the core rods pass.

11.5.4 Die Accessories

All die sets require a number of additional accessories to be produced, including core rod holders, punch adapters, stops, fasteners, and so on. In general, these are produced from tool and other alloy steels.

11.6 Presses for Powder Compaction

Powder compaction presses may be mechanically or hydraulically driven and differ mainly in the number of actions present in the press mechanisms. Presses are available in a wide range of capacities up to around 25,000 kN (2800 tons). Single-action presses and tooling, in which parts are compacted from one side only, are restricted to relatively thin one-level parts. Double-action presses and tooling systems allow compaction of the part from both sides. Various tool set mechanisms allow the compaction of multilevel parts to be accommodated, although two-level parts are most commonly processed. Multiple-action (adjustable stop) presses, which are capable of producing the most complex parts, are also available.

11.6.1 Factors in Choosing the Appropriate Press

Table 11.3 lists some relevant data for a representative range of compaction presses. The main items that determine the appropriate press for a particular part are as follows:

The number of vertical punch motions possible
Load capacity of the machine
Maximum fill height possible
Maximum ejection stroke possible
Maximum die diameter that can be accommodated

11.6.1.1 Punch Motions

Some machines are only capable of pressing from one direction and consequently can only be used for relatively thin single-sided parts. Other machines can press from above and below using separate punch actions at the same time, and with suitable tooling they can be used to produce multilevel parts.

TABLE 11.3

Data on a Range of Typical Compaction Presses

Type of Press	Capacity (kN)	Maximum Stroke Rate (per min)	Minimum Stroke Rate (per min)	Maximum Fill Height (cm)	Maximum Die Insert Diameter (cm)
SA	36	150	25	1.524	5.72
DA	45	90	15	3.810	7.30
SA	53	150	20	1.905	9.52
DA	89	60	10	5.080	11.18
DA	134	60	10	6.985	15.24
SA	142	100	15	1.905	13.34
DA	178	50	8	8.255	20.99
DA	267	50	8	8.255	20.32
SA	312	60	10	1.905	15.24
DA	400	40	7	11.430	15.24
DA	534	40	7	15.875	20.32
MA	534	40	7	15.875	20.32
DA	587	34	12	11.430	19.20
DA	890	30	7	15.875	20.32
DA	979	30	12	15.240	21.74
MA	1113	40	7	15.875	21.59
DA	1335	30	7	15.875	21.59
MA	1780	30	7	15.875	22.86
DA	1958	30	10	15.240	26.67
DA	2670	25	7	11.430	25.40
DA	3115	25	7	15.875	25.40
MA	4450	20	7	15.875	25.40
DA	4895	18	6	11.430	50.80

SA, single action; DA, double action; MA, multiple action.

11.6.1.2 Load Required

The total load required for a part is determined by the product of the pressure needed to compact the part to the required density and the projected area of the part in the compaction direction. Determination of the compaction pressure has been described in Section 11.4.2.

11.6.1.3 Fill Height

The fill height or depth of the fill (Figure 11.14) is the height of the loose powder required to give the part thickness after compaction. The value is determined by the compressibility of the loose powder at the required density. The fill height is obtained by multiplying the finished part height by the compression ratio of the material:

$$\text{Fill height, } h_f = tk_r \tag{11.6}$$

where t is the part thickness and k_r is the compression ratio.

If the fill height is greater than the maximum that can be accommodated in the press selected on the basis of the compacting load required, a larger-capacity machine must be used. This may be necessary for thick parts with a relatively small cross-sectional area.

11.6.1.4 Ejection Stroke

The ejection stroke is equivalent to the part thickness plus the penetration of the upper punch into the die (Figure 11.12). If a greater ejection stroke is required than is available on the press selected on the basis of compacting load, then a large-capacity machine must be used, but often this problem can be overcome by suitable design of the tooling. Consequently, ejection stroke is not a major determining factor in press selection.

11.6.1.5 Maximum Die Diameter

Presses and tool sets have a maximum die size that can be accommodated. The required die size for a particular part is determined by the procedure described in Section 11.5.1. If the required die size is greater than that can be used in the press selected from the compaction load, it is necessary to use a press of larger capacity that can accommodate the required die size. This may be necessary for a part that has a large circumscribing circle diameter, but a relatively small projected area in the compaction direction.

11.6.2 Presses for Coining, Sizing, and Repressing

Presses for secondary pressing operations, including coining, sizing, and repressing, are similar to compaction presses, but the powder fill mechanisms are replaced by part loading systems. The shorter strokes required for these operations result in faster cycle times than for compaction presses of similar capacities. Tool designs are similar to compaction, but punch and core rod lengths are considerably smaller as a result of the shorter working strokes required. Table 11.4 lists data on a selected range of secondary operation presses. Selection procedures for these presses are essentially the same as for compaction presses, and it is normally assumed that the loads required are the same as for compaction.

TABLE 11.4

Data on a Range of Typical Coining and Sizing Presses

Type of Press	Capacity (kN)	Maximum Stroke Rate (per min)	Minimum Stroke Rate (per min)	Maximum Clearance Height (cm)	Maximum Die Insert Diameter (cm)
DA	30	112	47	1.600	5.08
DA	45	200	50	1.600	5.08
DA	80	90	15	3.000	6.35
DA	134	200	50	2.540	7.62
DA	150	100	17	4.000	8.89
DA	267	60	10	3.810	11.43
DA	300	60	22	6.500	12.70
DA	356	150	30	4.140	15.24
DA	534	100	15	5.080	21.59
DA	890	60	10	5.080	20.32
DA	1000	50	17	7.500	20.32
DA	1780	60	10	5.080	20.32
DA	2500	30	5	10.000	20.32

DA, double action.

11.7 Form of Powder Metal Parts

Parts suitable for manufacture by the powder metallurgy process generally consist of one or more levels, with each level being effectively an extruded two-dimensional profile. The profiles at each level may be complex and contain intricate shape features. For example, finished gear profiles can be readily produced. Figure 11.15 shows some typical powder metal parts from industry.

The prime objective in compaction is to compress the powder and achieve a relatively uniform density in the compact. Thin (<6 mm) single-layer parts can be successfully pressed from one side only with a single punch and require a relatively simple single-action press. Steps of less than 15% of the part thickness can be accommodated by steps in the punch faces without too much variation in density. Thicker single-layer parts require pressing from both sides, with two punches moving from above and below at the same time. In multilevel parts, each level requires a separate moving punch for successful compaction. Such parts require more complex tooling and require presses capable of multiple-action pressing. The number of separate moving punches that can be accommodated in a die set is limited and parts with up to three levels per side of the part can be produced, but most parts have fewer levels than this (Figure 11.16). Through holes can be formed during compaction and each hole requires a separate core rod, which passes through the punches in the die set.

Tooling costs are increased by the number of levels in the part and the number of through holes. Small-sized through holes require fragile core rods, and their presence tends to increase tool maintenance costs.

The MPIF [9] classifies parts into four complexity levels as follows:

Class I—thin one-level parts of any contour

Class II—thick one-level parts of any contour

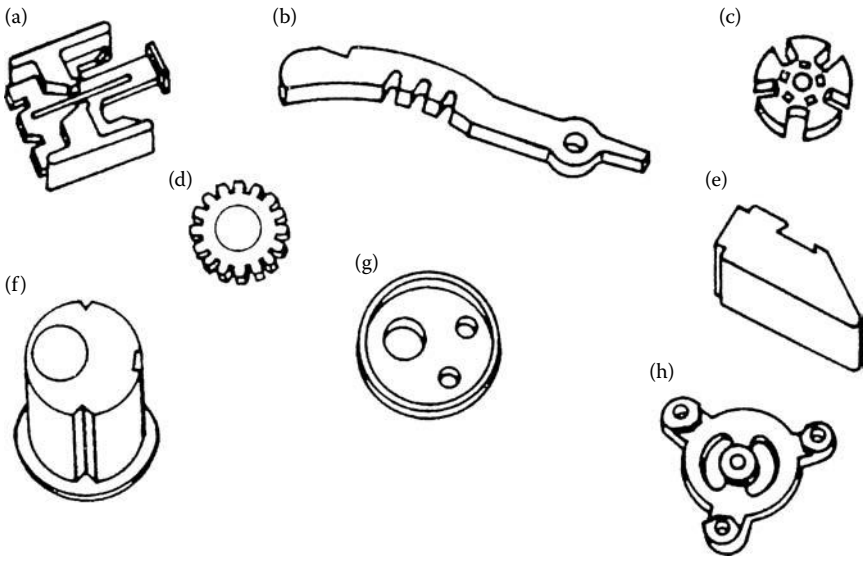

FIGURE 11.15
Typical powder metal parts.

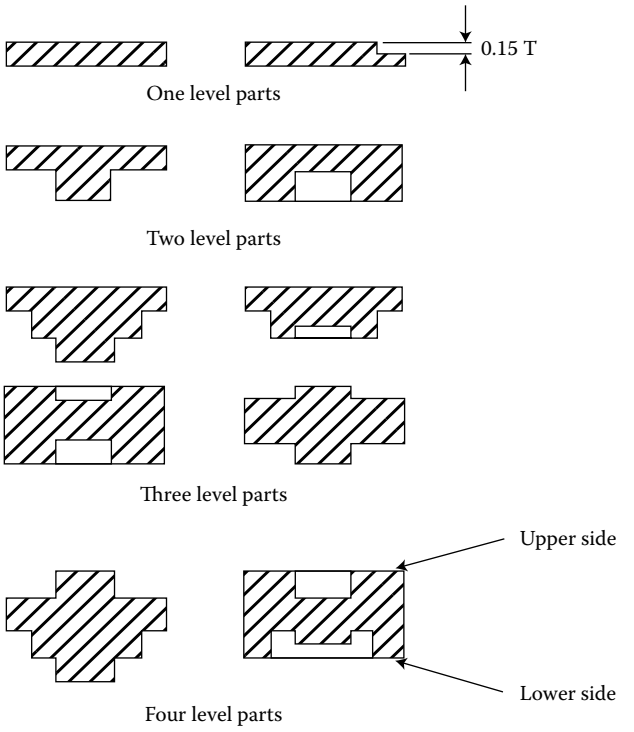

FIGURE 11.16
Levels in powder metal parts.

Class III—two-level parts of any thickness and contour
Class IV—multilevel parts of any thickness and contour

Table 11.5 indicates the pressing requirements of these classes of parts. However, some consideration of the profile complexity and number of cores is required to indicate increased tool complexity.

11.7.1 Profile Complexity

Intricate profiles of almost any shape can be obtained in the outside profile of the part and similarly in the through holes and individual levels. An indication of increased profile complexity can be determined by a suitable complexity factor. A relation that indicates the

TABLE 11.5
Press Requirements for MPIF Parts Classification [1]

Part Class	Number of Levels	Press Actions
1	1	Single
2	1	Double
3	2	Double
4	>2	Double or multiple

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profile complexity is the ratio of the perimeter to the perimeter of a circle containing the same area; this is the shortest perimeter that can contain the same area, that is,

$$F_c = \frac{P_r}{2\sqrt{(\pi A)}} \tag{11.7}$$

where F_c is the complexity factor, P_r is the profile perimeter, and A is the area contained within the perimeter.

11.8 Sintering Equipment Characteristics

Sintering is the process during which the powder particles bond together at temperatures below the melting point of the major constituent elements. In order to achieve the required material properties, the compacts must be heated in a controlled atmosphere to a prescribed temperature (sintering temperature) and held at this temperature for a prescribed time (sintering time). Normally, a preheating phase, mainly to burn off lubricants added to aid compaction, is used prior to the sintering phase. A controlled cool down period is also required. Table 11.6 shows typical sintering temperatures and times for some of the major material classes processed.

11.8.1 Sintering Equipment

Furnaces for sintering can be divided into two main types: continuous-flow and batch-type furnaces. For high productivity continuous-flow furnaces are preferred because of the high throughput rates possible. However, when high temperatures or very pure atmosphere conditions are required, batch-type furnaces may be necessary (Table 11.7).

TABLE 11.6

Typical Sintering Temperatures and Times for Different Materials

Material Type	Sintering Temperature (°C)	Sintering Time (min)
Bronze	815	15
Copper	870	25
Aluminum	600	20
Brass	870	20
Iron-based	1150	25
Nickel	1040	38
Stainless steel	1150	40
Ferrites	1370	10–600
Cemented carbides	1460	90
Molybdenum	2050	120
Tungsten	2350	480
Tantalum	2400	480
Titanium	1200	120

TABLE 11.7

Typical Operating Temperatures for Sintering Furnaces

Furnace Type	Maximum Operating Temperature (°C)
Continuous flow	
Belt	1150
Pusher	1150
Roller-hearth	1150
Walking beam	1650
Batch type	
Bell	2800
Elevator	2800
Vacuum	2800

11.8.1.1 Continuous-Flow Furnaces

Four distinct types of continuous flow furnaces are used (shown schematically in Figure 11.17): mesh belt furnaces, roller-hearth furnaces, pusher furnaces, and walking-beam furnaces. Table 11.8 lists the basic features of a range of commercially available continuous-flow furnaces. Mesh belt furnaces are the most widely used, particularly for small parts, mainly because of the ease of maintaining a consistent temperature profile throughout the furnace. Parts are placed directly on the belt or onto thin ceramic or graphite plates on the belt. Mesh belt furnaces have limitations on belt load [usually less than 20 lb/ft^2 (73.34 kg/m^2)] and in maximum temperature (usually 1150°C).

In roller-hearth furnaces, parts are carried on trays driven by rollers. These furnaces can be of large capacity and carry heavier loads than conveyor furnaces. Maximum temperatures are limited to around 1150°C (2100°F). In pusher furnaces, parts are loaded

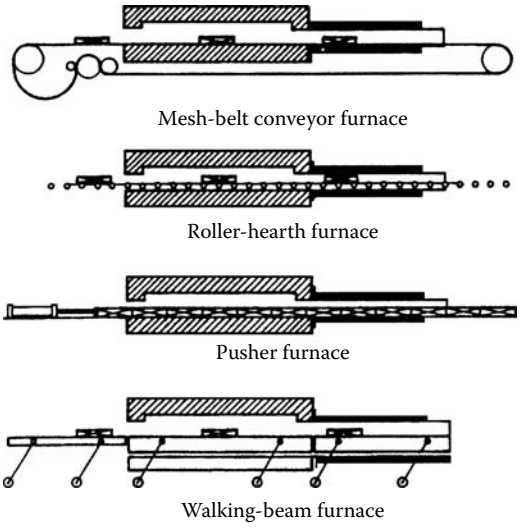

FIGURE 11.17
Continuous-flow furnaces. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

TABLE 11.8

Data on Typical Continuous Furnaces

Type of Furnace	Maximum Temp. (°C)	High-Heat Zone Length (m)	Overall Length (m)	Feeder Width (cm)	Throat Height (cm)	Load Capacity (kg/m²)	Operating Cost ($/h)
Belt	1150	0.91	4.57	15.24	7.62	73.24	100
Belt	1150	1.83	9.14	30.48	10.16	73.24	120
Belt	1150	2.44	12.19	45.72	15.24	73.24	144
Belt	1150	3.05	14.78	60.96	15.24	73.24	170
Belt	1150	3.66	14.78	60.96	15.24	73.24	180
Belt	1150	4.57	15.54	66.04	15.24	73.24	216
Belt	1150	5.49	17.17	60.96	15.24	73.24	240
Beam	1204	2.23	8.03	30.48	15.24	244.15	156
Beam	1232	3.05	13.11	60.96	15.24	244.15	192
Beam	1232	3.66	15.54	43.18	12.70	244.15	240
Beam	1371	4.27	18.59	38.10	10.16	244.15	300
Beam	1371	9.14	24.54	76.20	10.16	244.15	300
Pusher	1399	1.52	4.82	20.32	7.62	97.66	120
Pusher	1427	2.44	7.32	30.48	10.16	97.66	168
Pusher	1427	3.05	10.06	30.48	10.16	97.66	240

onto trays or ceramic plates that are pushed through a stationary-hearth furnace. Throughput rates are generally lower, but these furnaces can operate at higher temperatures [1650°C (3000°F)]. For walking-beam furnaces, parts are placed on ceramic carrier plates and moved through the furnace by a walking-beam mechanism. These furnaces have high load capacities and can sustain higher maximum temperatures than mesh belt furnaces [1650°C (3000°F)].

Most continuous-flow furnaces are divided into three zones: a burnoff zone, a sintering or high-heat zone, and a cooling zone. A typical temperature profile for parts passing through the furnace is as shown in Figure 11.18. In the burnoff zone, moderate temperatures

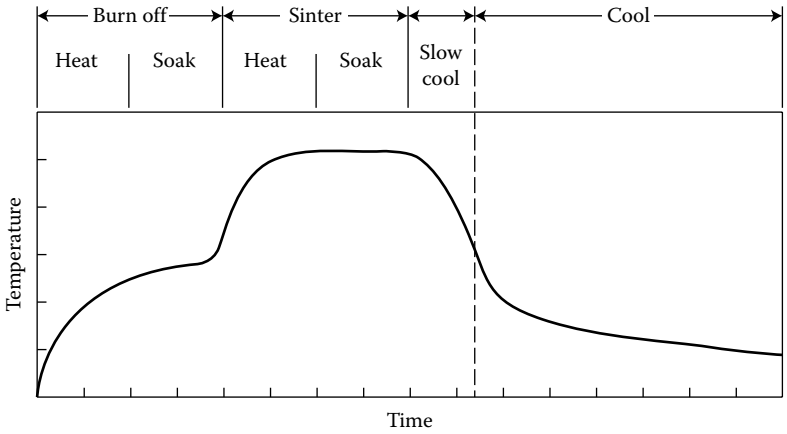

FIGURE 11.18

Temperature profile for continuous-flow furnace. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

of about 650–950°C are maintained. The purpose of this zone is to remove any lubricant and so on, before final sintering takes place. In the sintering zone, parts must be maintained at the sintering temperature for a length of time equal to the sintering time appropriate for the part material. These two parameters determine the speed at which parts move through the furnace, which, combined with the number of parts that can be accommodated across the width of the furnace conveyor, determine the overall throughput of parts.

In the cooling zone, parts are maintained in a controlled atmosphere until the temperature is low enough to prevent oxidation occurring if the parts are discharged into the air.

11.8.1.2 Batch Furnaces

Batch-type furnaces are generally capable of higher maximum temperatures than continuous-flow furnaces (Table 11.7), but production rates are relatively low. The two main types of batch furnace are bell (Figure 11.19) and elevator furnaces. In both cases, the batch of parts is stacked on the furnace base before being loaded into the furnace. Most vacuum furnaces are also batch-type furnaces, although some continuous-flow vacuum furnaces are in use.

Cycle times for batch furnaces are long and may extend to 10 h or more. Figure 11.20 shows a typical heating and cooling cycle for a batch vacuum furnace. Parts must still be maintained at the sintering temperature and time appropriate for the material of the part. However, the cycle time is dominated by the long heating and cooling times required for batch furnaces. Table 11.9 shows the parameters of a range of commercially available batch furnaces.

11.9 Materials for Powder Metal Processing

Practically all metals and some ceramics can be made into powder and processed into parts by using basic powder metallurgy methods. The most widely used metal material

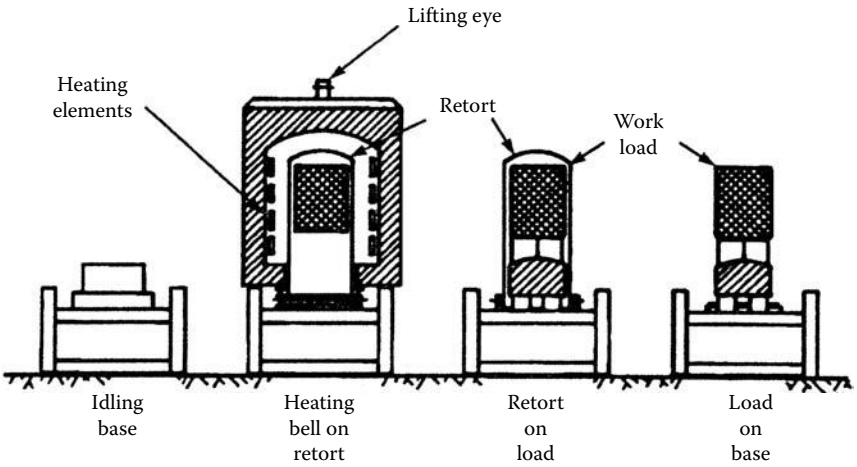

FIGURE 11.19
Bell-type batch furnace. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

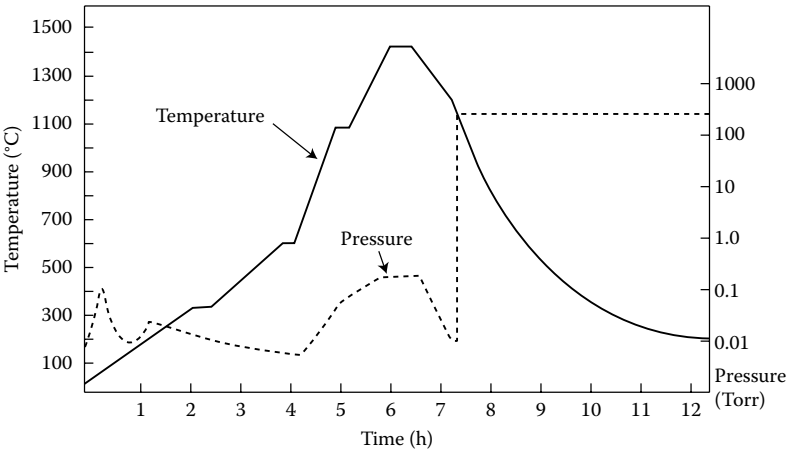

FIGURE 11.20
Heating and cooling cycle for a vacuum batch furnace. (Adapted from Bradbury, S., *Powder Metallurgy Equipment Manual*, Metal Powder Industries Federation, Princeton, NJ, 1986.)

groups are carbon steels, alloy steels, stainless steels, copper alloys, and aluminum alloys. Table 11.10 lists some basic groups of materials that are processed by using powder metallurgy methods. The MPIF has established a range of standard structural materials [5], including iron, carbon steels, copper steels, nickel steels, low-alloy steels, copper-infiltrated steels, stainless steels and brass, bronze, and nickel silver materials. In addition, there is a range of standard self-lubricating bearing materials [6]. The MPIF has not yet established the standards for aluminum alloys, but industry standards exist to help designers in selecting these materials.

A significant database of material parameters is required for estimating processing costs for powder metal parts. For the purposes of the discussion in this chapter, the relevant parameters for three important standard materials classes are given in Tables 11.11 through 11.13. Table 11.11 covers the MPIF standard iron and carbon steels. The two values of density and compaction pressure given in the table enable a power law relationship between compaction pressure and density to be derived, as described in Section 11.4.1.

TABLE 11.9
Data for Typical Batch Sintering Furnaces

Type of Furnace	Maximum Temp. (°C)	Heating Space Dimensions			Operating Cost ($/h)
		Length (m)	Width (m)	Height (m)	
Vacuum	1316	0.36	0.20	0.15	96
Vacuum	1316	0.61	0.46	0.23	108
Vacuum	1316	0.91	0.61	0.51	120
Vacuum	1316	1.22	0.91	0.61	168
Bell	1538	1.22	1.75	1.75	216
Elevator	1528	1.22	1.22	1.40	240
Bell	1649	1.22	1.22	1.22	216
Vacuum	1649	1.22	0.70	0.70	260

TABLE 11.10

Main Classes of Powder Materials

Iron and carbon steels[a]
Iron copper and copper steels[a]
Iron nickel and nickel steels[a]
Alloy steels[a] and tool steel
Stainless steels[a]
Infiltrated iron, steel, and other metals (with copper[a], etc.)
Brass, bronze, and nickel silver (structural applications)[a]
Aluminum and aluminum alloys
Refractory metals (tungsten, molybdenum, niobium, tantalum, etc.)
High-temperature super alloys (iron, nickel, and cobalt-based)
Self-lubricating bearing materials[a]
Other nonferrous metals
Intermetallic compounds (including mixtures with metals)
Nonmetals and metal/nonmetal mixtures

[a] MPIF Standard Material Classes.

Table 11.12 shows parameters for the standard copper-infiltrated steels designated by MPIF. In this case, the part density listed is the infiltrated density, but the compaction data are that corresponding to the iron-based skeleton material prior to infiltration. The percentage of infiltrant material by weight in the final part is included as a parameter for each material.

Table 11.13 lists relevant parameters for some of the standard self-lubricating bearing materials. In this case, the density given is the wet density after impregnation with oil, with the oil content by volume also given for each material. The compaction data again correspond to the base material prior to impregnation.

11.10 Contributions to Basic Powder Metallurgy Manufacturing Costs

The total manufacturing cost for parts produced by the powder metallurgy process is determined from the material cost, plus the cost associated with the operations in the processing sequence. In general, these processes can be treated independently. Part costs increase with increased geometrical complexity, but also as increased strength properties and densities are required, which may involve secondary processing (Figure 11.21). Discussion of processing costs will initially focus on basic structural materials, and the modifications necessary for infiltrated and self-lubricating bearing materials will be discussed later.

11.10.1 Material Costs

The material costs for powder metallurgy parts include the cost of the raw powders, the costs of lubricants added to the mixture, and an allowance for losses during processing. Powder losses in industry are generally 2–3%. The powder mixtures can be made up from elemental powders or prealloyed powders, depending on the application. For some standard materials, premixed powders are obtainable from the suppliers. As with most raw materials, the actual costs are heavily dependent on the quantities ordered. The material

TABLE 11.11

Data for MPIF Standard Iron and Carbon Steel Powder Metal Materials

Material Designation	Material Condition (AS or HT)	Yield Stress (N/mm^2)	Ultimate Strength (N/mm^2)	Part Density (g/cc)	Cost ($/kg)	Sintering Temp. (°C)
F-0000-10	AS	89.6	124.1	6.10	0.84	1121
F-0000-15	AS	124.1	172.4	6.70	0.84	1121
F-0000-20	AS	172.4	262.0	7.30	0.84	1121
F-0005-15	AS	124.1	165.5	6.10	0.84	1121
F-0005-20	AS	158.6	220.6	6.60	0.84	1121
F-0005-25	AS	193.1	262.0	6.90	0.84	1121
F-0005-50HT	HT	413.7	413.7	6.60	0.84	1121
F-0005-60HT	HT	482.6	482.6	6.80	0.84	1121
F-0005-70HT	HT	551.6	551.6	7.00	0.84	1121
F-0008-20	AS	172.4	200.0	5.80	0.84	1121
F-0008-25	AS	206.9	241.3	6.20	0.84	1121
F-0008-30	AS	241.3	289.6	6.60	0.84	1121
F-0008-35	AS	275.8	393.0	7.00	0.84	1121
F-0008-55HT	HT	448.2	448.2	6.30	0.84	1121
F-0008-65HT	HT	517.1	517.1	6.60	0.84	1121
F-0008-75HT	HT	586.1	586.1	6.90	0.84	1121
F-0008-85HT	HT	655.0	655.0	7.10	0.84	1121

continued

TABLE 11.11 (continued)

Data for MPIF Standard Iron and Carbon Steel Powder Metal Materials

Material Designation	Sinter Time (min)	Theor. Density (g/cc)	Apparent Density (g/cc)	Density (A) (g/cc)	Pressure (A) (N/mm^2)	Density (B) (g/cc)	Pressure (B) (N/mm^2)
F-0000-10	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0000-15	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0000-20	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-15	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-20	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-25	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-50HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-60HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0005-70HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-20	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-25	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-30	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-35	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-55HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-65HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-75HT	25	7.87	2.95	6.00	234.4	7.00	551.6
F-0008-85HT	25	7.87	2.95	6.00	234.4	7.00	551.6

Adapted from MPIF Standard No. 35, *Material Standards for P/M Structural Parts*, Metal Powder Industries Federation, Princeton, NJ, 2007.

TABLE 11.12

Data for MPIF Standard Copper-Infiltrated Steels

Material Designation	Material Cond. (AS or HT)	Yield Stress (N/mm^2)	Ultimate Strength (N/mm^2)	Part Density (g/cc)	Material Cost ($/kg)	Sintering Temp. (°C)	Sintering Time (min)
FX1000-25	AS	220.6	351.6	7.30	0.84	1121	25
FX1005-40	AS	334.8	530.9	7.30	0.84	1121	25
FX1005-110HT	HT	827.4	827.4	7.30	0.84	1121	25
FX1006-50	AS	413.7	599.9	7.30	0.84	1121	25
FX1008-110HT	HT	827.4	827.4	7.30	0.84	1121	25
FX-2000-25	AS	255.1	317.2	7.30	0.84	1121	25
FX-2005-45	AS	413.7	517.1	7.30	0.84	1121	25
FX-2005-90HT	HT	689.5	689.5	7.30	0.84	1121	25
FX-2008-60	AS	482.6	551.6	7.30	0.84	1121	25
FX-2008-90HT	HT	689.5	689.5	7.30	0.84	1121	25

Material Designation	Theor. Density (g/cc)	Apparent Density (g/cc)	Density (A) (g/cc)	Pressure (A) (N/mm^2)	Density (B) (g/cc)	Pressure (B) (N/mm^2)	Infiltrant Quantity (%)	Infiltrant Density (g/cc)	Infiltrant Cost ($/kg)
FX-1000-25	7.87	2.95	6.00	234.4	7.00	551.6	11.5	8.86	3.53
FX-1005-40	7.87	2.95	6.00	234.4	7.00	551.6	11.5	8.86	3.53
FX-1005-110HT	7.87	2.95	6.00	234.4	7.00	551.6	11.5	8.86	3.53
FX-1006-50	7.87	2.95	6.00	234.4	7.00	551.6	11.5	8.86	3.53
FX-1008-110HT	7.87	2.95	6.00	234.4	7.00	551.6	11.5	8.86	3.53
FX-2000-25	7.87	2.95	6.00	234.4	7.00	551.6	20.0	8.86	3.53
FX-2005-45	7.87	2.95	6.00	234.4	7.00	551.6	20.0	8.86	3.53
FX-2005-90HT	7.87	2.95	6.00	234.4	7.00	551.6	20.0	8.86	3.53
FX-2008-60	7.87	2.95	6.00	234.4	7.00	551.6	20.0	8.86	3.53
FX-2008-90HT	7.87	2.95	6.00	234.4	7.00	551.6	20.0	8.86	3.53

Source: Adapted from MPIF Standard No. 35, *Material Standards for P/M Structural Parts*, Metal Powder Industries Federation, Princeton, NJ, 2007.

TABLE 11.13

Portion of Data for MPIF Standard Self-Lubricating Bearing Materials

Material Designation	Material Condition (AS or HT)	Strength Constant (N/mm^2)	Part Density (g/cc)	Material Cost ($/kg)	Sintering Temp. (°C)	Sintering Time (min)	Theor. Density (g/cc)
CT-1000-K19 bronze	AS	131.0	6.2	3.40	827	15	8.71
CT-1000-K26 bronze	AS	179.3	6.6	3.40	827	15	8.71
CT-1000-K37 bronze	AS	255.1	7.0	3.40	827	15	8.71
CTG-1001-K17 bronze	AS	117.2	6.2	3.24	827	15	8.69
CTG-1001-K23 bronze	AS	158.6	6.6	3.24	827	15	8.69
CTG-1001-K33 bronze	AS	227.5	7.0	3.24	827	15	8.69
CTG-1004-K10 bronze	AS	68.9	6.0	3.20	827	15	8.63
CTG-1004-K15 bronze	AS	103.4	6.4	3.20	827	15	8.63
F-0000-K15 iron	AS	103.4	5.8	0.84	1121	25	7.86
F-0000-K23 iron	AS	158.6	6.2	0.84	1121	25	7.86
F-0005-K20 Fe-C	AS	137.9	5.8	0.84	1121	25	7.86
F-0005-K28 Fe-C	AS	193.1	6.2	0.84	1121	25	7.86

Material Designation	Apparent Density (g/cc)	Density (A) (g/cc)	Pressure (A) (N/mm^2)	Density (B) (g/cc)	Pressure (B) (N/mm^2)	Oil Content (%)
CT-1000-K19 bronze	3.40	5.90	68.9	7.65	413.7	24.0
CT-1000-K26 bronze	3.40	5.90	68.9	7.65	413.7	19.0
CT-1000-K37 bronze	3.40	5.90	68.9	7.65	413.7	12.0
CTG-1001-K17 bronze	3.40	5.90	68.9	7.65	413.7	22.0
CTG-1001-K23 bronze	3.40	5.90	68.9	7.65	413.7	17.0
CTG-1001-K33 bronze	3.40	5.90	68.9	7.65	413.7	9.0
CTG-1004-K10 bronze	3.40	5.90	68.9	7.65	413.7	11.0
CTG-1004-K15 bronze	3.40	5.90	68.9	7.65	413.7	7.0
F-0000-K15 iron	2.95	6.00	234.4	7.00	551.6	21.0
F-0000-K23 iron	2.95	6.00	234.4	7.00	551.6	17.0
F-0005-K20 Fe-C	2.95	6.00	234.4	7.00	551.6	21.0
F-0005-K28 Fe-C	2.95	6.00	234.4	7.00	551.6	17.0

Source: Adapted from MPIF Standard No. 35, *Material Standards for P/M Self-Lubricating Bearings*, Metal Powder Industries Federation, Princeton, NJ, 1998.

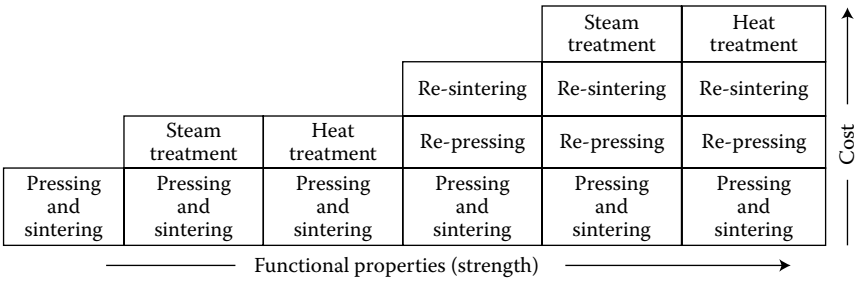

FIGURE 11.21
Cost related to increased part material properties. (Adapted from Fumo, A., Early Cost Estimating for Sintered Powder Metal Components, M.S. Thesis, Department of Industrial and Manufacturing Engineering, University of Rhode Island, Kingston, 1988.)

cost for each part is determined from the weight of the part, the cost of the material per unit weight, and an allowance of, say, 2% for powder losses during processing. The material costs per unit weight in the database include the cost of mixing and handling. The overall costs for mixing are generally small, with values in the range of \$0.09–\$0.13 per kilogram being typical. Thus, the material cost for basic powder metallurgy parts is given by

$$C_m = V\rho(1 + l_p)C_p \tag{11.8}$$

where V is the part volume, ρ is the part density, l_p is the powder loss during processing, typically 0.02, C_p is the cost per unit weight of material, including mixing costs, as given typically in Tables 11.11 through 11.13.

EXAMPLE

Consider the two-level part shown in Figure 11.22. The approximate volume of this part is 4.97 cm^3. Assuming the material of the part is F-0005-20, then the final density of the part is 6.60 g/cc and the material cost is \$0.84/kg (Table 11.11). Thus, the material cost of this part is

$$C_m = 4.97 \times 6.6(1 + 0.02)0.84/10 \text{ cents} = 2.8 \text{ cents}$$

11.10.2 Compacting Costs

The cost of compaction is largely determined by the tooling required to compact the part and the press to be used. For each batch of parts, a setup cost is also required. The required press type and capacity are determined by the part complexity and the compacting pressure needed. Tooling costs are also determined by the part complexity.

11.10.2.1 Press Selection

A press must be selected to suit the compaction requirements of the part. The main features that determine the suitability of compaction presses for a particular part are as follows:

1. The number of vertical punch motions possible
2. Load capacity of the machine
3. Maximum fill height possible
4. Maximum die diameter that can be accommodated

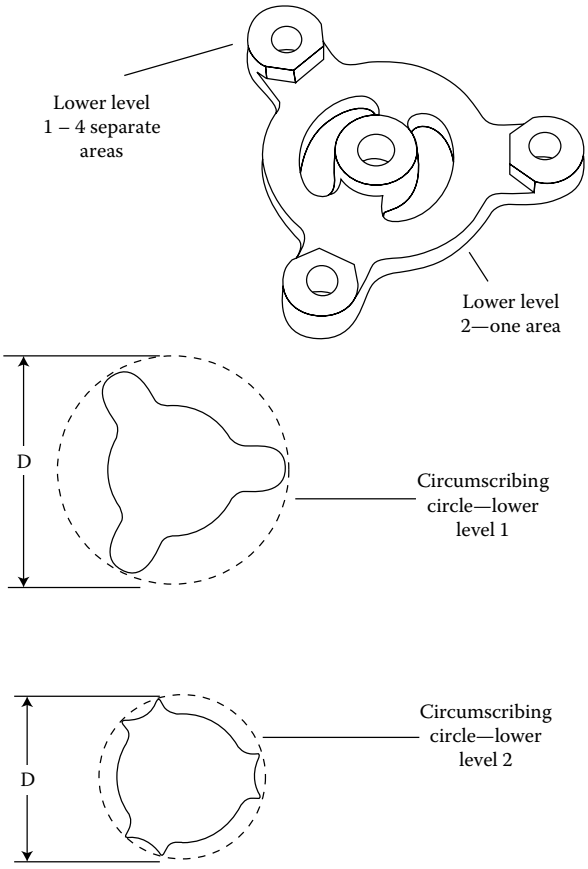

FIGURE 11.22
Typical two-level powder metal part.

The press load required is obtained by multiplying the required compaction pressure by the projected area of the part. A press with this capacity, plus an excess allowance of, say, 10%, can be used, provided the required fill height and die size can be accommodated. If not, a press of larger load capacity may be required in order to provide the excess fill height or die size requirements.

The compaction pressure is determined directly from the part density, unless repressing and resintering are required. A basic rule is that repressing should be used if a density of greater than 89% of the equivalent wrought material density is required. Initial compaction at a pressure corresponding to 89% of the wrought density is assumed. This is followed by presintering and repressing. It is generally assumed that the repressing load is the same as for the initial compaction.

For the selected press, the compaction cost is determined from the product of the cycle time per part and the operating cost per unit time (Table 11.3), which includes labor and overhead costs. The cycle time can be estimated from the following commonly applied rule:

Stroke rate = maximum press rate minus 10% for every level in the part more than one minus 15% for every 13 mm of fill depth more than 13 mm minus half of the percentage of the maximum load capacity required.

If this resulting value is less than the minimum stroke rate for the selected press, then the minimum rate is used. One part is produced for each cycle of the press.

EXAMPLE

For the part shown in Figure 11.22, which is assumed to be made of F-0005-20 low-carbon steel, the following can be determined.

The projected area of the part is 7.02 cm^2. Table 11.11, the compaction characteristics of F-0005-20 are defined by the following:

Density 6.00 g/cc, pressure 234.4 N/mm^2
Density 7.00 g/cc, pressure 551.6 N/mm^2

Assuming the compaction pressure as $P = A\rho^b$, then for these values $P = 0.01\rho^{5.558}$. Thus, for a part density of 6.6 g/cc the corresponding compaction pressure is $0.011 \times 6.6^{5.558}$, which gives 395 N/mm^2. No correction is necessary for part thickness in this case. The compaction load required is $7.02 \times 395/10$, which equals 277 kN. Thus, assuming a safety margin of 15%, the press load required is 320 kN. From Table 11.3, the smallest press to provide this load is rated at 400 kN and has the following characteristics:

Maximum fill height: 11.43 cm
Maximum die insert diameter: 15.24 cm

These must be checked against the part requirements. The fill height required is given by

Powder compression ratio = 6.6/2.95 = 2.24
Part thickness = 8.89 mm and the fill height required = $8.89 \times 2.24/10 = 2.0$ cm

The die insert size required is given by the following calculation: the enclosing circle diameter for the part is 4.76 cm. Thus, the insert diameter required is (4.76 + 2.0) 3, which gives 20.3 cm. Thus, a larger press must be used that would accommodate this size die insert, which from Table 11.3 has the following characteristics:

Load capacity: 534 kN
Maximum stroke rate: 40 per min
Minimum stroke rate: 7 per min
Operating cost: $63/h

The press stroke rate for this part is then given by

$$40(1 - 0.1 - 0.05 - 0.5 \times 277/534) = 24 \text{ strokes/min}$$

Thus, the press cycle time per part is 60/24, which equals 2.54 s, from which the compaction cost is $63 \times 2.54/3600$, or $0.04 per part.

11.10.2.2 Setup Cost

As the number of levels and complexity of the part increase, the setup time for each batch of parts is increased, due to the need for more complex tools that require more setup time. A rule used for estimating setup time is as follows:

$$\text{Setup time} = 1 \text{ h} + 1 \text{ h for every level more than 1} + 1 \text{ hour for thickness tolerances} \leq 0.25 \text{ mm} \quad (11.9)$$

The setup cost per part is then determined from the product of the setup time and the press cost per unit time divided by the batch quantity of parts produced. As an example, consider the part shown in Figure 11.22. This part has two levels and, assuming no close tolerances in the compaction direction, the setup time estimate is 2 h. Thus, assuming a batch size of 24,000 parts, the setup cost per part is

$$2 \times 100 \times 63/24{,}000 = 0.53 \text{ cents per part}$$

11.10.3 Compaction Tooling Costs

The total tooling costs for powder compaction are determined from three elements:

1. The initial cost of the dies, punches, and core rods required for the part.
2. The cost of tooling accessories, including punch holders, core rod holders, powder feeding devices, and so on.
3. The tool replacement costs, particularly for punches and core rods, which can have relatively short lives in practice.

The life of the die is usually high (>500,000 parts), but cores and punches may require replacement more frequently, particularly if they have small cross-sectional areas. Cores for small-sized through holes and punches that have small width steps would be relatively fragile and would require more frequent replacement and increased maintenance.

Each of these three cost contributions is determined primarily by the size and complexity of the part and secondarily by the press required for compaction of the part.

11.10.3.1 Initial Tooling Costs

The costs of the basic tooling elements for compacting a part are divided into the tool material costs and the tool manufacturing costs.

11.10.3.2 Tool Material Costs

The tool material costs can be determined from some general design rules for compacting tooling that have been brought together from a number of sources [10]. These rules are based upon accepted practice in the industry and enable the volumes of tool materials required to be estimated. The basic information required for this determination is as follows:

Fill height: h_f

Enclosing diameter of the whole part: D_o

Enclosing diameter of the separate levels: D_{li}, where i = 1, 2, 3 …

The following general rules are then applicable. For dies:

Die thickness: $T = h_f + 17.8$ mm

Carbide insert diameter: $D_c = D_o + 20$ mm

Die case diameter = $3D_c$ or size of corresponding press recess

From these, the volumes of the material required are readily determined:

$$\text{Carbide insert cost} = \frac{\pi D_c^2 T C_c}{4} \tag{11.10}$$

where C_c is the cost of tungsten carbide per unit volume, typically \$1.22/cm^3.

$$\text{Cost of the tool steel die case} = \frac{\pi(D_d^2 - D_c^2)T\rho_t C_t}{4} \tag{11.11}$$

where D_d is the die case diameter for the selected press, ρ_t is the density of tool steel, 7.86 g/cc (0.283 lb/in.^{3}), C_t is the cost of tool steel, typically \$17.6/kg. For the separate lower punches, the punch lengths are given by

$$\begin{aligned} L_1 &= h_f + 88.9\,\text{mm} \\ L_2 &= h_f + 119.4\,\text{mm} \\ L_3 &= h_f + 127.0\,\text{mm} \end{aligned} \tag{11.12}$$

The stock diameter for each punch is $D_{pi} = D_{li} + 38.1$ mm, where D_{li} is the punch face enclosing the circle diameter.

Similarly, for the separate upper punches (usually up to two) the lengths are given by

$$\begin{aligned} U_1 &= 0.5h_f + 68.6\,\text{mm} \\ U_2 &= 0.5h_f + 87.4\,\text{mm} \end{aligned} \tag{11.13}$$

Again the stock diameter for each punch is $D_{li} + 38.1$ mm.

The following basic rules are applied to determine which punch corresponds to each level:

1. The longest punch corresponds to the level with the smallest enclosing diameter and the shortest punch to the level with the largest enclosing diameter.
2. If two levels have the same enclosing diameter, then the level with the smallest enclosed area corresponds to the longer punch.

Again, from these values the volume of the punch materials can be estimated. Punch material costs are given by

$$\frac{\pi D_{pi}^2 L_i \rho_t C_t}{4} \tag{11.14}$$

where D_{pi} is the punch stock diameter and L_i is the punch length (L_1, to L_3, U_1, U_2).

EXAMPLE

For the sample part under consideration, one upper and two lower punches are required, with six separate core rods passing through the punches.

Fill height: 20 mm
Enclosing diameter of whole part: 47.6 mm
Enclosing diameter of lower level 1: 47.6 mm
Enclosing diameter of lower level 2: 18.1 mm

From these data, the following are determined for the die material costs:

Die thickness: 20 + 17.8 mm = 37.8 mm
Carbide insert diameter: 47.6 + 20 = 67.6 mm

Die case diameter corresponding to selected press: 20.32 cm
Cost of the carbide insert material = $\pi \times 67.6^2 \times 37.8 \times 1.22/4000 = \$165.5$
Cost of die case material = $\pi(203.2^2 - 67.6^2)37.8 \times 7.86/(4 \times 10^6) = \$19.18$

The following are determined for the punch material costs:

Length of upper punch: $0.5 \times 20 + 68.6 = 78.6$ mm
Length of lower punch 1: $0.5 \times 20 + 88.9 = 98.9$ mm
Length of lower punch 2: $0.5 \times 20 + 119.4 = 129.4$ mm
Stock diameter for upper punch: $47.6 + 38.1 = 85.7$ mm
Stock diameter for lower punch 1: 85.7 mm
Stock diameter for lower punch 2: $38.1 + 38.1 = 76.2$ mm

Material costs for these punches are as follows:

Upper punch cost: $\pi 85.7^2 \times 78.6 \times 7.86 \times 17.6/(4 \times 10^6) = \$62.76$
Lower punch 1 cost: $\pi 85.7^2 \times 98.9 \times 7.86 \times 17.6/(4 \times 10^6) = \$78.92$
Lower punch 2 cost: $\pi 76.2^2 \times 129.4 \times 7.86 \times 17.6/(4 \times 10^6) = \$81.63$

11.10.3.3 Tool Manufacturing Costs

The procedure for estimating the tool element manufacturing costs is to consider the machining operations required to produce each tool element, and then utilize estimating procedures developed for machining (Chapter 7), to develop expressions that give the times to machine each element related to the profile complexities and other geometrical features [10]. The manufacturing costs are then determined by multiplying the manufacturing times by a suitable tool shop cost rate, $/h (say $45/h).

11.10.3.4 Dies

The die profiles are assumed to be produced by wire electro discharge machining (EDM) and then finished and lapped to the punches. Figure 11.23 shows a typical relationship between cutting time and die thickness for wire EDM. The following expressions are used to estimate the machining and finishing times:

$$\text{EDM cutting time: } 1.6 + \frac{[e^{(0.5T/25.4+3)}]P_r}{(60 \times 25.4)\text{h}} \tag{11.15}$$

$$\text{Finishing time: } 1.0 + \frac{P_r F_c T}{25.4^2\,\text{h}} \tag{11.16}$$

where F_c is the complexity factor for the outside profile of the whole part.

EXAMPLE

As an example for the sample part, the following are determined:

Part projected area: 7.02 cm^2
Part outside perimeter: 13.4 cm
Die thickness: 37.8 mm

Then the part outside profile complexity factor, $F_c = 13.4/2\sqrt{(p7.02)} = 1.43$. The EDM cutting time for the die profile = $1.6 + e^{(0.5 \times 37.8/25.4+3)} \times 134/(60 \times 25.4) = 5.32$ h. The die finishing time = $1.0 + 134 \times 1.43 \times 37.8/25.4^2 = 12.23$ h. Thus, the total die manufacturing time = 16.55 h. Therefore,

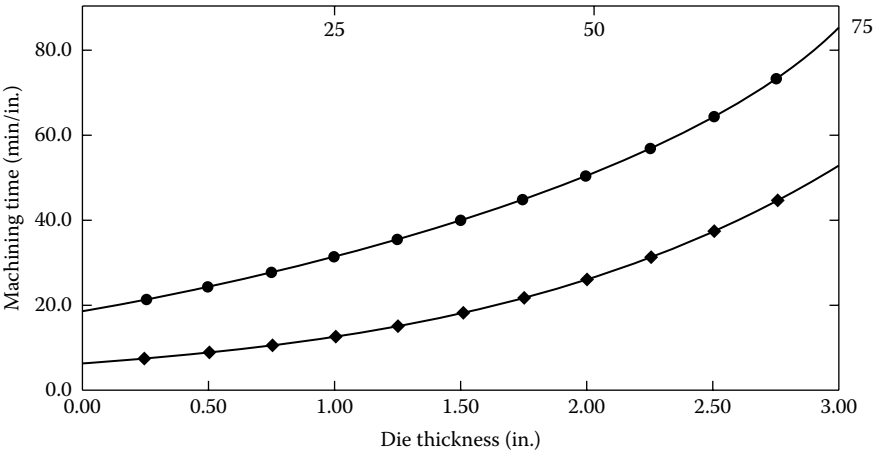

FIGURE 11.23
Relationship between cutting time and material thickness for wire EDM processing (● carbide; ◆, tool steel). (Adapted from Fumo, A., Early Cost Estimating for Sintered Powder Metal Components, M.S. Thesis, Department of Industrial and Manufacturing Engineering, University of Rhode Island, Kingston, 1988.)

assuming a die shop manufacturing rate of \$45/h, the die manufacturing cost becomes $16.55 \times 45 = \$745$.

11.10.3.5 Punches

Similar expressions have been developed for the machining and finishing of the external punch profiles and for the holes that must pass through some of the punches. Holes are required for core rods and for the longer punches to pass through the next shorter punches as required. In each case, the relationships to determine the manufacturing times utilize the perimeters, enclosed areas, and complexity factors of each separate level and through-hole.

The times for machining and finishing the outside profiles of punches are given by

$$\text{Machining time } (h) = 1.25 + 0.1\sum \frac{P_r}{25.4} + 0.89\left(\frac{0.6L_\text{i} + 9.53}{25.4^3}\right)\left(\frac{\pi D_\text{pi}^2}{4} - A_\text{t}\right) + \frac{0.18L_\text{i}\sum P_\text{r}}{25.4^2} \tag{11.17}$$

$$\text{Finishing time } (h) = \frac{0.4L_\text{i}\sum(F_\text{c}P_\text{r})}{25.4^2} \tag{11.18}$$

In these expressions, $\sum P_\text{r}$ is the sum of perimeters of all the separate regions at the level on which the punch acts. Similarly, A_t is the total area enclosed for all the separate regions on which the punch acts. For one-level parts $\sum P_\text{r}$ is the outside perimeter of the whole part and A_t the total enclosed area. The term $\sum(F_\text{c}P_\text{r})$ is the sum of the product of the perimeter and complexity factor for all regions at the level on which the punch acts.

EXAMPLE

For the sample part, consider the manufacture of the outside profile of the lower punch corresponding to level 2. In this case, one separate region exists at this level, so that ΣP_r is the length of the perimeter for this level, which is 119.1 mm.

The following data have been determined previously:

Punch length: $L_i = 129.4$ mm
Enclosing diameter: $D_{li} = 38.1$ mm

The area enclosed by the perimeter at this level is 689 mm^2. From these, the complexity factor for this level is $119.1/2\sqrt{(p689)}=1.29$. Thus, for this level $\Sigma P_r F_c$ is $1.29 \times 119.1 = 153.6$.

The machining time for this punch is given by

$$1.25 + 0.1 \times 119.1/25.4 + 0.89(0.6 \times 129.4 + 9.53)(\pi 38.1^2/4 - 689)/25.4^3$$

$$+ 0.18 \times 129.4 \times 119.1/25.4^2 = 8.16\text{h}$$

The finishing time for the punch is $0.4 \times 129.4 \times 153.3/25.4^2 = 12.3$ h. Thus the total punch manufacturing cost is $(12.3 + 8.16) \times 45 = \$920.7$.

Holes are required through the punches for core rods to pass through and for the longer punches to pass through the shorter punches. These holes are produced by a combination of drilling and EDM for nonround holes. In most cases, a hole is drilled part way through the punch from the back, and then the actual hole profile is produced by EDM through the remainder of the punch. Finally, these holes must be finished and lapped to the corresponding punch element or core rod.

For circular holes, the processing times are given by

$$\text{Machining time } (h) = 0.006 D_h^2 L_i/25.4^3 \tag{11.19}$$

plus a setup time of 15 min/hole and

$$\text{finishing time} = P_t L_i/25.4^2 \tag{11.20}$$

where L_i is the length of the punch, P_r is the hole perimeter, and D_h is the hole diameter.

EXAMPLE

Consider the cost of producing a circular hole through the long lower punch for the sample part. The hole diameter is 4.76 mm, the hole perimeter 14.95 mm, and the punch length 129.4 mm. Thus, the machining time is $0.006 \times 4.76^2 \times 129.4/25.4^3 = 0.001$ h, and the finishing time is $14.95 \times 129.4/25.4^2 = 3$ h.

For noncircular holes, the following assumptions are made: The hole profile is machined by EDM for a length of punch given by $L_h = 0.5\,(T + 12.7)$ mm. The remainder of the punch length is drilled out to a diameter equal to the circumscribing diameter of the hole profile, D_h. For larger-sized holes, the portion of punch length machined by EDM is initially drilled through with a smaller drill, to reduce the amount of material to be removed by the EDM process. An equivalent hole diameter can be calculated as $D_{eh} = 2(A_h/\pi)^{0.5}$, where A_h is the cross-sectional area of the hole required. If D_{eh} is less than 19 mm, then the following apply:

$$A_{hol} = A_h/3 \quad \text{and} \quad Q = 0, \quad \text{otherwise} \quad A_{hol} = A_h \quad \text{and} \quad Q = 8A_hL_i/(3\pi)$$

The machining time (h) for the hole is then given by

$$0.8 + (0.006D_h^2(L_i - L_h) + 0.006Q + 12.56A_{hol}L_i)/25.4^3 + 0.16(A_{hol}L_h/25.4^3)^{0.5} \quad (11.21)$$

The finishing time (h) for the hole is given by

$$P_r F_c L_h/25.4^2 \quad (11.22)$$

These calculations are repeated for all holes required through all punches.

EXAMPLE

Consider the manufacturing time for one of the crescent-shaped holes for the sample part in Figure 11.22. The following data apply:

Die thickness: $T = 37.8$ mm
Hole enclosing diameter: $D_h = 15.08$ mm
Cross-sectional area of hole: $A_h = 53.74$ mm^2
Hole perimeter: $P_r = 44.5$ mm
Punch length: $L_i = 129.4$ mm

Thus, $L_h = 0.5(37.8 + 12.7) = 25.25$ mm and $D_{eh} = 2(53.74/\pi)^{0.5} = 8.27$ mm, which is less than 19 mm. Thus, $A_{hol} + 53.74/3 = 17.91$ and $Q = 0$. The hole machining time is then given by

$$0.8 + (0.006 \times 15.08^2(129.4 - 25.25) + 12.56 \times 17.91 \times 25.25)/25.4^3$$
$$+ 0.16 \times (17.91 \times 25.25/25.4^3)^{0.5} = 1.177\,\text{h}$$

The hole complexity factor is $44.5/2(\pi 53.74)^{0.5} = 1.71$, and hence the hole finishing time is given by $44.5 \times 1.71 \times 53.74/25.4^3 = 0.25$ h. Thus, the total hole manufacturing time is 1.43 h.

11.10.3.6 Core Rods

From an examination of the costs of a number of core rods [10], the equivalent processing time (including an allowance for material) can be determined from the following relationship:

$$(4.375D_{eh}/25.4 + 2.7)F_c, \quad (11.23)$$

where D_{eh} is the equivalent hole diameter corresponding to the core rod as determined above and F_c is the hole profile complexity. If the hole area is less than 6.45 mm^2, then it is assumed that the processing time is doubled, to account for increased difficulty of manufacture.

EXAMPLE

The part in Figure 11.22 requires six core rods in all. Consider first the rods for the circular holes. In this case, the complexity factor is 1, the equivalent hole diameter is 4.775 mm, and the cross-sectional area of the hole is 17.42 mm^2. Therefore, the core rod manufacturing time is $4.375 \times 4.775/25.4 + 2.7 = 3.52$ h, which at \$45/h gives an equivalent cost of \$158.

Similarly, for the crescent-shaped holes the following data apply:

Hole equivalent diameter = 8.27 mm
Cross-sectional area = 53.74 mm^2
Hole complexity factor = 1.71

Thus, the core rod manufacturing time is $(4.375 \times 8.27/25.4 + 2.7)1.71 = 7.05$ h, which gives an equivalent core rod cost of $317.

11.10.3.7 Total Tool Manufacturing Costs

At the end of this procedure, the total time involved in machining and fitting all tooling elements is obtained. This result is multiplied by a suitable tool manufacturing rate ($/h) to determine the total tooling manufacturing costs. These costs are added to the tool material costs, determined as described above, to give the total tool costs.

11.10.4 Tool Accessory Costs

In addition to the dies, punches, and core rods required for a part, various tooling accessories are needed, including filling mechanisms, punch and core rod holders, and so on. Examination of data from powder metal processing companies has shown that tool accessory costs increase with the size of the press required for the part. The procedure adopted in this analysis is to relate the cost of the different tool accessories to the press capacity through the following relationships.

1. Basic cost for one level part without through-holes (includes filling mechanism, one upper and one lower punch holder, etc.)

$$\text{Cost (\$)} = 0.4C_{20}(C_{AP})^{0.3} \tag{11.24}$$

2. Core rod holder

$$\text{Cost (\$)} = 0.04C_{20}(C_{AP})^{0.3} \tag{11.25}$$

3. Additional lower punch holders (each lower level over one)

$$\text{Cost (\$)} = 0.16C_{20}(C_{AP})^{0.2} \tag{11.26}$$

4. Additional upper punch holders (each upper level over one)

$$\text{Cost (\$)} = 0.2C_{20}(C_{AP})^{0.3} \tag{11.27}$$

In these expressions, C_{20} is the cost of the tool accessories for a one-level part for a typical 20 ton (178 kN) compaction press, and this value is supplied by the user to calibrate these relationships. The parameter C_{AP} is the required press capacity in tons (kN/8.896).

EXAMPLE

For the sample part shown in Figure 11.22, the press selected has a capacity of 534 kN (60 tons), a second lower punch holder is required and a core rod holder is required also. Thus, assuming C_{20} is $500, then the tool accessory costs become:

Basic cost = $0.4 \times 500(60)^{0.3} = \$683$
Core rod holder = $0.04 \times 500(60)^{0.3} = \$68$
Lower punch holder = $0.16 \times 500(60)^{0.2} = \$181$

giving a total tool accessory cost of $932.

11.10.5 Tool Replacement Costs

The estimating procedure also allows tooling replacement costs and maintenance. In general, the dies for compaction can be expected to last for the order of half a million parts before replacement is necessary [10]. For punches, the useful life can be 200,000–300,000 parts [10], but this may be severely reduced for punches with sections of reduced area or thickness. Core rods are subject to considerable stress and friction during the compaction cycle, with the stress changing from compressive to tensile during each cycle. Thus, thin-section core rods often break before wear becomes significant, whereas thicker core rods have longer lives and replacement is required when excessive wear has occurred. A simple model for tool replacement and maintenance has been built into the estimating procedure, which increases the frequency of punch and core rod replacements for small-section tool elements. The life of the die is usually high (>500,000 parts), but cores and punches may require replacement more frequently, particularly if they are fragile. Cores for small-sized through holes and punches that have small width steps are relatively fragile and require more frequent replacement and increased maintenance.

By assuming a logarithmic relationship for the life of the various tooling components and fitting some life data, the following expressions can be obtained:

$$\text{For core rods } \ln(l_f) = 14.5 - \ln(25.4P_r/A_h) \tag{11.28}$$

where l_f is the life in the number of parts produced, P_r is the hole perimeter, and A_h is the area enclosed by the perimeter.

For punches, for each separate region on which the punch acts then

$$\ln(l_f) = 14.9 - 1.2\ln(25.4P_r/A_h). \tag{11.29}$$

When the punch has more than one separate region, the lowest life determined in this manner is taken as the punch life.

Tool replacement costs are obtained by first determining the number of replacement items required as follows:

$$\text{No. of replacement items, } N_r = \text{integer part of } (P_V/l_f), \tag{11.30}$$

where P_V is the production volume required. This is then multiplied by the original tool element costs to determine the tool replacement costs.

EXAMPLE

For the sample part in Figure 11.22, the tool life for circular core rods is given by

$$\ln(l_f) = 14.5 - \ln(25.4 \times 14.96/17.41)$$

which gives a life of 90,846 parts, and therefore, assuming a required production volume of 200,000 parts, the number of replacement items is given by

Integer part of (200,000/90,846), or 2 additional rods per hole

Similarly, for the punch for lower level 1, the individual regions at this level are considered separately to determine the punch life as follows:

1. Circular central region punch life is given by
   $\text{Ln}(l_t) = 14.9 - 1.2\text{Ln}(25.4 \times 32.41/84.52)$, or 192,630 parts
2. For the three outer regions, the punch life is given by
   $\text{Ln}(l_t) = 14.9 - 1.2\text{Ln}(25.4 \times 29.69/63.23)$, or 151,065 parts

Thus, the lowest life from these separate regions determines the punch life and the number of replacement punches becomes the integer part of (200,000/151,065), or one replacement punch in this case. Similar calculations are carried out on the other punches and core rods to determine the total number of replacement tooling elements.

11.10.6 Validation of the Tool Cost-Estimating Procedure

The reliability of this tool cost-estimating procedure has been validated by application to a number of parts manufactured by the powder metallurgy industry. Figure 11.24 compares the tooling costs estimated by this procedure, with estimates of the corresponding costs obtained from industry for the parts shown in Figure 11.15. Only the die, punches, and core rods are considered. A similar comparison for a wider range of parts is illustrated in Figure 11.25.

11.10.7 Sintering Costs

During sintering, the compacted parts are passed through a furnace in a controlled atmosphere. Sintering costs are determined from the operating cost of the furnace used and the throughput rate of parts. The furnace operating costs per unit time include the atmosphere costs, labor, and an allowance for maintenance. The rate of throughput of parts is given by the number of parts per unit area of belt and the area of belt passing through the furnace per unit time. The number of parts per unit area for a given furnace is dependent on the part material, the projected area of the part, and the belt width. Several basic rules can be applied:

1. For iron containing <4% alloying elements, parts can be stacked up to the recommended load capacity of the belt or furnace handling system.

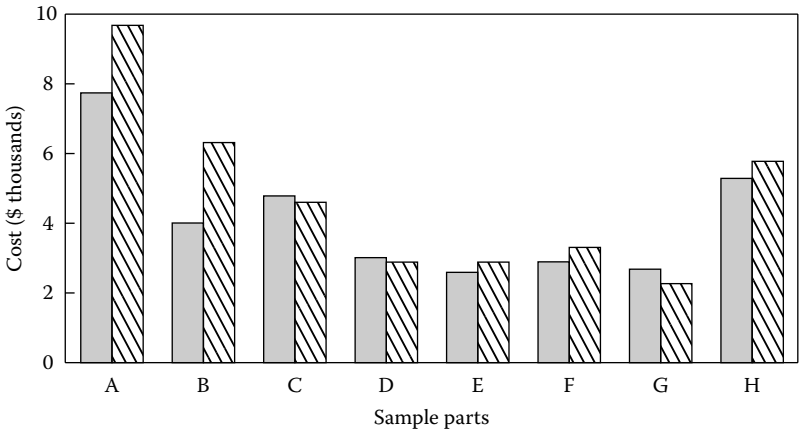

FIGURE 11.24
Comparison of tooling cost estimates with industry values for a range of powder metal parts.

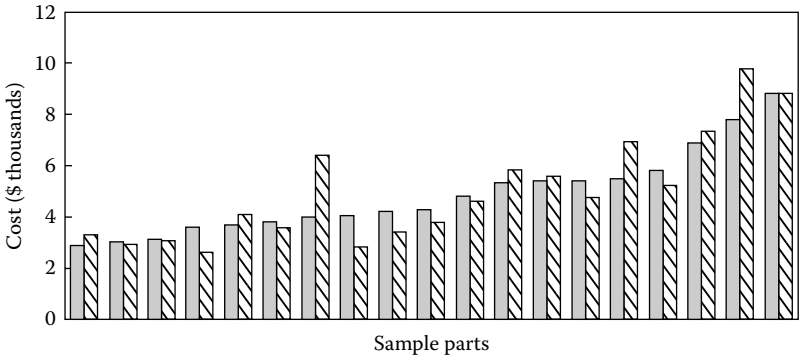

FIGURE 11.25
Comparison of tooling cost estimates with industry values for a larger range of powder metal parts.

2. For bronze, brass, and aluminum, a gap of 3 mm must be left between parts.
3. For iron containing over 4% alloying elements, a gap of 3 mm must be left between parts.

11.10.7.1 Continuous-Flow Furnaces

A suitable continuous-flow furnace is normally selected based on the sintering temperature required for the part material. However, mesh belt furnaces are most commonly used. The selected furnace has certain dimensional characteristics that determine the sintering costs per part. These items include

Furnace overall length: L_{FL}
Sintering zone length: L_{HT}
Width of the belt or feeder: w_F
Height of the furnace opening: H_F
Maximum weight of parts per unit area: W_{max}

The belt or feeder speed, v_F, is determined from the sintering time, T_s, appropriate to the material and the length of the sintering zone of the furnace:

$$v_F = \frac{L_{HT}}{T_s} \tag{11.31}$$

The throughput rate of parts is determined from the manner in which parts can be stacked or placed on the belt or feeder. For pusher, roller-hearth, and walking-beam furnaces, parts must be placed on trays or plates, and some allowance for the thickness of these plates, say about 1 cm, should be made. The number of parts, N_{fw}, which can be placed across the width of the furnace, limited by the height of the furnace opening, is dependent on whether the parts can be stacked or must be spaced out on the belt or feeder. Allowance for any nesting of parts possible should also be made. From N_{fw} the length of furnace that the batch of parts would take up is determined as

$$B_L = \frac{B_s L}{N_{fw}} \tag{11.32}$$

where B_s is the batch size and L is the part length. Therefore, the time for the batch of parts to pass through the furnace is $(B_L + L_{FL})/v_F$ and the throughput time per part is given by

$$t_{FL} = (B_L + L_{FL})/(v_F B_s) \tag{11.33}$$

From this the sintering cost per part is determined as $t_F C_{LF}$, where C_{LF} is the cost of operating the furnace per unit time, including labor and atmosphere costs.

EXAMPLE

Assume that the following belt furnace is selected from Table 11.8, which has the following characteristics:

High heat zone length: 1.83 m
Overall length: 9.14 m
Furnace width: 30.48 cm
Throat height: 10.16 cm
Load capacity: 73.34 kg/m^2
Operating cost: \$120/h

The sample part is made from the standard material F-0005-20, which has a sintering temperature of 1121°C and a sintering time of 25 min. In addition, the dimensions of the part are as follows:

Part length: 47.625 mm
Part width: 47.625 mm
Part thickness: 8.89 mm
Part weight: 0.033 kg

The belt velocity in this case is given by 1.83/25 m/min = 0.0732 m/min. The material of the part allows stacking of the parts and therefore the number of parts that can be placed across the furnace width is the integer part of 304.8/47.625 = 6 parts, and the number of parts that can be stacked vertically is the integer part of 101.16/8.89 = 11 parts. Thus, the number of parts in each row is 66, and the load per unit area becomes $66 \times 0.033/(0.3048 \times 0.047)$ kg/m^2 = 147 kg/m^2, which considerably exceeds the allowable load of 73.34 kg/m^2. Therefore, the number of layers of parts must be reduced to five to meet this constraint. Thus, the number of parts that can be placed across the belt is 30.

Assuming a batch quantity of 24,000 parts, the length of the batch in the furnace is $47.625 \times 24{,}000/30$ mm = 38.1 m. From this the throughput time per part is

$$(30.1 + 9.14)/(0.0732 \times 24{,}000) = 0.022 \text{ min}$$

From this the sintering cost per part becomes $0.022 \times 120/60$ = \$0.04 per part.

11.10.7.2 Batch Furnaces

For batch furnaces the number of parts that can be placed inside the furnace is determined from the part dimensions and the dimensions of the heating chamber. Allowance should be made for any plates required between the layers of parts. This number or the batch size, whichever is smaller, is the furnace load, N_{BF}.

In order to estimate the time necessary to process the parts in the furnace, an approximation to the heating and cooling cycle as shown in Figure 11.26 can be used. Assuming a constant heating rate R_1(°C/h) and a constant cooling rate R_2, if the sintering temperature is θ_S, the sintering time T_s, the burnoff temperature, θ_b, and the burnoff time, T_B, then the furnace cycle time is given by

$$t_{FB} = \theta_s/R_1 + T_B + T_s + \theta_s/R_2 \tag{11.34}$$

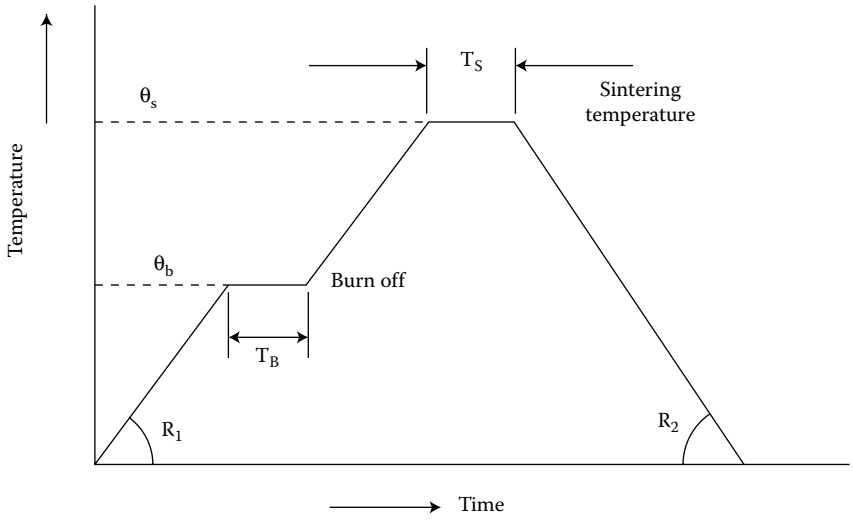

FIGURE 11.26
Approximate heating and cooling cycle for batch-sintering furnaces.

From this the sintering cost per part for batch furnaces is

$$\frac{t_{FB}C_{FL}}{B_s} \tag{11.35}$$

11.10.8 Repressing, Coining, and Sizing

The secondary pressing operations of repressing, coining, and sizing must be treated similar to the cold compaction process. The appropriate press load is determined and the corresponding machine selected. From the operating costs of the machine and the estimated cycle time, the cost per piece is determined. For repressing, the same load as for the initial compaction is used, and for sizing, 80% of the compacting load is used. It is reasonable to assume that the tooling costs for these operations are 80% of the initial compaction costs.

11.11 Modifications for Infiltrated Materials

Infiltration can be carried out during the initial sintering process or as a separate process after the initial sintering. In either case, a compact of the infiltrant material, usually copper, must be prepared. The required amount of copper must be estimated and the compaction cost determined in a similar manner to the compaction of the main part, except that the compact would be a simple one-level part. For the separate infiltration operation, the cost of a second pass through the furnace must be estimated, together with some additional handling costs for the infiltrant compacts.

11.11.1 Material Costs

For infiltrated materials, such as the copper-infiltrated steels listed in Table 11.12, the material costs are determined as follows:

$$\text{Compaction density of the skeleton material, } \rho = \rho_w(1 - q_i)\rho_p \tag{11.36}$$

$$\text{Weight of infiltrant, } V\rho_p q_i \tag{11.37}$$

The total material cost for the part is therefore

$$C_m = V\rho(1 + l_p)C_p + V\rho_p(1 + l_p)q_i C_i \tag{11.38}$$

where ρ_w is the equivalent wrought density of the skeleton material, q_i is the percent by weight of the infiltrant material, ρ_p is the part density including infiltrant, ρ_i is the infiltrant material wrought density, and C_i is the cost per unit weight of the infiltrant material. These values can be obtained from Table 11.12.

11.11.2 Compaction Costs

The part prior to infiltration is compacted to the density ρ determined above. The cost of this compaction is determined in the same manner as discussed in Section 11.10. An additional compaction operation is required for the compact of infiltrant material. For this purpose, the compaction of a one-level part in the infiltrant material is assumed. If it is assumed that the projected area of the infiltrant compact is, say, 80% of the part projected area, then the height of the infiltrant compact can be obtained from the volume determined as described in the previous section. Assuming that the infiltrant compact density is 80% of the equivalent wrought density of the infiltrant raw material, the procedures for press selection, tool cost calculation, and so on, for processing the one-level compact proceed as described previously for part compaction. Compaction of the main part is determined as for noninfiltrated parts.

11.11.3 Sintering Costs

The sintering operation for infiltrated parts is carried out in a similar manner to that for non-infiltrated parts, with the infiltration step done either as a separate operation after sintering or during the initial sintering process. In both cases, when infiltration is being done, only a single layer of parts can be passed through the furnace and the extra height and weight from the infiltrant compact must be allowed for in any furnace selection procedures. Otherwise, estimates of sintering costs are determined largely as described previously.

11.12 Impregnation, Heat Treatment, Tumbling, Steam Treatment, and Other Surface Treatments

11.12.1 Processing Costs

Costs for secondary processes are largely independent of the shape complexity of the final part. Consequently, for early cost-estimating purposes, a simple cost per unit weight of part, or per unit part surface area, is sufficient to estimate the processing costs. Table 11.14 gives a list of typical processing cost for these operations.

11.12.2 Additional Material Costs

Some parts are impregnated with oil for self-lubricating properties or with polymers or resin to seal the surface-connected porosity in the sintered compact. The costs of the

TABLE 11.14

Typical Costs for Secondary Processes

Secondary Process	Cost ($/kg)
Tumbling	0.22
Impregnation	2.22
Steam treatment	4.41
Quench and tempering	2.31
Carburizing	1.54
Nitriding	2.31
Precipitation hardening	2.31
Annealing	1.54
	Cost (cents/50 cm²)
Cadmium plate	0.54
Hard chrome plate	1.55
Copper plate	0.70
Nickel plate	0.78
Zinc plate	0.39
Anodize	0.93
Chromate	0.39
Prime and paint	1.40

impregnant material must be allowed, together with the actual cost of the impregnation operation.

11.12.2.1 Self-Lubricating Bearing Materials

For standard self-lubricating bearing materials, such as those listed in Table 11.13, the following relationships apply:

$$\text{Part compaction density, } \rho = \rho_p - \rho_o q_o \tag{11.39}$$

$$\text{Volume of oil in the part, } V_o = q_o V \tag{11.40}$$

Therefore, the total material costs $C_m = V\rho(1 + l_p)C_p + q_o V C_o$, where ρ_o is the density of oil, typically 0.875 g/cc, q_o is the percent by volume of the impregnant oil, C_o is the cost of the oil per unit volume, typically $1.10/L.

Compaction and sintering costs for the parts are then determined in the same manner as for nonimpregnated parts described previously, but using the compaction density determined as outlined in this section.

11.12.2.2 Materials Impregnated with Oil or Polymer

For powder metal parts impregnated with other materials, such as oil, resin, or polymer, the basic powder material cost is determined as given in Section 11.10.1. The extra material costs are determined as follows:

$$\text{Volume of polymer or oil, } V_o = V(1 - \rho/\rho_w)$$

Hence the impregnant cost, $C_r = V(1 - \rho/\rho_w)C_o$

where C_o is the cost of oil or polymer per unit volume. This cost must be added to the basic powder material cost of the part.

11.13 Some Design Guidelines for Powder Metal Parts

The complexity of powder metal parts increases with the number of levels in the part and with the number of through-holes in the part, since these require separate tooling elements in the tool set, which increase tooling and other costs. Intricate profiles, including those with significant detail, can be readily produced. However, features that result in thin sections in the compaction tooling elements, which may have a detrimental effect on their life, should be avoided if possible. For example, in multilevel parts, small step widths in the part can result in very thin punch elements that are prone to premature failure and reduced tool life (Figure 11.27). Thus, minimum step widths for all level changes should be specified. Similarly, changes in thickness of the part that result in weak punch sections should be avoided. For example, the compaction of a near spherical shape can be achieved by suitable redesign, as shown in Figure 11.28. Also the shape of the individual level profiles may result in very fragile punch profiles (Figure 11.29), particularly where edges meet tangentially. Small changes in the level profiles that avoid very thin punch sections should be made where appropriate.

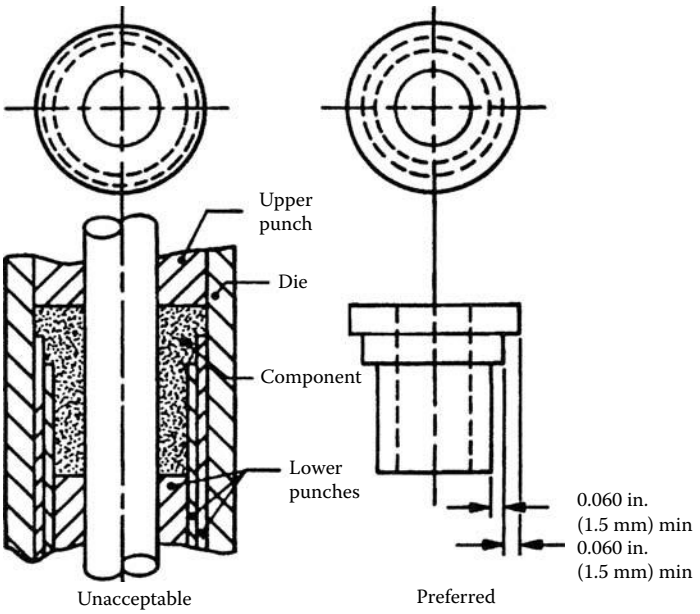

FIGURE 11.27
Design recommendations for minimum level widths. (Adapted from MPIF, *Powder Metallurgy Design Manual*, 3rd ed., Metal Powder Industries Federation, Princeton, NJ, 2007.)

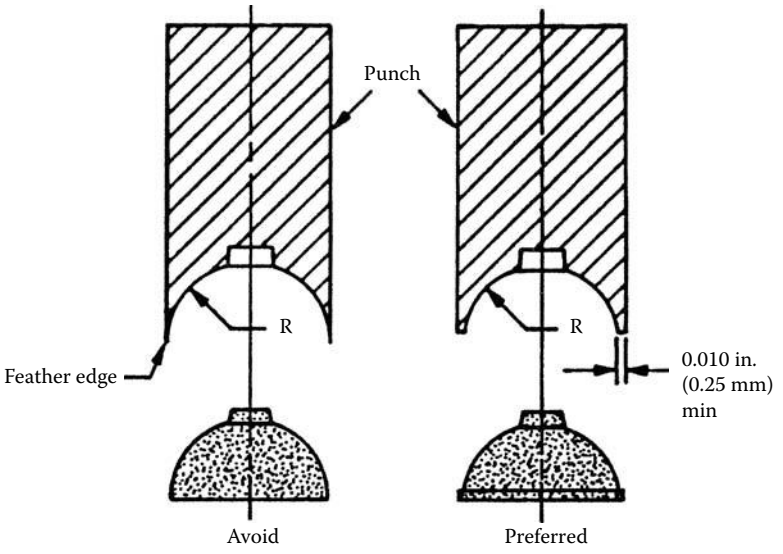

FIGURE 11.28
Design modifications to reduce weak punch sections. (Adapted from MPIF, *Powder Metallurgy Design Manual*, 3rd ed., Metal Powder Industries Federation, Princeton, NJ, 2007.)

11.14 Powder Injection Molding

A process that also uses the input raw materials in powder form is metal injection molding (MIM) or more precisely powder injection molding (PIM), as nonmetallic powders are also processed [11–13]. The PIM process combines the geometrical complexity possible from injection molded plastic with the mechanical properties of high performance metallic

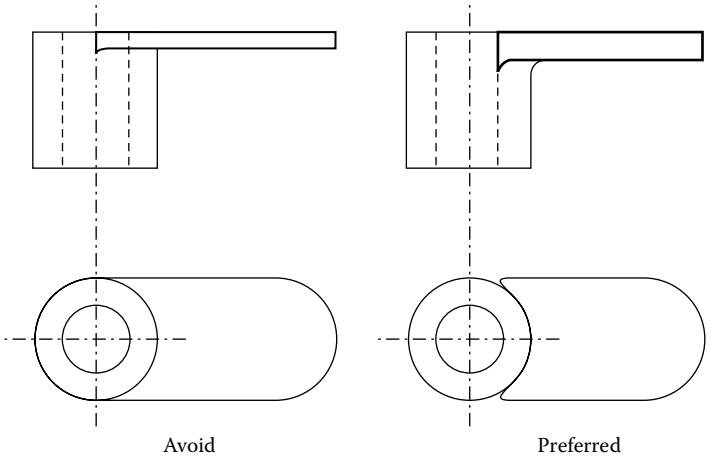

FIGURE 11.29
Design modifications to eliminate small punch sections. (Adapted from MPIF, *Powder Metallurgy Design Manual*, 3rd ed., Metal Powder Industries Federation, Princeton, NJ, 2007.)

alloys and ceramics. High-volume production in a full range of metallic alloys and ceramic materials is possible.

Parts are made by thermally injecting feedstock in a process similar to that for plastic parts. Essentially any shape that can be injected into plastic can be made in metals and ceramics. However, the PIM process is usually most economic for relatively small parts. Part design greatly impacts the process capability. Final densities are typically 97–100% of the equivalent wrought materials, depending on the alloys used.

As with conventional powder metal processing, PIM consists of several stages. Figure 11.30 shows the main processing steps [13], which are as follows:

- Feedstock preparation and pelletization
- Molding
- Debinding
- Sintering
- Secondary operations

11.14.1 Feedstock Preparation and Pelletization

The feedstock for PIM processing is a mixture of metal or ceramic powders and a binder. Fine powders are combined with a binder of a specially formulated blend of plastics and/or waxes. Almost any metal or ceramic that can be produced in a suitable, micron-sized, fine powder can be processed. The final feedstock is about 60% by volume of metal and 40% binder. Binders are, for the most part, mixtures of organic compounds that can include anything from synthetic polymers, such as polyolefins, to natural waxes, such as beeswax, together with surfactants and other property-modifying additives.

It is important to ensure homogeneity of the feedstock to avoid defects in subsequent processing. Uniform quantities of particles and binder are needed in all portions of the mixture. As a result of the small particle size of the powders used, this is difficult to achieve. Consequently, intensive mixing of the constituents of the feedstock is required.

Mixing is usually carried out at elevated temperatures. First, the binder is mixed starting with the highest melting point components, then the binder temperature is decreased and the lower melting point components added to avoid evaporation and degradation. Once

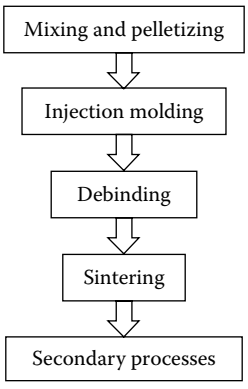

FIGURE 11.30
Steps in the powder injection-molding process.

the binder is mixed, the powder is added and mixed into the binder. At this point, the mixture cools because of the higher heat capacity of the powder and to avoid problems progressive addition of the powder is recommended. Final mixing is often carried out in a vacuum to fully degas the mixture.

Once the feed stock is satisfactorily mixed, it is pelletized for storage and transfer to the injection-molding machines. Pelletizing also allows any recycled material to be added to the feedstock. This recycled material comes from the sprues, runners, and rejected parts from the molding process. The use of this recycled material is economically necessary because of the relatively high cost of the feedstock materials, particularly the powders. In addition, since most PIM parts are relatively small, the actual parts make up only a small proportion of the shot volume.

11.14.2 Molding

After the feedstock preparation, the material is injection molded, just like plastic. Standard injection-molding machines are employed utilizing standard tooling. The molding process is essentially the same as used for thermoplastics as described in Chapter 8. However, the molding of PIM parts differs somewhat from the molding of plastics because of the nature of the feedstock materials. The molding machines are equipped with wear-resistant screws and barrels, and may have a number of special options. After molding, PIM parts are called "green" parts and at this stage the molded part contains both the binder and powder. The parts shrink considerably during sintering and therefore the molded parts are initially about 15–20% larger than the finished object. Typical injection pressures are in the range of 15–30 MPa, which compares with 90–130 MPa for thermoplastics. This, combined with the relatively small size PIM parts, means that the molding machines used have a relatively low clamp force and shot size requirements. Due to the rheology of the feedstock, high injection rates are usually necessary.

The high thermal conductivity and lower heat capacity of the PIM feedstock allows faster cooling, but this can also cause incomplete die filling if the feedstock temperature and injection pressures are not high enough. Thus, careful temperature and pressure control during molding is important. Prediction of the molding parameters requires extensive experience and testing for each part. This is different from the plastics industry where suppliers of feedstock material usually provide the recommended molding parameters. Table 11.15 compares injection molding parameters of the PIM process with those for thermoplastic molding.

Estimation of the tooling costs for molding and determination of the optimum number of cavities can be carried out using the same approach as for plastic injection molding described in Chapter 8.

11.14.3 Debinding

After injection molding, the binder must be largely removed, with the final traces of binder removed by evaporation during the initial stages of the sintering process [11–13]. The debinding cycle is designed to remove the lower melting point components, which comprise the majority of the binder, usually 80% by weight. The remaining component is typically a thermoplastic, which remains in the compact to be finally removed during the first stage of sintering.

The removal of the binder from the green part is a key stage of the process and one that requires most careful control. Historically, this has been a slow step in PIM processing,

TABLE 11.15

Injection Molding Parameters for PIM and Plastics Molding

	Powder Injection Molding	Plastic Injection Molding
Barrel temperature, °C	100–180	20–40
Nozzle temperature, °C	145–175	420–625
Mold temperature, °C	35–40	80–220
Injection temperature, °C	70–90	125–290
Injection pressure, MPa	15–30	90–130
Packing pressure, MPa	3–7	–
Injection time, s	0.5–5	1–5
Packing time, s	2–12	–
Cooling time, s	18–45	15–60
Total cycle time, s	25–65	18–70

with debinding times ranging from as short as 2 h to as much as 50 h as section thicknesses increase and particle sizes decrease. During debinding, the green part shrinks to become what is called a "brown part" and the strength decreases as the part becomes more porous. The resulting porous body, however, retains sufficient mechanical strength such that it can be handled and transported, but care must be taken in handling brown parts. Although they have shrunk, brown parts are still considerably larger than the finished parts because of the much larger shrinkage during sintering. There are two basic processes for debinding—thermal debinding and solvent debinding.

1. *Thermal debinding.* The classical approach to debinding is to slowly evaporate some of the binder by oxidizing the compact in air, followed by heating to higher temperatures in a protective atmosphere to decompose or evaporate most of the remainder of the binder. Oxides produced during the first stage of debinding must be removed by hydrogen reduction prior to sintering. The equipment used for thermal debinding is typically ovens used for drying applications. The process has to be done with great care in order to avoid distortion of the part, and the use of binders with several ingredients that decompose or evaporate at different temperatures is advantageous. The process normally takes many hours with the time being dependent on the thickness of the thickest section of the part. The recent introduction of catalytic debinding of polyacetal PIM feedstock using gaseous nitric acid or oxalic acid has greatly reduced the time for debinding and equipment has been developed whereby catalytic debinding and sintering can be executed on a continuous production basis. This process is quicker than conventional thermal debinding and takes place at milder temperatures. This leads to distinctly fewer rejects, due to a breakage or deformation of the parts.
2. *Solvent debinding.* The second debinding process, applicable to certain binder systems only, is to dissolve out the binder with suitable liquid solvents. Alternatively the parts may be exposed to the hot vapors of the heated solvent. Solvent extraction by immersion requires that some of the binder be insoluble in the solvent in order that some binder remains to hold the particles together prior to sintering. Typically solvent fluids such as ethylene dichloride, trichloroethane, and heptanes are used and these are heated to increase the debinding rate. After immersion, the

insoluble portion of the binder holds the particles together while the compact is dried. The equipment used for solvent debinding is usually modified degreasers used in industry to solvent clean metal parts.

Although models of debinding times have been developed, these do not determine a critical debinding rate that minimizes debinding time while preventing defects [13]. Debinding cycles are still often developed by trial and error for each component and material. In practice, the debinding time increases proportionally to the square of the component's maximum wall thickness.

When a PIM compact is placed in a solvent, the soluble component of the binder egresses from the compact by diffusion. The binder concentration gradient between the compact interior and the surrounding solvent gives an approximate model for the isothermal solvent debinding [14]:

$$-\frac{D_{bs} t \pi^2}{h_{cm}^2} \tag{11.41}$$

where c_d is the average concentration of the remaining binder in the compact, c_i is the initial concentration of the binder, D_{bs} is the binder–solvent interdiffusional coefficient, t is the extraction time, and h_{cm} is the section thickness. Since the solvent is continuously cleaned, D_{bs} is substantially constant, with typical values in the range of 10^{-2} to 10^{-4} mm^2/s. Thus, Equation 11.41 can be rearranged to give an expression for the solvent debinding time, t_{dc}:

$$t_{dc} = \frac{h_{cm}^2}{-D_{bs}\pi^2 \ln\left(\frac{c_c}{c_t}\right)} \tag{11.42}$$

If this expression is fitted to production data and assuming that 95% of the binder is removed, then the solvent debinding time in hours becomes [13]

$$t_{dc} = 0.084 h_{cm}^2 \tag{11.43}$$

However, to account for a basic debinding time for small parts, a minimum time should be added. It is reasonable to assume that an equation of a similar form is applicable to all debinding processes:

$$t_{dc} = t_0 + C_{db} h_{cm}^2 \tag{11.44}$$

where t_0 is the minimum cycle time and C_{db} is a coefficient for debinding determined from industrial data. The debinding cycle time can then be estimated by entering a value of the maximum section thickness for the part.

11.14.4 Sintering

After molding, the PIM parts are sintered at temperatures from 600°F to 2200°F. The process and equipment used is the same as for conventional powder metal processing and includes controlled-atmosphere continuous-flow or batch-type high-temperature furnaces.

During the sintering process, the powder particles are fused into a dense homogeneous part with dimensions approximately 15% less than the injected part. The actual process is more complex than simply eliminating the porous volume and involves a diffusion of atoms and chemical reactions between the various powder components and the reaction gases.

The sintering of PIM parts is essentially the same as is for conventional powder metal parts. The main difference is that the first stage of the process involves heating the parts to a moderate temperature to remove the remaining binder prior to holding the parts at the sintering temperature. The final sintering usually takes place in a controlled protective atmosphere. Since very little compaction occurs during molding, PIM parts shrink considerably during sintering.

Estimation of the costs for sintering can be carried out in the same way as for conventional powder metal parts as described in Section 11.10.7.

11.14.5 Secondary Operations

After sintering, additional operations, such as machining, heat treating, or plating, may be undertaken to achieve tighter tolerances or enhanced properties. The secondary processes are essentially the same as those used for conventional powder metal parts. However, since PIM parts are near full density, those processes that take advantage of the porosity of the parts, such as infiltration and impregnation, are not used.

11.14.6 Feedstock Characteristics

Almost any metal that can be produced in a suitable powder form can be processed by PIM. Aluminum is an exception, because the adherent oxide film that is always present on the surface inhibits sintering. The list of metals that have been used includes plain and low-alloy steels, high-speed steels, stainless steels, superalloys, intermetallic compounds, magnetic alloys, and hard metals (cemented carbides). However, the most promising candidates from the economic point of view are the more expensive materials. This is because there is very little waste material in the process, which helps to offset the high cost of producing the powder in the required form. A wide range of materials have been processed and some are listed in Table 11.16, together with some relevant processing parameters [15].

The feedstock for molding is a mixture of the powder and the binder, with an appropriate ratio of powder to binder for effective processing. The powders used in PIM have a small particle size, usually <10 μm. This compares with an average particle size of about 100 μm for conventional powder metal parts. A small particle size is needed for complete cavity filling for complex parts and for efficient sintering.

The binder is necessary to hold the powder particles together until sintering occurs and also provide the appropriate characteristics for molding. A number of different binder compositions have been used and in general these are a mixture of waxes and wax-like short polymer chains of polyethylene or polypropylene. Table 11.17 lists some of the materials that have been used in binder systems. A wide range of binder compositions have been used, with individual companies developing their own proprietary mixtures. Table 11.18 lists some typical binder compositions that have been used for PIM processing and Table 11.19 gives their corresponding process-related parameters.

The solids content of the feedstock (powder loading) should be selected for successful molding. The theoretical density of the feedstock is given by

$$\rho_f = \phi_v \rho_p + (1 - \phi_v)\rho_b \tag{11.45}$$

TABLE 11.16

Some Materials Used for the Powder Injection Molding Process

Material	Density (gm/cc)	Thermal Conductivity (W/m/°K)	Specific Heat (J/kg/°K)	Sintering Temperature (°C)	Sintering Time (min.)	Critical Powder Loading Φ_c	Cost ($/kg)
316L Stainless Steel	7.999	15	490	1370	30	0.65	30
17-4 PH Stainless Steel	7.805	14	500	1350	30	0.65	30
M2 Tool Steel	8.193	22	500	1239	45	0.64	26
2% Nickel–Iron	7.899	75	440	1239	60	0.63	13
8% Nickel–Iron	7.899	76	450	1260	60	0.63	14
Tungsten-7% Nickel-3% Iron	16.884	150	480	1770	60	0.62	32
Aluminum Oxide (Al_2O_3)	3.792	27	200	1750	120	0.56	12
Zirconium Oxide (ZrO_2)	5.204	10	210	1750	120	0.55	16
Silicon Carbide (SiC)	3.211	10	200	1750	120	0.56	11
Tungsten Carbide (WC–Co)	10.103	100	480	1750	120	0.62	34

where ϕ_v is the volumetric powder loading, ρ_p is the true density of the powder material, and ρ_b is the density of the binder. This gives a linear relationship between density and the powder loading. However, at high powder loadings this relationship breaks down. Figure 11.31 shows a typical loading curve for a powder/binder mixture [11]. As powder is added to the binder, the density of the feedstock increases linearly, but at high loadings the powder cannot flow to fill all the space and there can be insufficient binder to fill the spaces between the particles. The mixture density then falls below the theoretical density given by Equation 11.45, because of the voids. The point of maximum density is termed the critical solids loading, ϕ_c, and this typically is from 0.55 to 0.65, depending on the types of

TABLE 11.17

Some Materials Used in PIM Binder Systems

Material	Thermal Conductivity (W/m/°K)	Specific Heat (J/Kg/°K)	Density (g/cc)	Melting Temperature (°C)
Paraffin wax	0.12	300	0.910	59
Carnauba wax	0.12	300	0.970	84
Polyethylene wax	1.75	2500	0.900	–
Bees wax	1.10	300	0.900	–
Microcrystalline wax	2.25	300	0.910	–
Polypropylene	1.15	2470	0.900	147
Polyethylene	0.90	2500	0.910	–
Stearic acid	0.85	300	0.941	75

TABLE 11.18

Sample Binder Compositions for PIM

	Proportion by Weight (%)							
Binder System	**Paraffin Wax**	**Carnauba Wax**	**Polyethylene Wax**	**Bees Wax**	**Microcrystalline Wax**	**Polypropylene**	**Polyethylene**	**Stearic Acid**
Wax/polypropylene	69	10				20		1
Polypropylene/wax					22	67		11
Mixed wax	33		33	33				1
Polyethylene/carnauba		50					50	
Polyethylene/paraffin wax	55						35	10

powder particles used. It has been found that the appropriate loading for molding is about 96% of the critical loading [11]; thus,

$$\phi_v = 0.96\phi_c \tag{11.46}$$

The models for estimating cycle times for plastic injection molding can also be used for the feedstock. These models have been described in Chapter 8. In particular, the cooling time for the injected part is dependent on the thermal diffusivity of the material given by

$$\alpha = \frac{k}{H\rho_f} 10^3 \tag{11.47}$$

TABLE 11.19

Processing Parameters for Sample Binder Compositions

	Thermal Conductivity	**Specific Heat**	**Density**	**Cost**	**Injection Temperature**	**Mold Temperature**	**Ejection Temperature**
	k_b	H_b	ρ_b	C_b	T_i	T_m	T_x
Binder System	**W/m/°K**	**J/kg/°K**	**gm/cc**	**$/kg**	**°C**	**°C**	**°C**
Wax/polypropylene	0.13	731	0.905	1.65	130	30	80
Polypropylene/wax	0.18	1754	0.907	1.35	140	35	90
Mixed wax	0.12	300	0.927	1.45	100	30	60
Polyethylene/carnauba	0.19	1400	0.940	2.20	140	35	80
Polyethylene/paraffin wax	0.17	1070	1.51	1.25	130	30	85

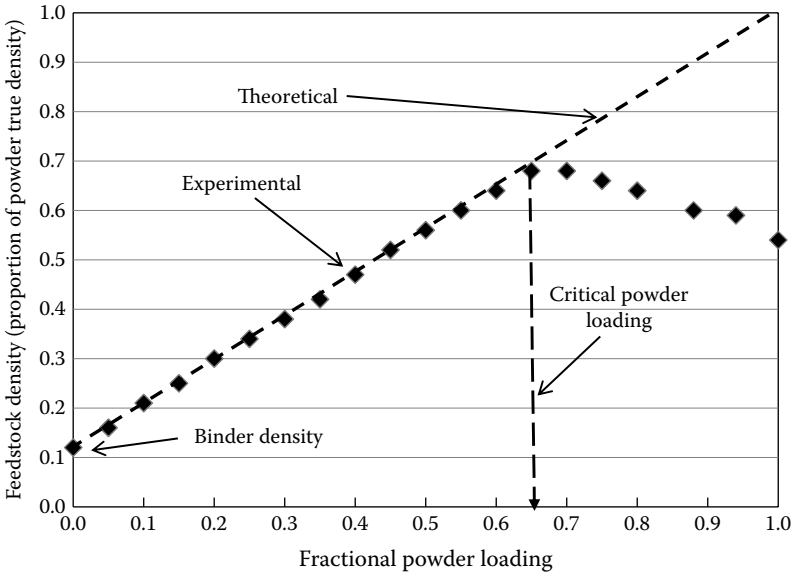

FIGURE 11.31
Density of the feedstock as the powder loading is increased. (Adapted from German, R.M., *Powder Injection Molding*, Powder Industries Federation, Princeton, NJ, 1990.)

where k is the thermal conductivity in W/m/K, ρ_f is the feedstock density in gm/cc, and H is the specific heat capacity in J/kg/K. Thus, it is necessary to determine the conductivity and heat capacity of the feedstock.

The specific heat capacity of the feedstock, H_f, follows the rule of mixtures with respect to the mass based solids loading:

$$H_f = \phi_m H_p + (1 - \phi_m) H_b \tag{11.48}$$

and the mass based powder loading is given by

$$\phi_m = \phi_v \left(\frac{\rho_p}{\rho_f} \right) \tag{11.49}$$

The estimation of the thermal conductivity of the feedstock is more difficult. In many composite systems, such as fiber composites, the dispersed phase is in continuous contact with the matrix phase throughout the part and in this case the thermal conductivity can be determined by the rule of mixtures similar to the above. However, this is not the case for the PIM feedstock, which is a particulate composite, with the dispersed phase not interconnected and thus does not form a continuous conduction path. The rule of mixtures considerably overestimates the feedstock thermal conductivity. The following equation developed by Jeffrey [16,17] has been found to give a better estimate of the feedstock conductivity:

$$k_f = k_b \left(1 + 3\xi\phi_v + \phi_v^2 \left(3\xi^2 + \frac{3\xi^3}{4} + \frac{9\xi^3(\lambda + 2)}{16(2\lambda + 3)} + \frac{3\xi^4}{2^6} \right) \right) \tag{11.50}$$

where $\xi = (\lambda - 1)/(\lambda - 2)$, $\lambda = k_p/k_b$, k_p is the thermal conductivity of the powder material and k_b is the thermal conductivity of the binder.

EXAMPLE

A part is to be made from 316 stainless steel using a wax/polypropylene binder. The critical powder loading from Table 11.16 is 0.65. Thus, from Equation 11.46, the volumetric powder loading, $\phi_c = 0.65 \times 0.96 = 0.624$. The true density of the powder material is 7.999 gm/cc (Table 11.16) and the true density of the binder material is 0.905 gm/cc (Table 11.19). From Equation 11.45, the feedstock density is $\rho_f = \phi_v\rho_p + (1 - \phi_v)\rho_p = 0.624 \times 7.999 + (1 - 0.624) \times 0.905 = 5.33$ gm/cc. The mass-based solid loading, Φ_m, is given by (Equation 11.49) $\phi_m = \phi_v(\rho_p/\rho_f) = 0.624(7.999/5.33) = 0.937$.

The specific heat of the powder material, H_p, is 490 J/kg/°K (Table 11.15) and the specific heat of the binder, H_b, is 731 J/kg/°K (Table 11.19). The specific heat of the binder is (Equation 11.48) $H_f = \phi_m H_p + (1 - \phi_m)H_b = 0.9367 \times 490 + (1 - 0.937) \times 731 = 505.28$ J/kg/°K.

The thermal conductivity of the powder material, k_p, is 15 W/m/°K (Table 11.15) and the thermal conductivity of the binder, k_b, is 0.13 W/m/°K (Table 11.19). Hence,

$$\lambda = \frac{k_p}{k_b} = \frac{15}{0.13} = 115.38$$

and

$$\xi = \frac{\lambda - 1}{\lambda - 2} = \frac{115.38 - 1}{115.38 - 2} = 1.0088.$$

From Equation 11.50, the feedstock thermal conductivity is

$$k_f = k_b\left(1 + 3\xi\phi_v + \phi_v^2\left(3\xi^2 + \frac{3\xi^3}{4} + \frac{9\xi^3(\lambda + 2)}{16(2\lambda + 3)} + \frac{3\xi^4}{2^6}\right)\right)$$

$$= 0.13\left(1 + 3 \times 1.0088 \times 0.624 + [0.624]^2\left(3 \times [1.0088]^2 + \left(\frac{(3 \times [1.0088]^3)}{4}\right)\right.\right.$$

$$\left.\left. + \left(\frac{(9 \times [1.0088]^3(115.38+2))}{16(2 \times 115.38 + 3)}\right) + \left(\frac{(3 \times [1.0088]^4)}{2^6}\right)\right)\right) = 0.483 \text{ W/m/°K}$$

The thermal diffusivity of the feedstock is then given by Equation 11.47.

$$\alpha = \frac{k}{H\rho_f}10^3 = \frac{0.586}{505.28 \times 5.33} \times 10^3 = 0.218 \text{ mm}^2/\text{s}.$$

11.14.7 Material Costs

The unit cost of the feedstock can be determined by the rule of mixtures:

$$C_f = \phi_m C_p + (1 - \phi_m)C_b \tag{11.51}$$

where C_p is the unit cost of the powder material, C_b is the unit cost of the binder material, and ϕ_v is the mass-based powder loading given by

$$\phi_m = \phi_v\left(\frac{\rho_p}{\rho_f}\right) \tag{11.52}$$

The part undergoes a significant amount of shrinkage during sintering after the molding process and the volume of material in the die cavity, V_c, is given by

$$V_c = V_p\left(\frac{f_f}{\Phi_v}\right) \tag{11.53}$$

where V_p is the volume of the finished part, Φ_v is the initial fractional density of the molded part, and f_f is the fractional density of the finished part, given by ρ/ρ_p. The mass of feedstock in the cavity or the mass of the as molded part is

$$M_m = V_c\rho_f \tag{11.54}$$

For plastic molding, the volume of material in the runner system is related to the cavity volume. It appears that the volume of material in the runner systems for PIM is roughly twice that for plastic molding [13]. The volume of material in the runner system can be estimated from:

$$V_r = 2.1V_c^{.52} \tag{11.55}$$

with V_c in cu.cm and the mass of material in the runner system is

$$M_r = V_r\rho_f \tag{11.56}$$

The feedstock is relatively expensive and the waste material in the runners and unacceptably molded parts must usually be reground and reused. There are losses associated with recycling this material from contamination and property degradation. An unacceptable increase in viscosity may result from the overuse of recycled feedstock. Thus, the material cost per part is given by

$$C_{rp} = C_f\left(\frac{M_m}{Y_dY_s} + (M_m(1 - Y_m) + M_r)(1 - Y_r)\right) \tag{11.57}$$

where Y_m is the molding process yield, Y_r is the usable regrind yield, Y_d is the debinding yield, and Y_s is the sintering yield.

EXAMPLE

A cylindrical cup-shaped part, 20 mm diameter and 20 mm tall, with a uniform wall thickness of 3 mm is to be made from the 316 stainless-steel feedstock in a single-cavity mold. The volume of this part, V_p, is given by $V_p = \pi \times 20^3/4 - \pi \times 14^2 \times 17/4 = 3.666.24 = 3.67$ cm^3. Assuming a final fractional density after sintering of 0.98, the volume of the cavity, V_c, is given by Equation 11.53: $V_c = 3.67 \times 0.98/0.624 = 5.76$ cm^3.

The mass-based solid loading of the feedstock is given by Equation 11.52:

$$\phi_m = \phi_v\left(\frac{\rho_p}{\rho_f}\right) = 0.624 \times \frac{8.0}{5.33} = 0.937$$

From Tables 11.16 and 11.19 the powder cost, C_p, is \$30/kg and the binder cost, C_b, is \$1.65/kg. The cost of the feed stock, C_b, from Equation 11.51 is given by

$$C_f = 0.937 \times 30 + (1 - 0.937) \times 1.65 = \$28.21/\text{kg}$$

The as-molded mass of the part is given by Equation 11.54: $M_m = 5.76 \times 5.33 = 30.7$ g.

The volume of material in the runners is given by Equation 11.55: $V_r = 2.1 \times (5.76)^{0.52} = 5.21$ cm^3. From Equation 11.56, the mass of material in the runners is given by

$$M_r = 5.21 \times 5.33 = 27.77 \text{ g}.$$

Assuming that the yield from sintering, Y_s, is 0.98; the yield from debinding, Y_d, is 0.98; the yield from molding, Y_m, is 0.98; and the yield from regrinding the waste material, Y_r, is 0.95, then the material cost for the part is given by Equation 11.57:

$$C_{rp} = C_f\left(\frac{M_m}{Y_d Y_s} + (M_m(1 - Y_m) + M_r)(1 - Y_r)\right)$$

$$= \frac{28.21}{1000}\left(\frac{30.7}{0.98 \times 0.98} + (30.7(1 - 0.98) + 27.77)(1 - 0.95)\right) = \$0.94$$

11.14.8 Mold Cavity Geometry

A considerable amount of shrinkage occurs during the sintering of PIM compacts and the appropriate die cavity dimensions must be determined from the finished part dimensions. For this purpose, a volumetric expansion factor, K_v, can be derived:

$$K_v = \frac{\rho_s}{\rho_p \phi_v} = \frac{f_f}{\phi_v} \tag{11.57}$$

where f_f is the finished part fractional density, which is the ratio of the sintered density, ρ_s, to the true density of the part material, ρ_p.

From this the corresponding cavity, volume is given by

$$V_c = K_v V_p \tag{11.58}$$

where V_c is the cavity volume and V_p is the final part volume. The required shot size for the injection-molding machine is determined by adding the volume of material in the runners.

The projected area of the mold cavity, A_c, is determined from the part projected area, A_p, as

$$A_c = A_p K_v^{2/3} \tag{11.59}$$

This area with the addition of the projected area of the runners is used to estimate the minimum clamping force required for the injection molding machine.

Any linear dimension of the mold cavity is obtained by multiplying the corresponding part dimension by $K_v^{1/3}$.

11.14.9 Molding Costs

In order to estimate the injection-molding costs for a PIM part, the following parameters are required:

- The hourly operating cost of the injection-molding machine, M, in \$/h.

- The molding cycle time, t_m, in s.
- The number of cavities in the mold, n.

These parameters are derived in the same manner as for plastic injection-molding machines as described in Chapter 8 except for the derivation of the molding cycle time must be modified for the PIM process. As with plastic injection molding, the molding cycle is broken down into four separate phases: injection, packing, cooling, and resetting (see Figure 8.1).

Based on industrial data [13] and by analyzing the cycle times for specific PIM parts, it would seem that an average fill rate of around 15 cc/s is an appropriate fill rate. This filling (injection) time, t_i, can be estimated as

$$t_i = \frac{Q}{15} \tag{11.60}$$

where Q is the shot size, determined from the total cavity volume plus the volume of material in the runners (Equation 11.55).

Once the material has been injected into the mold, it is held at a more or less constant pressure for a period (packing time) to improve part accuracy and provide a more uniform stress field in the molded part. The packing time, t_p, is dependent on a number of factors, including the cavity volume, V_c, part complexity, X_c, and the packing pressure, P_p. An empirical relationship for the packing time has been developed from production data [13]:

$$t_p = 1.4 + 3.4 \log V_c + 1.7 X_c + 1.9 P_p \tag{11.61}$$

The complexity factor, X_c, is derived from the number of surfaces on the part as described in Chapter 8 and is on a scale from 0 to 10.

The cooling time for PIM moldings is determined in the same way as for plastic injection moldings as described in Chapter 8. The cooling time, t_c, is given by

$$t_c = 3 + \frac{h_{cm}^2}{\alpha \pi^2} \ln \frac{4(T_i - T_m)}{\pi (T_x - T_m)} \tag{11.62}$$

where h_{cm} is the maximum section thickness of the molded part in mm, T_x is the part ejection temperature, T_m is the mold temperature, T_i is the injection temperature, and α is the thermal diffusivity of the feedstock, which is determined as described in Section 11.14.6. The injection, ejection, and mold temperatures are determined by the thermal properties of the binder system and appropriate values for some sample binders are given in Table 11.18.

The resetting time, t_r, includes the time required for mold opening, part ejection, and mold closing. A model for resetting the time for plastic injection-molded parts is given Chapter 8. This is modified slightly for the PIM process as follows:

$$t_r = 3 + 1.75 t_d \left[\frac{2D_c + 5}{L_s} \right]^{\frac{1}{2}} \tag{11.63}$$

where t_d is the dry cycle time of the injection molding machine, D_c is the depth of part in the cavity in cm, and L_s is the length of the ejection stroke in cm.

The total cycle time, t_m, is the sum of t_i, t_p, t_c, and t_r.

EXAMPLE

For the cup-shaped part the shot volume, Q, is the sum of the cavity volume, V_c, and the runner volume, V_r, and is therefore equal to $5.76 + 5.21 = 10.96$ cm^3. From Equation 11.59, the injection time, t_i, is given by $Q/15$, which equals 10.96/15 or 0.73 s.

Using the approach described in Chapter 8, the part has two internal surfaces and three external surfaces, and therefore the complexity factor, X_c, is 0.5. Assuming a packing pressure of 5 MPa, Equation 11.60 gives the packing time, t_p:

$$t_p = 1.4 + 3.4\log V_c + 1.7X_c + 1.9P_p = 1.4 + 3.4\log 5.76 + 1.7 \times 0.5 + 1.9 \times 5 = 14.34 \text{ s}$$

The maximum wall thickness of the part is 3 mm and in the cavity this becomes larger, due to the shrinkage during sintering. The volumetric expansion factor, K_v, is given by Equation 11.57: $K_v = 0.98/0.624 = 1.57$ and therefore the maximum cavity thickness, h_{cm}, is $3 \times 1.57^{1/3} = 3.49$ mm. From Table 11.19, the injection-molding temperature, T_i, is 130°C; the mold temperature, T_m, is 30°C; and the ejection temperature, T_x, is 80°C. The thermal diffusivity of the feedstock was determined above to be 0.179 mm^2/s. The cooling time for the molding is given by Equation 11.61:

$$t_c = 3 + \frac{h_{cm}^2}{\alpha\pi^2}\ln\frac{4(T_i - T_m)}{\pi(T_x - T_m)} = 3 + \frac{3.49^2}{0.179 \times \pi^2}\ln\left(\frac{4(130 - 30)}{\pi(80 - 30)}\right) = 9.89 \text{ s.}$$

The part depth is 2 cm and from this the cavity depth, D_c, is $2 \times 1.57^{1/3} = 2.32$ cm. Assuming that the dry cycle time of the molding machine is 1.7 s and the ejection stroke is 15 cm, then the mold resetting time, t_r, is given by Equation 11.62:

$$t_r = 3 + 1.75t_d\left[\frac{2D_c + 5}{L_s}\right]^{\frac{1}{2}} = 3 + 1.75 \times 1.7\left[\frac{(2 \times 2.32 + 5)}{15}\right]^{\frac{1}{2}} = 5.39 \text{ s.}$$

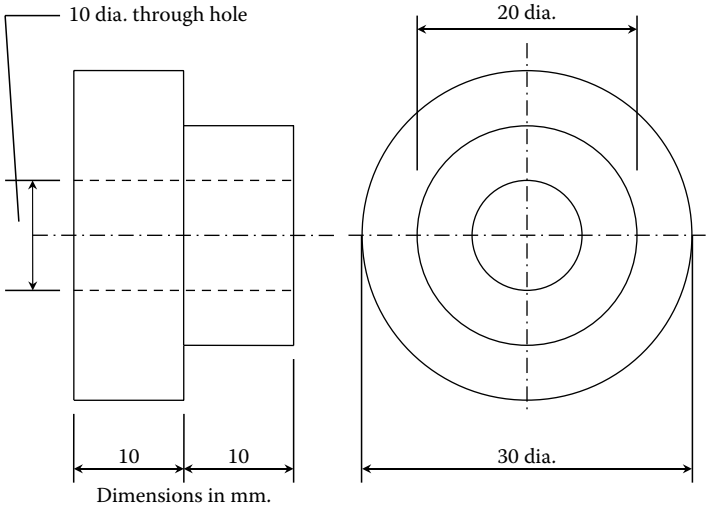

FIGURE 11.32
Two-level iron part produced by powder compaction and sintering.

The molding cycle time is therefore given by 0.73 + 14.34 + 9.89 + 5.39 = 30.35 s. The molding cost is then determined by multiplying the cycle time by the operation cost rate of the molding machine.

PROBLEMS

1. The two-level part shown in Figure 11.32 is made from iron powder with the compaction characteristics given. The part is compacted to a density of 7.0 g/cc.
   a. Determine the dimensions of the loose powder fill in the compaction tooling.
   b. If the loose powder costs $2.2/kg then estimate the material cost for the part, assuming a powder loss of 1.5%.
2. a. Based on the information given in Figure 11.32, select the most appropriate press from Table 11.3 for the part.
   b. Determine the compaction cycle time, setup time, and the compaction costs per part, assuming a batch size of 5000 parts. Assume a press operation cost rate and setup rate of $90/h.
3. For the part shown in Figure 11.32, estimate the initial cost of the compaction tools (die, punches, and core rods). Assume that tool steel costs $20/kg and carbide for the die insert costs $20/cc.
4. The part shown in Figure 11.32 is sintered using a mesh belt continuous flow furnace with the following characteristics:

   Furnace length (m) 9.14
   High heat zone length (m) 1.83
   Belt width (cm) 30.48
   Throat height (cm) 10.16
   Load capacity (kg/m^2) 73.24
   Operating cost ($/h) 120

   Assuming that the parts must be separated by at least 2 mm, estimate the sintering cost per part for a batch size of 5000.
5. Feedstock for powder injection molded parts is made up from 8% nickel–iron alloy powder and a polyethylene/carnauba binder. Using the data in Tables 11.16 and 11.19, determine the following:
   a. The volumetric powder loading of the feedstock.
   b. The feedstock density.
   c. The mass-based powder loading of the feedstock.
   d. The thermal conductivity of the feedstock.
   e. The specific heat of the feedstock.
   f. The thermal diffusivity of the feedstock.
6. Repeat Problem 5 for a feedstock made from tungsten—7%, nickel—3%, iron alloy powder, and a mixed wax binder.
7. A part with a finished volume of 10 cm^3 is produced by powder injection molding in a single-cavity mold, from the feedstock material in Problem 5. The final sintered part has a density which is 0.99 of the true density of the metal alloy. Using the data in Tables 11.16 and 11.19 determine the following:
   a. The cost per kg of the feedstock.
   b. The material cost per part, assuming that the reject rates for molding, debinding, and sintering are 1% and the yield from regrinding the waste feedstock material after molding is 95%.
8. Determine the molding cycle time for the part in Problem 7. The part has a maximum wall thickness of 5 mm and a depth of 4 cm. The complexity factor for the part is 2.0 and a packing pressure of 7 MPa is used in the molding process. The molding machine used has a dry cycle time of 2 s and the ejection stroke is 15 cm.

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12

Design for Sand Casting

12.1 Introduction

Sand casting is a process in which molten metal is poured into sand molds, which are broken away from the cast part after the metal has solidified. The sand molds are made of two halves in which impressions are made by a pattern. When the two halves are assembled, the impressions form a cavity into which the molten metal is poured. The pattern resembles the part, but is slightly larger to accommodate for the metal shrinkage that occurs during cooling. Patterns may contain multiple impressions, to form multicavity sand molds, for the economical production of large quantities of castings.

A mixture of sand and a binding agent is compacted around the pattern to form the two mold halves in separate metal flasks. Historically, the lower mold half is named the drag, and the upper mold half is referred to as the cope. Channels are formed in the drag to feed the molten metal to the cavity, or cavities in a multicavity mold. The opening of a feed channel to its cavity is the gate, but often the complete set of feed channels is referred to as the gating system. A pouring cup and vertical tapered channel in the cope are used to deliver molten metal to the feed channels. Two additional features may sometimes be required in a sand mold. First, one or more separate sand cores may be placed in formed locations, called core prints, during assembly of the mold halves. Second, an additional cavity, called a riser, may be formed in the cope to supply molten metal pressure during the solidification and shrinkage of the casting.

Sand cores are used in sand casting to produce internal cavities or undercuts. Since the cores are broken out of the casting after solidification, complex internal cavities are readily producible. The main requirement is that the internal surfaces be accessible for the subsequent cleaning processes to remove adhering sand particles. An assembled cope and drag mold, with both a sand core and a riser, is shown in Figure 12.1. After metal solidification and cooling in this mold, the casting is broken out of the sand, the gating system is removed, and the cast part is cleaned of adhering sand particles.

Sand castings can be produced singly on the foundry floor with weights measured in tons, or small castings can be produced on high-speed automated lines in quantities measured in hundreds of thousands. The latter type of casting production is a central part of automobile manufacture for such items as pump housings, flywheel blanks, crankshafts, and so on. Small brass castings are produced in a similar manner in large volumes for the plumbing and associated industries.

Sand castings can be made with extremely complex outer shapes. For economical high-volume production, the shape should contain a parting line around its perimeter, each side of which has taper, called draft, for separation from the sand mold. This is required not for

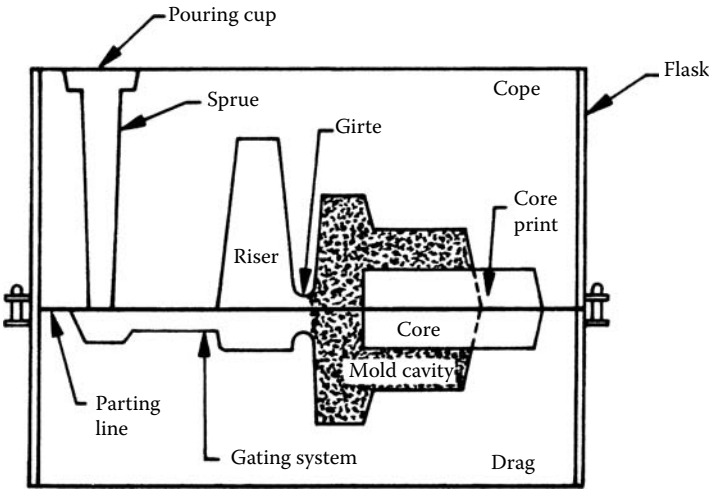

FIGURE 12.1
Assembled cope and drag mold.

separation of the finished casting from the mold, but rather for removal of the pattern after the mold sand has been compacted around it. Castings without draft may be produced by the use of multipiece patterns. In these cases, the pattern pieces can be disassembled for removal in different directions from the compacted mold. This is a labor-intensive and slow process used only for limited production of very complex parts. When reviewing the economics of sand casting later in this chapter, we will focus on economical batch production in modern automated foundries.

12.2 Sand Casting Alloys

Almost any metal alloy can be sand cast, although specific alloying elements are used to increase the metal fluidity and to improve characteristics for feeding the mold. Table 12.1 gives generic casting alloys. Each of these generic alloys represents a long list of available alloys designed for specific applications [1,2].

The castability rating in Table 12.1 is related to fluidity, amount of shrinkage, and the temperature range over which the alloy solidifies. Steels, for example, are not as suitable as irons for casting because of the wider temperature range, called the freezing range, over which they solidify. This results in greater difficulty in mold filling and in avoiding cavities in the solidified casting.

The cost of metal ingots for casting varies substantially with the quantity to be purchased. The typical costs given in Table 12.1 are the costs likely to be paid by a small to medium-sized foundry. Large, automated foundries involved in mass production obtain lower prices. Also included in Table 12.1 are typical scrap values of the different alloys. These values are needed to calculate the material cost of cast parts, as shown later in this chapter.

TABLE 12.1

Commonly Used Sand Casting Alloys

Generic Alloy	Tensile Yield Strength, MN/m^2	Elastic Modulus, GN/m^2	Castability	Cost[a] of Metal Ingots, $/kg	Scrap Value[a], $/kg
Ductile iron	515	165	Excellent	0.29	0.07
Gray iron	—	130	Excellent	0.22	0.07
Malleable iron	310	180	Good	0.35	0.07
Carbon steels	345	175	Fair	0.73	0.09
Stainless steel	515	200	Fair	2.53	0.40
Aluminum	95	70	Excellent	1.87	0.50
Magnesium	95	45	Excellent	4.00	1.00
Bronze	345	115	Good	6.00	1.30
Nickel alloys	600	195	Fair	14.00	3.00

[a] Material costs are subjected to constant change and are strongly influenced by the quantity of purchase—text values are intended for design comparison exercises only.

12.3 Basic Characteristics and Mold Preparation

A mold is produced for each casting, or set of castings with multicavity molds. Thus, the cost of sand casting is driven, more than by any other factor, by the efficiency of mold preparation. This involves multiple operations from the mixing of mold sand to the inclusion of extra mold features to control cooling and to avoid defects resulting from the metal shrinkage. These will be described in the following sections.

12.3.1 Sand Preparation

The sand must be carefully controlled to ensure consistency, thereby providing each mold with the same properties. Typical molding sand consists of 88% silica, 9% clay, and 3% water. The sand is mixed to evenly disperse the clay additive and to provide uniform coating of the sand grains. This serves to bind the sand grains during compaction, thus providing the required mold strength.

Most foundry sand may be reused. However, the sand must be conditioned before it can be used again, since the sand removed from castings contains impurities and tends to remain in large chunks. Lump breakers, screens, and magnetic separators are used to break sand clumps and remove metal particles. Some new sand is constantly added to help maintain the sand quality. This is necessary, since the used sand still contains some burned clay even after conditioning. Although only a small portion of sand is lost in the foundry operation, this can still involve the disposal of a large amount of material. In recent years, because of the increasing expense of landfill disposal and environmental concerns, foundries have made increasing efforts to reclaim as much sand for reuse as possible.

12.3.2 Gating System

The gating system in a sand mold consists of a series of channels and reservoirs designed to feed molten metal to all parts of the mold cavity. The design of the gating system

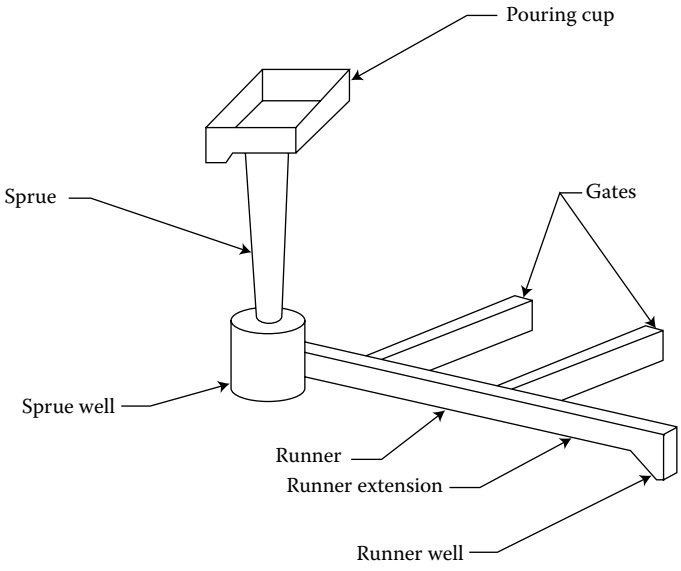

FIGURE 12.2
Typical gating system.

influences a number of factors that can affect the casting's quality and ease of finishing. The common parts of a gating system are shown in Figure 12.2. Molten metal enters the mold through the pouring cup. It then travels down the tapered sprue and into the sprue well. From there, runners deliver the metal to gates, which open into the mold cavities. Runner extensions and wells capture the early metal flow. This is important because the flow picks up any loose particles in the gating system, and these degrade the metal properties.

The design of the system determines the rate at which the metal flows and the amount of cooling that takes place before it reaches the mold cavity. The liquid metal may start to solidify in the feeding passages if it loses too much heat during its journey to the mold cavity. This can block passages (this condition is called a cold shut) and cut off the supply of liquid metal to parts of the mold, resulting in an incomplete casting.

The gating structure must also keep the molten metal from becoming turbulent. Turbulence can lead to excessive absorption of gases into the liquid metal, creating a more porous casting. Turbulence also increases oxidation of the metal and may erode the mold wall.

Another way to prevent mold particles from entering the mold is by using filters. Two types of ceramic filters can be inserted into the runner system. One type of ceramic filter looks like a rectangular sponge. It is used to capture foreign particles in the molten metal passing through it. A simpler, less expensive type of filter consists of a group of holes in a rectangular ceramic brick. Both types of filters reduce erosion of the mold and gas absorption in the metal by creating a more laminar flow.

12.3.3 Mold Risers and Chills

To understand pattern and gating system design, it is important to appreciate the effects on the casting of metal shrinkage. Three types of metal shrinkage may occur during the casting process.

Liquid shrinkage results from the molten metal losing volume as its temperature drops and it approaches the solidification temperature. The shrinkage that occurs in the liquid metal is negligibly small and does not affect the process or the design of the feed system, because new metal constantly flows to fill the mold cavity. Solidification shrinkage occurs as the metal continues to cool and the liquid metal changes to a higher-density solid. This occurs at a single temperature for pure metals but takes place over a range of temperatures (called a freezing interval) for alloys. Metals and alloys with short freezing ranges, like pure metals and eutectic alloys, have a tendency to form large cavities as they shrink. Directional solidification can be used to combat this problem. This is accomplished by designing the feed system so that the metal furthest away from the feed gate freezes first and solidification continues toward the feed point, allowing the shrinkage void to be continuously filled as it is formed. The final void ends up in the gating system and not as a defect in the casting.

Alloys with a wide freezing range result in a mixed-state metal (partially solid and partially liquid) that does not flow so readily in the mold. As the cooler areas solidify, it is more difficult for new liquid metal to fill in the voids that form, which results in castings with a large number of small defects. This type of shrinkage is extremely hard to control through the design of the gating system, and a porous casting may be unavoidable. If an air-tight casting is required, then the metal may be impregnated with another material in a secondary operation.

Solid shrinkage, also called patternmaker shrinkage, occurs as the solid casting cools from its solidification temperature to room temperature. It is accounted for by making the pattern for the casting slightly larger than the desired product.

Sometimes, as mentioned in the introduction, an extra cavity is formed in the sand mold to hold a reservoir of molten metal. This cavity, called a riser, is located in the gating system of a casting to feed metal into voids that form during metal shrinkage. In order to accomplish this, the riser must solidify after the casting. Ideally, the mold cavity begins to solidify at the part that is farthest away from the riser and then continues toward the riser, so that liquid metal will always be available to fill in shrinkage voids. However, sometimes this is not possible, and multiple risers are needed. In this case, different sections of the casting solidify in the direction of their respective risers [3–7].

In addition to risers, elements called chills are sometimes used to produce sound castings. Chills are used to assist in directional solidification and may reduce the number of risers required to feed the casting. This is accomplished by increasing the speed at which parts of the casting solidify. External chills are made up of material that has a high heat capacity and high thermal conductivity. When these materials are placed next to the mold cavity, they promote directional solidification and thereby extend the distance that a riser may effectively feed. Internal chills are pieces of metal placed within the mold cavity to absorb heat and assist in increasing the solidification rate. They are usually more effective than external chills, but care must be taken since they ultimately become part of the casting.

12.3.4 Pattern Types

The patterns used to form sand molds may be made of wood, metal, or plastic. Draft, or taper, must be added to the vertical edges of the pattern so that it may be withdrawn from the sand mold without causing damage. The amount of draft depends on the type of pattern or type of sand mold. Patterns may have core prints (recesses in the mold to accommodate cores), runners, and risers included on the pattern plates so that these do not need to be formed separately.

The material used for patterns depends on the number of molds to be created from the pattern. Hardwood or plastic patterns may be used for a few thousand molds, while cast iron patterns may produce more than 100,000 molds [8]. For the highest-volume production automated casting lines, patterns are often made from stainless steel.

Patterns are commonly made in two pieces, or two halves, split along the parting line of the casting. The parting line is determined by the geometry of the part and must be chosen so that each pattern half may be withdrawn from the mold.

Alternatively, patterns may be mounted to opposite sides of a common board. This arrangement is called a match-plate pattern and provides consistency in mold making from a single former, since the board surfaces define the mold parting surface. A match-plate pattern has the advantage of being a single piece of tooling. It has the disadvantage that the two mold halves cannot be made simultaneously (see Figure 12.3).

12.3.5 Sand Compaction Methods

A sand mold is created by compacting sand around the pattern. It is necessary to pack the sand as densely and homogeneously as possible to obtain good detail and tight tolerances. For this reason, it is very uncommon for a mold to be compacted (rammed up) without some type of machine assistance. Molding machines greatly increase the quality of the mold produced and decrease the skill required of the operator [9]. These machines usually involve a combination of jolting and squeezing actions. Cope and drag machines, for example, begin by pouring sand into flasks mounted over the separate pattern halves. The flasks are then lifted and dropped several times to produce the jolt action. Then a squeeze head is used to further compress the sand. Next, the patterns are removed from the cope and drag. Finally, the cope is lifted, rotated 180° so that the cope impression is facing the drag impression, and then the cope is located onto the drag half by pins and bushings.

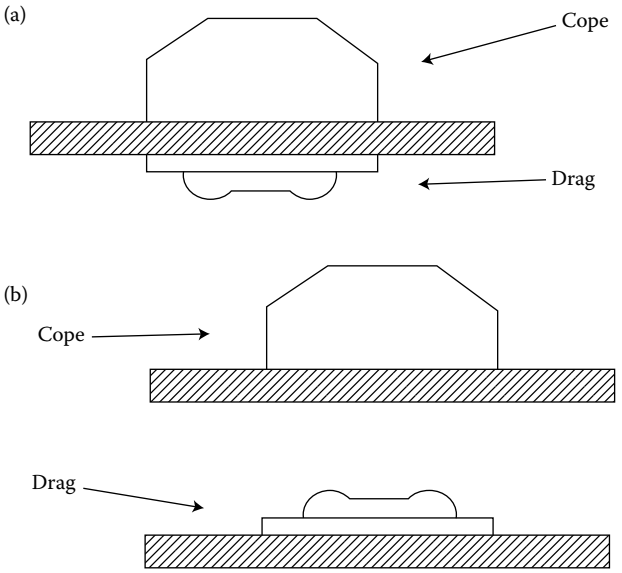

FIGURE 12.3
(a) Match-plate pattern; (b) separate cope and drag pattern plates.

Note that the jolt action tends to compress the sand most tightly nearest to the pattern. Squeezing has the opposite effect of compressing the sand most near the outside of the flask. The combination of these two actions thus produces more uniform sand density.

The most modern automated casting systems are referred to as vertically parted flaskless. Vertically parted flaskless molding is a break from traditional mold-making methods. As the name implies, no flask is used to contain the sand during molding. The machine uses hydraulic rams to simultaneously squeeze the cope pattern on one side of a sand block and the drag pattern on the other side. The block is then pushed out of the machine. A new block is then formed and mated to the original block (cores are inserted before closing if needed), creating a complete mold cavity at the interface. The molds form a long, rectangular block of sand coming out of the molding machine. A pouring station is located close to the molding machine. The interconnected molds then travel down a conveyer. The length of the conveyer depends on how long the castings need to cool before being broken out of the molds. A station at the end of the conveyer breaks the mold up, and the castings are separated from the sand. This process is more efficient, because a complete mold cavity is formed in each block of sand. Other methods, whether bench or molding transfer line, require separate cope and drag sections to produce one mold. Vertically parted flaskless molding is normally used for relatively simple castings, to be produced in large quantities, with a few, if any, cores.

12.4 Sand Cores

One of the most powerful aspects of sand casting is its ability to create internal cavities or exterior undercuts. This is done by using sand shapes, called cores, placed within the mold cavity. Coring allows forms to be produced that cannot be made using any other process. However, a casting designer needs to be aware that cores can significantly increase the cost of a casting, and their use should be avoided if possible.

When developing tooling for a casting, it is always more desirable to create a single large core instead of a number of smaller ones. This is because the labor involved increases proportionally with the number of cores, as does the likelihood of dimensional inaccuracies.

Modern core-making systems use air pressure to blow the sand, mixed with a resin or oil binding agent, from a hopper down into the core-making dies (called core boxes). In a typical core-making process, the cores are removed immediately from the core boxes and put on dryer plates. The cores are then baked in ovens until they attain the required strength. Alternatively, with the so-called hot box process, heated tooling is used to cure the cores in the die cavities. The hot box process may also be combined with subsequent baking in ovens to achieve final cured strength.

12.5 Melting and Pouring of Metal

The equipment used for melting the metal ingots varies from large cupolas for producing iron in bulk, to a variety of crucibles, electric furnaces, and induction furnaces [10]. The choice is simply a matter of economics and required production rates. Whichever method is used, the end result is liquid metal at the correct temperature for pouring. The

soundness of a casting is largely determined by how the metal enters the mold and solidifies. Therefore, the pouring and handling of the molten metal is an extremely important stage in the casting process. Inefficient handling can lead to excessive heat loss, resulting in premature solidification within the mold and incomplete filling. This is referred to as a cold shut. Faulty pouring can result in air entrapment producing cavities in the casting. This occurs most commonly if the sprue is not kept full during pouring. Short pours are another common example of faulty pouring technique [11].

The pouring operation may be done manually, with mechanical assistance, or automatically. In the case of a manual pour, the worker physically transports a ladle containing liquid metal to the mold and pours it into the mold. The amount of metal poured is limited by the individual's strength. Because of this limitation, hand pouring is usually reserved for low production quantities of small castings.

With mechanical assistance, a much larger cylindrical vessel (still called a ladle) is usually suspended from an overhead monorail system. The metal is poured by turning a handwheel, or by pulling a lever that causes the container to tilt until the metal runs out into the mold. Many more castings may be filled than with the manual method.

High-production foundries pour metal automatically. Instead of transporting the metal to the molds, the molds are transported to the pouring station. A predetermined amount of metal is then poured into the mold. This method allows most control over the delivery of the metal into the molds and, if initially designed and executed correctly, it produces castings with a high degree of consistency.

12.6 Cleaning of Castings

Once the casting has cooled, it must be cleaned before any final operations may be performed. Cleaning consists of the removal of all adhering sand from the casting together with the removal of the gating system and any flash (sometimes call fins in sand casting) of metal around the parting line. The techniques employed in cleaning, or shakeout, are described below [12,13].

Shakeout is the first stage of cleaning. Shakeout is a foundry term referring to a mechanical operation used to separate the casting from its mold. This should occur without damaging the casting and while keeping noise and dust emissions to a minimal level. An ideal shakeout should achieve the following:

- Separate the sand, casting, and flask
- Remove as much adhering sand from the casting as possible
- Clean the flask of all adhering sand
- Break large mold lumps

It is desirable to remove the casting from the mold as soon as possible, because the sand cores are harder to remove from the casting once they have cooled. However, in some cases the casting is left in the mold to keep it from cooling too quickly. In most modern foundries, shakeout is accomplished by using either vibratory or rotary drum systems.

Shakeout is usually followed by shot blasting. The shot blasting machine is used to provide the casting with a good surface finish and to remove any interior sand that is still

adhering to the casting. It is often the most expensive piece of cleaning room equipment in the foundry and is expensive to maintain. For this reason, it is important that as much sand be removed from the casting as possible before it is shot blasted. Adhering sand wears the wheel vanes and cups, shot blast liners, and dust collection systems, and creates a less pleasant working environment for the workers.

The abrasive metal shot is focused at concentrated areas, using either spinning wheels or concentrated air pressure to project it. The casting is moved through the shot blast streams on a conveyor, rotated on a fixture, or tumbled through the machine.

After the first stage of cleaning, called finishing, the next operation is to remove the gating system and any flashing from the castings. Optimizing the finishing process of a casting is very important, because up to 40% of the direct labor content of the casting can be accounted for in these final manual process steps.

Castings sometimes have to go through a grinding operation after the removal of gating and flash projections. This is done to remove unwanted surface protrusions such as the base of removed flash and gating system contact areas. Grinding operations may be done manually or by using automation. Manual grinding is usually done with handheld grinders on larger castings. Small castings may be ground using stand grinders and hand manipulation of the castings.

Fixed automation may be possible, depending on the part geometry and the nature of the material being removed. Using fixed automation, the part is held in a fixture and can be touched by several grinding wheels simultaneously. Well-designed coring for the casting can increase the feasibility of using automation. If the flash to be removed grows out from the casting surface, then grinding wheels can easily remove it. Flash growing sideways below the boundaries of the casting surface is very difficult to remove with automation. Such removal is almost always done manually. However, robots with small grinders can be programmed to follow the contour of pockets being cleaned.

For steel, cast iron, and some copper-based castings, chipping is still a common operation performed to remove the flash. Chipping is performed using pneumatic chisels to quickly cut away unwanted metal. A line of operators equipped with chippers is able to handle a wide variety of castings at the same time. This provides a great deal of flexibility, because several different castings can pass down the same line to be cleaned, but this flexibility is gained at the expense of more manual labor.

12.7 Cost Estimating

Determining the cost of producing a sand casting is a very complicated procedure, because of the large variations possible in the casting process. Accurate cost estimation is hindered by the amount of equipment involved, and the different combinations in which the equipment and processes may be linked. The cost estimation procedure presented here is divided into three main categories: metal cost, tooling cost, and processing cost.

12.7.1 Metal Cost

The melting department of a foundry represents a very important stage in the casting process. The foundry's ability to manufacture sound castings depends greatly on the chemistry of the metal produced in the melting department. Besides being the cornerstone

of the casting process, the melt department also represents a very substantial percentage of the cost of the finished casting. The melt department typically generates as much as 30–50% of the processing costs involved in sand casting.

The first step in determining the total metal cost is to calculate how much material is needed to produce the casting. An examination of a wide variety of castings was carried out [14] to determine the minimum risering and feeding requirements. Variations in the casting size were found to occur, due to differences in the feeding requirements for different metals and differences in the arrangement of impressions on the pattern plates.

It is not uncommon to produce siamese castings, where two symmetrical parts are produced as a single piece and are later separated (cut apart). Ideally, the combined dimensions of the siamese casting should be used in the feed calculations. However, this is an example of a foundry technique of which the part designer is unlikely to be aware. For such situations, the model used here overestimates the size of the gating system and thus gives a small cost overestimate.

It was found that the total casting weight could be predicted using only the final part envelope dimensions with accuracy within 15% of actual values [14]. The relationship for the poured casting weight obtained from this study [14] is

$$W_{\mathrm{p}} = \rho V_{\mathrm{fc}} \left[1 + 1.9 \left(\frac{(L+W)}{D} \right)^{-0.701} \right] \tag{12.1}$$

where

ρ = metal density, kg/m^3
V_{fc} = volume of metal in finished casting, m^3
L = part length, mm
W = part width, mm
D = part depth, mm.

Once the poured weight is estimated, the cost of the metal must be determined. The cost of the metal must include the cost of the raw material, the cost of the energy to raise the metal to the required pouring temperature, and the cost of operating the furnace and ancillary equipment. The sum of these costs gives the cost of poured metal, and is referred to as the cost of metal "at the spout." The steps involved in calculating the cost of metal at the spout are presented below.

Furnace energy cost, measured in dollars per kilogram, is given by

$$C_{\mathrm{en}} = \frac{E_{\mathrm{ct}} M_{\mathrm{me}}}{(F_{\mathrm{ff}}/100)} \tag{12.2}$$

where

E_{ct} = cost of electricity, \$/(kW h)
M_{me} = minimum melt energy, (kW h)/kg
F_{ff} = furnace efficiency.

Values of \$0.067 for E_{ct} (average industry price for September 2009) and 80% for F_{ff} can be used for typical U.S. foundry operations. M_{me} values for a range of typical casting metals are given in Table 12.2.

TABLE 12.2
Furnace Cost Data for Sand Casting Alloys

Generic Alloy	Density, kg/m³	Minimum Melt Energy (kW.h)/kg	Cost of Poured Metal, $/kg
Ductile iron	7110	0.391	0.38
Gray iron	6920	0.390	0.31
Malleable iron	7280	0.395	0.44
Carbon steels	7830	0.393	0.82
Stainless steel	7750	0.405	2.62
Aluminum	2710	0.326	2.02
Magnesium	1800	0.332	4.21
Bronze	8800	0.185	6.07
Nickel alloys	9250	0.341	14.08

In addition to the cost of energy, a fixed furnace cost is usually applied to cover the capital investment. This cost can be given by

$$C_{fk} = \frac{F_{fc}}{\rho} \tag{12.3}$$

where
F_{fc} = fixed furnace cost, $/(m³ of metal)
ρ = material density, kg/m³.

For a 1000 kg furnace a value for F_{fc} of $284/m³ represents a reasonable value for current calculations in the United States.

Finally, the labor cost for furnace operation, per kilogram of poured metal (C_{lk}), must be accounted for. This can be estimated for a foundry on a per shift basis—that is, the cost of furnace workers for one shift divided by the weight of metal poured per shift. A typical value for the furnace labor cost for a midsize automated U.S. foundry is $0.02/kg.

The cost of metal at the spout can thus be represented by

$$C_{ms} = C_{rm} + C_{en} + C_{fk} + C_{lk} \tag{12.4}$$

where
C_{rm} = cost of raw material (given in Table 12.1), $/kg.

For example, using the values of C_{rm}, M_{me}, and ρ from Tables 12.1 and 12.2 for gray iron gives

$$C_{ms} = \frac{0.22 + 0.067 \times 0.39 \times 0.8 + 284}{6920 + 0.02}$$
$$= \$0.31/kg$$

Calculated typical values of C_{ms} for the other metal categories are given in Table 12.2.

The cost of metal in a finished casting is higher than this value because of the wasted metal in the feed system as defined by Equation 12.1, and which has scrap value as given in Table 12.1. With this adjustment the cost of metal in a finished casting is given by

$$C_{mf} = \frac{\left(C_{ms}W_p - C_{cv}(W_p - \rho V_{fc})\right)}{(1 - S_g / 100)} \tag{12.5}$$

where

C_{ms} = cost of metal at the spout, \$/kg
W_p = weight of poured metal, kg
ρ = density of metal, kg/m^3
V_{fc} = volume of finished casting, m^3
C_{cv} = metal scrap value, \$/kg
S_g = percentage of scrap castings; typical 2%.

If, in cost-estimating procedures, the cost of metal ingot, C_{rm}, is used instead of C_{ms} in Equation 12.5, then the costs of energy and furnace operations are added to the costs of the other casting operations discussed in Section 12.4.7.

12.7.2 Sand Costs

The cost of new mold sand can range from \$13/ton up to \$35/ton depending on the fineness of the grain. This cost does not include the shipping cost, which is the major source of variation between supplier's prices. Transportation cost is important, because the characteristics of the sand can vary depending on the site at which it was mined.

Foundries are often willing to pay more for sand from the Midwest, because it has better grain characteristics than the angular sand from New Jersey, which requires more binding agents. The need for more binding agents adds expense and creates pollution problems that may justify the higher transportation costs from the midwestern site. Treated sand is considered a hazardous waste and disposal costs can vary from \$300 to \$500 per ton.

Sand must be properly conditioned with the appropriate additives to give it the desired molding properties. The sand must then be transported to the molding area to be used. After use, the sand is separated from the finished casting, transported back to the sand area, is cooled, and any impurities are removed before it can be reconditioned and used again. New grains, as well as binder additives, are added to the recovered sand before it is used again in the system.

Since the influence of the mold sand cost on the casting's manufacturing price is very slight, often less than 3% of the total manufacturing cost, a simple procedure determined from a survey of U.S. foundries is used. Based on this data [14], it appears that mold sand cost can be approximated as \$0.018/kg of metal poured. Thus, the cost of mold sand per part can be represented by

$$C_{msd} = 0.018 W_p, \text{ \$/part,} \tag{12.6}$$

Core sand is considerably more expensive than mold sand. This is because finer sand is necessary to produce cores strong enough to withstand the pressures of pouring metal.

From the same foundry data [14], an average cost for core sand was determined to be \$0.084/kg.

Cores are frequently damaged during processing, and the scrap rates can vary from 4 to 40%, depending on how delicate the core configuration is and on the type of core-making process being used. For the majority of cases a scrap rate of 8% provides a reasonable estimate. The cost of the core sand for producing a casting is then

$$C_{csd} = \frac{\rho_{cs} V_c C_{cs}}{(1 - S_c/100)} \tag{12.7}$$

where

ρ_{cs} = density of core sand, kg/m^3 (=1387)
V_c = volume of core, m^3
S_c = core scrap rate, % (=8% average)
C_{cs} = cost of core sand, \$/kg (=0.084).

12.7.3 Tooling Costs

The cost of tooling is usually determined in industry through comparisons with similar tools made in the past. The estimator, a tooling expert, then adjusts the cost of the new tooling depending on how much easier or harder the job being estimated is compared to the one previously completed. This is an unacceptable method for the present purposes, because the users of the model developed here should not have to be experts in the costing process. Therefore, an alternative method is presented in this section for determining the cost of the tooling. The cost equations given below assume that patterns and core boxes inserts are made from stainless steel, and the mounting plates are iron castings; typical for large production quantities. To determine costs for other tooling materials, appropriate for smaller production quantities, a global multiplier, or relative cost factor is applied to the final cost estimate, as discussed later.

The first step in determining the cost of the tooling is to determine the equipment on which the tooling is to be used. This information is needed to determine the size of the tooling and the number of castings that may be produced per hour. If the casting requires cores, then the cost of core boxes required to support the mold line's core requirements must also be calculated.

To determine the cost of the required pattern, it is necessary first to review some of the principles of pattern design. Pattern design is an art and cannot be easily broken down into a few rules of thumb. The rules presented in this section provide a conservative method for locating patterns on a base plate. However, these rules are not absolute and an expert may be able to violate them with impunity.

The first step in pattern layout is to decide where the pattern line would be on the casting. This determines the geometries that would be mounted to the cope and drag plates and is needed to determine the proper spacing between the patterns for multicavity molds. The designer also needs to remember that a feed system is necessary. While casting designers cannot be expected to design this system, they should leave room in areas that they would expect the feed system to pass through. Additional space must also be left for risers when necessary. Finally, core prints should be designed and located so that the cores may be held securely in place. The following rules are suggested in determining the layout of the pattern plates.

For thicker castings, pattern spacing should be equal to the adjacent section heights of the casting. For example, a 20 cm high casting may taper down to 10 cm at the edge adjacent to the location for another pattern. The spacing between the patterns should be 10 cm. For shallower castings, those less than 5 cm high, the spacing rule is increased to 2 times the adjacent section height. The spacing should never become less than 1.5 cm between two sections.

A distance of 2.5–10 cm should be kept between the pattern and the edge of the plate. The spacing varies depending on the size and type of equipment being used. For the purposes of this model, a distance of 5 cm is recommended. There should also be approximately 5 cm of spacing between the end of a core print and the edge of the plate.

The main arteries of the gating system should have 2.5 cm of sand surrounding them. However, it is allowable for the runner system to come closer to, or even to contact, a core print.

The layout of the core box cost is simpler than for the pattern plate. The cavities should be laid out so that the shallowest dimension is in the vertical plane. The recommended core box design rules are provided below.

Include the core prints when developing the layout of the die cavities.

Keep a 2 cm wall between cavities.

A border of approximately 5 cm is required on the sides of the box.

A border of 5 cm is required on the top of the core box and 2 cm on the bottom.

For early cost estimating, the application of a standard separation of 5 cm between patterns, cavities, or from plate edges simplifies the process without significant cost effects.

The cost of cast iron mounting plates for the pattern impressions, or for the core box cavity inserts, can vary from $1.30 to $4.40 per kilogram depending upon the quantity to be made [14]. For the purpose of this costing model, it is assumed that the castings are manufactured in large quantities and a figure of $4.40 per kilogram is used. The cost of machining and rigging a mounting plate costs about $0.05 per cm^2 of plate area. Assuming a typical 7.5 cm thick gray cast iron plate, and converting the cost per kilogram to cost per cubic centimeter, the cost of the required two mounting plates can be given by [14]

$$C_{pm} = (0.1 + 0.064h_p)A_{pl}, \$ \tag{12.8}$$

where

C_{pm} = cost of a pair pattern half mounting plates
h_p = plate thickness; typical 7.5 cm
A_{pl} = plate area for single or multiple impressions, cm^2.

Once the cost of the pattern base plate is known, the next step is to calculate the cost of the pattern impressions. This is done by rating the complexity of the casting outer surface, based on the number of surface patches. As for tooling estimates for net-shape processes covered in previous chapters, a surface patch is defined as a segment that is either planar or has a constant or smoothly changing curvature. The intersection of two surface patches appears as a rapid change in slope or curvature. The counting procedure is described below.

Count the equivalent number of surface patches, n_{sp}, that are formed by the pattern but ignore any that are created by a core. When multiple identical features are located on the surface of a part, a power index of 0.766, corresponding to an 85% learning or progress curve, can be used to estimate the savings in machining identical features. For example,

for a boss with 6 surface patches that appears 10 times on a casting, the total number of surface patches for all of the bosses would be calculated as $6 \times 10^{0.766} = 35$ instead of 60. This index is also used to obtain the complexity factor in the equation for determining the reduced cost of machining multiple identical impressions. The cost of a set of identical pattern impressions is then given by

$$C_{pi} = R_t \left(5 + 5.83(X^{1.27}) + 0.085A_p^{1.2}\right) n_{pi}^{0.766} \tag{12.9}$$

where

R_t = toolmaking (pattern shop) rate, \$/hour
$X = 0.1n_{sp}$ is the geometrical complexity as used in other chapters
A_p = projected area of the impression, cm^2
n_{pi} = number of identical impressions.

Consistent with other rates given in this chapter, a pattern shop rate of \$40 per hour should be used.

For high-volume production the gating system is formed by additional pattern impressions. The cost of the gating system appears to be based on several factors. The first is the type of metal being fed. For example, gray iron generally does not require risers, and so its gating system is easier to design and build than for other metals. Another factor is the number of cavities that must be fed and the distances between the cavities. A survey of pattern costs for an automated casting line [14] revealed that the cost of gating system impressions typically adds 20–35% to the cost of the pattern tooling. The more inexpensive the impressions, the higher the percentage of the final cost the gating system. Using a mid-range value of 25%, total pattern cost can be represented by

$$C_{pt} = G_f(C_{pm} + C_{pi}) \tag{12.10}$$

where

G_f = gate factor
= 1 for a manual casting process
= 1.25 for an automated casting line.

While patterns require the machining of the outer surface geometry of the part to be cast, core box cavities require the machining of the inner surface geometries to be cored. The machining tasks are essentially the same, and depend in the same way on the size and complexity of the surfaces. Thus, Equations 12.8 through 12.10 above for pattern costs, can be applied equally to core boxes and core cavities, but in this case using the projected area, $A_{p,}$ of the core, the number of surface patches of the core, and the number, n_c, of cavities in the core box. An added task for core boxes is the inclusion of both an ejection pin system in the lower half to release the core, and passages in the upper half for the sand to flow through as it is blown into the core chamber. The complexity of these additions increase as size and complexity of the core increases, and a 25% increase should be made to the estimate from Equations 12.8 and 12.10.

The total cost of a core box is thus

$$C_{box} = 1.25(C_{pm} + C_{cc}) \tag{12.11}$$

TABLE 12.3

Tool Life and Relative Costs

Pattern or Core Box Material	Relative Cost Factor, R_{tf}	Tool Life per Cavity
Wood	0.20	2,500
Plastic	0.35	5,000
Cast iron	0.85	150,000
Stainless steel	1.00	180,000

where

C_{pm} = the cost of the core cavity mounting plates [given by Equation 12.8, but using a plate depth h_p = core depth + 7.5 cm]

C_{cc} = the cost of the core cavity blocks [given by Equation 12.9, but using the geometry of the core].

For smaller production quantities the pattern impressions and core cavities may be made of cast iron, engineering plastics, or wood. The costs for producing tooling from alternative materials can be approximated using the relative tooling costs in Table 12.3. Estimates of tool costs using Equations 12.10 and 12.11 are simply multiplied by the appropriate value of the relative tool cost factor R_{tf}.

Table 12.3 also provides information on the number of cycles for which a piece of tooling may be used before it is replaced. The data are for one pattern impression or one core box cavity. For example, the predicted production life of a four-cavity cast iron core box is 600,000 cores.

12.7.4 Processing Costs

Processing costs are broken down into three main categories: the cost of producing the cores, the cost of producing the molds and pouring the metal, and the cost of cleaning the castings.

There are a large number of variables in determining the cost to produce a core. The cost of the core is affected by its size, which affects the ecoonomic number of cavities per box and, therefore, the core machine production rate. The production rate of the machine largely depends on the type of core-making process employed. The type of core-making process and the design of the core influence the scrap rate. The core scrap rate can vary from 4% for a simple core to 40% for a very delicate core.

Some cores call for a refractory coating, which requires equipment and manpower to coat the cores and then bake them to dry the coating. All of these factors combine to form a formidable challenge to obtaining accurate estimates of individual core costs. It is typical, for estimating purposes, for the average weight of cores produced by the core shop per hour to be divided into the number of core process workers. This gives a production rate for the core shop expressed in core kilograms per worker hour. The cost of processing a particular core is then given by

$$C_{core} = \frac{\rho_{cs} V_c R_{cm}}{\left[P_{cm}\left(1 - S_c/100\right)\left(P_{ff}/100\right)\right]}, \$ \tag{12.12}$$

where
ρ_{cs} = density of core sand = 1387 kg/m^3
V_c = volume of core, m^3
P_{ff} = plant efficiency, % (actual production time/total available time) × 100; typical 85%
R_{cm} = worker rate for core making; (use \$50/h with other provided costs)
P_{cm} = core production rate; typical 53 kg/h/worker
S_c = core scrap rate; typical 8%.

From a survey of several large foundries [14], an average production rate for cores was found to be approximately 53 kg/worker-hour, with an associated burdened labor rate of \$50/h. The cost advantage of multicavity core boxes is not as significant as for other molding processes because of the secondary operations involved in removing flash, adding coatings, and curing. For approximate cost estimating, Equation 12.12 can be used irrespective of the configuration of the core box. As discussed earlier, when considering the cost of core sand, a scrap rate S_c of 8% is reasonable for early costing purposes.

The molding area costs are easier to determine than those of the core area, because there are fewer variations in the processing system. This is because the molding machine can be modeled as a transfer line. The mold area contains a variety of operations. However, since the majority of the operations take place on the mold line, the processing cost is based on the number of molds and corresponding castings produced per hour, the number of workers required to support the line, and a burdened labor rate per worker. A typical cope and drag casting line in the Midwest requires 21 workers to achieve a production rate of 285 molds per hour, 13.6 molds per worker per hour. The burdened rate per worker on this line is \$208 per hour. The casting scrap rate, like the core scrap rate, can vary widely depending on the geometry of the part and the type of metal poured. From a survey of a number of foundries [14], it was found that a value of 2% is reasonable for early cost estimating. The mold line processing cost per casting can be given by

$$C_{mp} = \frac{R_{mp}}{\left[N_c P_{mp}\left(1 - S_m/100\right)\left(P_{ff}/100\right)\right]} \tag{12.13}$$

where
R_{mp} = worker rate for molding line production, \$/hour
N_c = number of mold cavities
P_{mp} = molding line production rate; basis for costing = 13.6 molds/worker/hour
S_m = casting scrap rate; typical 2%
P_{ff} = plant efficiency; typical 85%.

It should be noted that the rate, R_{mp}, of \$208/h is for a large midwestern foundry capable of supplying large castings, with sizes in the region of 60 × 60 cm, at high production rates. The large capital equipment to provide this capability results in the very high burdened labor rate. A survey of smaller automated foundries in other parts of the United States [14] suggests that an appropriate rate for R_{mp} for high-volume production of medium-sized castings at the same production rate per worker, with sizes in the region of 20 × 20 cm, is approximately \$95/h. For early cost estimating we assume a linear

relationship between part size and burdened worker hourly rate, for the same mold production rate, given by

$$R_{mp} = 38.5 + 1.413(L + W),\ \$/h \tag{12.14}$$

where

L = part length or envelope length surrounding the set of cavities, cm
W = part width or envelope width surrounding the set of cavities, cm.

The final operation on the mold line is to remove the castings from the mold. This is usually accomplished by using a ram to push the sand mold out of the flask and to break the mold apart. The mold sand is reclaimed, and the castings are transported to the cleaning department.

The cost of cleaning a casting is mainly based on size and the geometry of the part. However, the type of material cast and the process employed also affect the ease with which the casting may be cleaned.

Cleaning a casting is the most labor-intensive job in the foundry. Even with the aid of automation to remove the gating system and scale from the casting, there can still be a substantial amount of manual work. Chippers and grinders are used to remove the flash and feed system contact area. Of course, the level to which this is done depends on how important the flash removal is. In some cases, the level of finish of the casting is not critical and cost savings can be realized.

The major cost driver in the cleaning process is the casting's geometry. The length of the parting line determines the amount of flash that must be removed. If the part is cored, then the flash formed around the cored openings in the casting must also be removed. However, other factors also affect the cleaning time. Some castings require more reorientations to clean the flash lines than others do, and the time to carry out these reorientations is based on the dimensions and the weight of the casting.

Deep pockets and small openings in a casting also create cleaning problems. A casting with large internal cavities and small holes can create very difficult problems. This is because the sand inside the casting is often not completely broken down and cannot, therefore, be easily removed.

A survey of a large number of castings suggests that the total labor time for cleaning castings (including sand removal, runner system and flash removal, and shot blasting) is approximately proportional to the square root of the casting weight. Regression analysis of casting data from a midsized automated foundry provided the following relationship for cleaning labor time.

$$T_{cl} = 88.4(W_p^{0.44}),\ s/\text{casting} \tag{12.15}$$

The cleaning cost is then given by

$$C_{cl} = \frac{R_{cl}T_{cl}}{3600} \tag{12.16}$$

where

T_{cl} = total cleaning time, s
R_{cl} = worker rate for cleaning room; (use \$37.5h with other provided costs)
W_p = poured casting weight, kg.

12.8 Design Rules for Sand Castings

A report written for the North Atlantic Treaty Organization (NATO) [15] states that the primary factor in the selection of sand casting is cost reduction. However, the most important factor in determining the cost of a casting is the design. The study states that the cost of a casting can "easily be doubled by factors controlled by the designer."

The following design rules are taken from industry handbooks [16–18]. Castings certainly can be produced that do not adhere to these design rules. However, this is always at the expense of increased scrap and possibly large increases in production cost.

12.8.1 Avoid Sharp Angles and Multiple-Section Joints

Metal structure is affected by the shape of the casting section. Solidification of the molten metal begins at the mold face, from which crystals grow into the casting at right angles. A straight section of constant thickness (see Figure 12.4a) results in uniform cooling, which

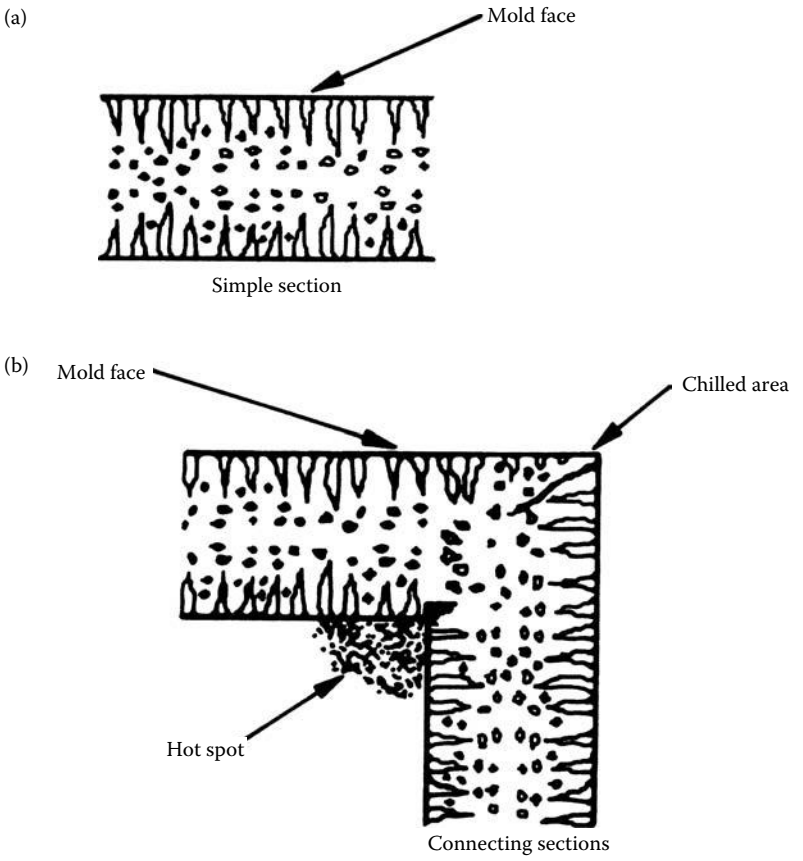

FIGURE 12.4
(a) Constant casting thickness with uniform cooling; (b) effects of nonuniform cooling caused by abrupt section changes.

in turn produces uniform material properties. On the other hand, sharp angles can cause large temperature variations in the casting, which often lead to casting defects. Hot spots result where the free cooling of the casting is interrupted as parts of the sand are loaded with more energy than other areas. Also, chilled areas arise on external corners from being exposed to two cooling planes (see Figure 12.4b). The resulting grain structure is not homogeneous and, in particular, weak areas in the casting are created in the areas where the cooling rate is excessive.

A well-designed casting brings the minimum number of sections together at intersections and avoids acute angles. Wherever a number of sections converge, the appropriate solution is to create a large hole like the center of a web. Examples of good and bad section configurations are shown in Figure 12.5.

12.8.2 Design Sections of Uniform Thickness

Design the casting so that all of the section thicknesses are as consistent as possible. This promotes even cooling of the casting, reducing the likelihood of defects. If larger masses of metal are unavoidable, the designer should make them accessible for feeding either directly or with a riser.

Designing for uniform thickness also reduces the amount of material in a casting, saving weight and reducing machining, and results in a stronger casting. However, if section thicknesses are too small, then feeding problems may occur. The increased cost of scrap caused by incomplete feeding (caused by metal freezing and blocking the section from being completely filled) is normally higher than the material savings in a lighter casting. The economical minimum section thicknesses of different metals to be sand cast are listed in Table 12.4.

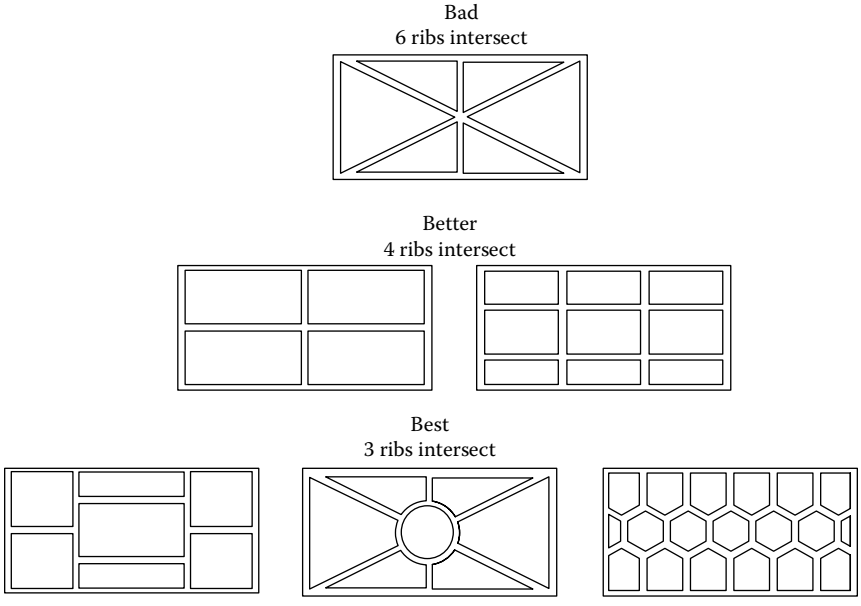

FIGURE 12.5
Examples of good and bad section configurations. (Adapted from Customers Foundry Orientation Manual, Robinson Foundry, Alexander City, AL, 1989.)

TABLE 12.4

Minimal Economical Section Thicknesses for Different Section Lengths, S_L

Generic Alloy	Thickness for Section Length 2.5 cm or Less (mm)	Thickness for Section Length between 2.5 and 15 cm (mm)	Thickness for Section Length Greater than 15 cm (mm)
Ductile iron	4.8	12.5	19.0
Gray iron	4.0	9.5	19.0
Malleable iron	3.3	6.4	14.0
Carbon steels	8.0	12.5	25.0
Aluminum	4.0	8.0	16.0
Magnesium	4.0	8.0	16.0

12.8.3 Proportion Inner Wall Thickness

Inner sections in a casting cool more slowly than a section exposed to the mold face. If a complex geometry is necessary, the designer should reduce the inner section thickness to 80% of the outer wall thickness. Also, core section thicknesses should always be greater than the section thickness of the surrounding metal. If the core is too small, it becomes overheated and slows down the solidification rate of the surrounding metal, leading to the possibility of defects.

12.8.4 Consider Metal Shrinkage in the Design

Almost all alloys shrink as they solidify. While the patternmaker is the one affected by the shrinkage, the designer must still compensate for it in the design. In a good design, the section thicknesses decrease as the distance from the feed system or riser increases. In order to accomplish this, the designer must be familiar enough with the casting process to be able to visualize how the casting is to be fed and adjust the casting's dimensions to assist the metal flow. The greater the shrinkage of the metal, the more the designer must consider it when designing the casting. Table 12.5 lists the shrinkage of several of the commonly cast alloy groups. The amount of shrinkage depends upon the precise carbon content for irons and steels and varies over the ranges shown.

12.8.5 Use a Simple Parting Line

A flat plane, known as a straight parting line separating the two mold halves, results in more economical casting than a tiered or contoured separating surface. More complex

TABLE 12.5

Shrinkage Allowances of Casting Alloys

Generic Alloy	Linear Shrinkage (%)
Gray iron	0.83–1.3
Malleable iron	0.78–1.0
Carbon steels	1.6–2.6
Aluminum	1.3
Magnesium	1.3

parting lines often result in fewer parts per mold, more costly patterns, less accuracy, and increased scrap. Also, the parting line should be positioned so that it has minimal effect on the functional characteristics of the part.

Locating the parting line in less critical parts of the casting is desirable for two main reasons. First, dimensions around the parting line are the hardest to control. Additionally, flash occurs at the parting line. If the surface around the parting line is not critical, then flash removal costs will be lower.

12.8.6 Define Appropriate Machining Allowances

The machining allowance is the material added to the casting to compensate for dimensional and surface variations in the as-cast part. The amount of stock added is a function of the size of the surface to be machined and to a lesser degree the machining method and the final accuracy required. Minimal additional material is needed if only flatness, possibly with some unmachined surface areas, is desired. A larger allowance is required if the full surface is to be machined without any imperfections. Normal machining allowances vary from 0.25 cm for small castings (<15 cm) to as much as 2.5 cm for large castings (>250 cm).

12.8.7 Use Economical Tolerances

The tolerances achievable by a foundry vary depending on the types of processes employed at the facility. For example, automated molding machines are capable of producing molds with tighter tolerances than might be produced by hand. Conservative tolerances which are readily achievable by most foundries and are therefore the most economical are used in the following discussion.

Tighter tolerances may be obtained by machining, which significantly increases the cost of the casting.

The most basic tolerance is the linear tolerance. It refers to how precisely the distance between two points can be produced. Linear tolerances of ±1.0 mm are readily achievable for small castings. An increase of ±0.03 mm should be allowed for every centimeter over 15 cm for larger parts.

An additional tolerance must be added to the linear tolerance of a dimension that passes through or originates from the parting surface. These additional tolerances reflect variations caused by expansion and contraction of the mold, the metal during solidification, patternmaking tolerances, and vibration of the pattern during removal from the mold. The size of the additional tolerance depends upon the projected area of the casting at the parting surface. The typical tolerance assignment is ±0.25 mm for each 10 cm^2 of projected area.

Cores create tolerance variation because of the clearance that is necessary for their placement into the mold. The features produced by the core surface can be held to a tighter tolerance than the features produced by the mold surface, because cores are stronger and able to be produced to tighter tolerances than the mold. However, the surface produced by the core may be displaced from the surface created by the mold because of core shift. The additional tolerance for core shift varies with the projected area of the core normal to the dimension being considered. The recommended value is the same as for the additional parting line tolerance given above.

The following list shows the tolerances that must be applied to the different dimensions for the part in Figure 12.6.

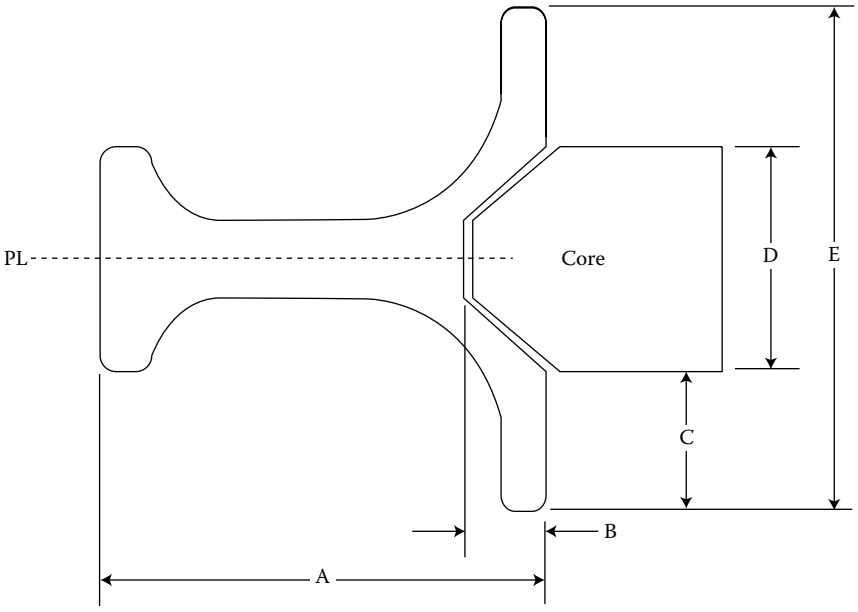

FIGURE 12.6
Appropriate tolerances for a cored casting.

A: linear tolerance
B: linear + core location tolerances
C: linear + core location tolerances
D: linear tolerance
E: linear + parting line tolerances.

12.9 Example Calculations

A concept sketch of a pump body is illustrated in Figure 12.7. It is to be manufactured from cast carbon steel, and a total of 10,000 are required. It is proposed that the bodies be made on a cope and drag casting line using single-cavity molds. The equations in Section 12.7 are used to provide initial estimates of the part cost and required tooling investments.

Part and core dimensions to be used in these calculations are:

Part	Core
Finished part volume $V_{fc} = 438$ cm^3	Core volume $V_c = 683$ cm^3
Part projected area $A_p = 222$ cm^2	Core projected area $A_{pc} = 222$ cm^2
Part length $L = 250$ mm	Core length $L_c = 250$ mm
Part width $W = 150$ mm	Core width $W_c = 150$ mm
Part depth $D = 50$ mm	Core depth $D_c = 50$ mm

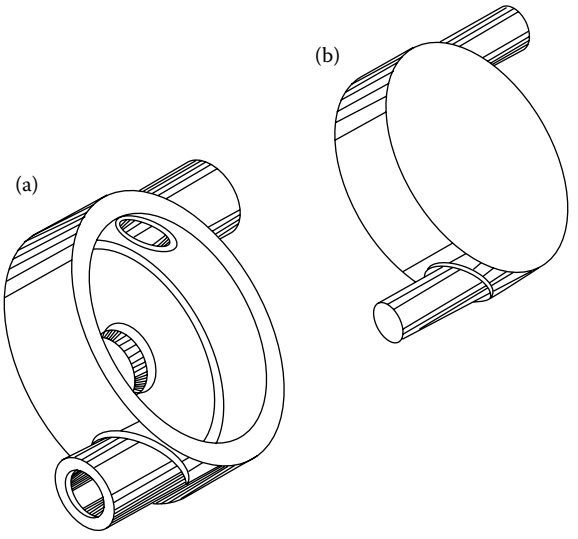

FIGURE 12.7
(a) Pump body casting; (b) casting core.

CASTING MATERIAL COST CALCULATIONS

From Table 12.2, the density of carbon steel is 7833 kg/m^3 and substituting into Equation 12.1, with appropriate unit conversion, gives the weight of poured metal per part

$$W_p = 7833 \times (439/10^6)\left(1 + 1.9\left(\frac{400}{50}\right)^{-0.701}\right)$$

$$= 4.95 \text{ kg}$$

The minimum melt energy from Table 12.2 is 0.393 (kw.h)/kg, and using the suggested values of E_{ct} = \$0.035/(kw.h) for electricity cost and E_{ff} = 80% for furnace efficiency, gives furnace energy cost from Equation 12.2 as

$$C_{en} = \frac{0.035 \times 0.393}{0.8}$$

$$= \$0.017/kg$$

The fixed furnace cost to cover capital investment is given by Equation 12.3, using F_{fc} = \$284/m^3

$$C_{fk} = \frac{284}{7833} = \$0.036/\text{kg}$$

Together with an ingot cost C_{rm} = \$0.73/kg (from Table 12.1), and the suggested furnace labor cost C_{lk} = \$0.02/kg, the cost of molten carbon steel at the spout is estimated to be

$$C_{ms} = 0.73 + 0.019 + 0.036 + 0.02 = \$0.82/\text{kg}$$

The weight of the finished casting, after removal of the feed system, is

$$W_{fc} = pV_{fc} = 7833 \times \left(\frac{438}{106}\right) = 3.43\text{kg}$$

Thus, the cost of metal per finished part, from Equation 12.5, using steel with scrap value C_{cv} = \$0.09/kg and scrap rate S_g = 2%, is

$$C_{mf} = \left(\frac{0.82 \times 4.95 - 0.09 \times (4.95 - 3.43)}{1 - 0.02}\right)$$
$$= \$4.00/\text{part}$$

MOLD AND CORE SAND COSTS

The estimated cost of mold sand per part is given by Equation 12.6:

$$C_{msd} = 0.018 \times 4.95 = \$0.09/\text{part}$$

Now turning our attention to the material cost of the cores, the volume of the single core illustrated in Figure 12.6 is V_c = 683 cm^3. Using the cost of core sand C_{cs} = \$0.084/kg, core sand density ρ_{cs} = 1387 kg/m^3, and a core scrap rate S_c = 8%, then Equation 12.7 gives the estimated cost of core sand per part to be

$$C_{csd} = 1387 \times (683/10^6) \times \frac{0.084}{(1 - 0.08)}$$
$$= \$0.09/\text{part}$$

CORE AND MOLD MANUFACTURING COSTS

We next estimate the core and mold processing costs in order to determine the likely part cost. The weight of each core to be used in casting a pump body is

$$W_c = 1387 \times (683/10^6) = 0.95 \text{ kg}$$

Using the typical values for core production given in Section 12.7.4, the processing cost per core is given by Equation 12.12:

$$C_{core} = \frac{0.95 \times 50}{(53 \times (1 - 0.08) \times 0.85)}$$
$$= \$1.15$$

It is assumed that the pump bodies are to be made in an automated foundry in the United States for which an appropriate rate R_{mp} is given by Equation 12.114 as

$$R_{mp} = 38.5 + 1.413(25 + 15) = \$95/\text{hour}$$

Equation 12.13 then gives the process cost per casting as

$$C_{mp} = \frac{21 \times 95}{(285 \times (1 - 0.02) \times 0.85)}$$
$$= \$8.40$$

CLEANING COSTS

Finally, the cost of cleaning the casting, and for removal of metal flash and the runner system, is given by Equations 12.14 and 12.15. Using the recommended value of $R_{cl} = 25\$/\text{hour}$

$$C_{cl} = 25 \times 88.4 \times \frac{4.95^{0.44}}{3600}$$
$$= \$1.24/\text{casting}$$

PIECE-PART COST

The piece part cost for the cast part comprises the total material and processing costs. From the preceding calculations these costs have been estimated to be

$$\text{Material cost} = 4.00 + 0.09 + 0.9$$
$$= \$4.18$$

$$\text{Processing cost} = 1.15 + 8.40 + 1.24$$
$$= \$10.79$$

$$\text{Piece part cost} = 10.79 + 4.18 = \$14.97$$

PATTERN AND CORE BOX COSTS

We now proceed to estimate the cost of the required tooling. Using a spacing of 5 cm between the impressions and the edge of the pattern plates, as recommended in Section 12.7.3, the area of the pattern plates is given by

$$A_{pl} = (25 + 2 \times 5)(15 + 2 \times 5) = 875 \text{ cm}^2$$

Thus, from Equation 12.8 the cost of the standard 7.7 cm thick pattern mounting plates is estimated to be

$$C_{pm} = (0.1 + 0.064 \times 7.5)(875) = \$508$$

The number of surface patches, which make up the pump body, equals 12; 5 for the main body, 3 for each side hollow projection, and 1 for the bottom cylindrical hole. Thus, complexity $X = 1.2$.

Using $A_p = 222$ cm^2 (the value given at the beginning of this example), and $R_t = \$40$/h, the cost of manufacture of the pattern impressions is given by Equation 12.9 as

$$C_{pi} = 40(5 + 5.83 \times 1.2^{1.27} + 0.085 \times 222^{1.2}) = \$2718$$

Thus, the cost of the two pattern plates, for the cope and drag flasks, manufactured from cast iron with stainless steel impressions, is given by Equation 12.10 as

$$C_{pt} = 1.25(508 + 2718) = \$4302$$

The core, illustrated in Figure 12.7, has a projected area in the vertical direction of 175 cm^2. The length, width and depth of the core are 25, 13.4, and 4.2 cm, respectively. The area of plates required to mount the cavity and core inserts is given by

$$A_{pl} = (25 + 2 \times 5)(13.4 + 2 \times 5) = 819 \text{ cm}^2$$

The required thickness of the plates for the cavity inserts is

$$h_p = 4.2 + 7.5 = 11.7 \text{ cm}$$

Thus, from Equation 12.8 the cost of core box plates is estimated to be

$$C_{pm} = (0.1 + 0.064 \times 11.7)(819) = \$695$$

The number of surface patches, which make up the core, equals 6; 3 for the main body and 2 for each side projection. Using $A_p = 175$ cm^2 in Equation 12.9, the cost of cavity and core inserts is estimated to be

$$C_{pi} = 40(5 + 5.83 \times 0.6^{1.27} + 0.085 \times 175^{1.2}) = \$1993$$

Thus, the cost of the core box, manufactured from cast iron with stainless steel cavity inserts, is estimated from Equation 12.11 to be

$$C_{box} = 1.25(1993 + 695) = \$3361$$

Hence, the total tooling investment is $4032 + 3361 \simeq \$7{,}500$

Finally, the tooling investment may be amortized over the total number of pump bodies to be produced to give

$$C_{tc} = \frac{7500}{10{,}000} = \$0.75$$

where C_{tc} is the tooling cost per casting.

PROBLEMS

For the problems below, use casting metal data from Tables 12.1 and 12.2, and the production data provided with the Equation variable definitions in Section 12.7.

1. Figure 12.8 shows a large Idler Arm, which is part of the mechanism on a construction machine, and is to be sand cast using malleable iron. A total production volume of 2000 castings are anticipated. The three large holes are to be cast into the part; the axial bore requiring a cylindrical core. Secondary machining operations are to be carried out to finish machine the three holes including the key slot, mill the faces of all the bosses and drill the smaller cross bore. Pattern and core dimensions are to be adjusted to leave material for the finish machining but this will not affect the cost estimating for the casting.

The basic geometry of the part and the core are given below:

Part:	**Core (for axial bore):**
Finished part volume V_{fc} = 16,100 cm^3	Core volume V_c = 1,861 cm^3
Part projected area A_p = 1,188 cm^2	Core projected area A_{pc} = 258 cm^2
Part length L = 80 cm	Core length L_c = 28 cm
Part width W = 30 cm	Core width W_c = 9.2 cm
Part depth D = 22 cm	Core depth D_c = 9.2 cm
No. of surface patches = 42[a]	No. of surface patches = 3

[a] Allowing for repeated features.

Obtain estimates for the following:

a. The cost of the malleable iron in the casting.
b. The mold and sand core costs per part.

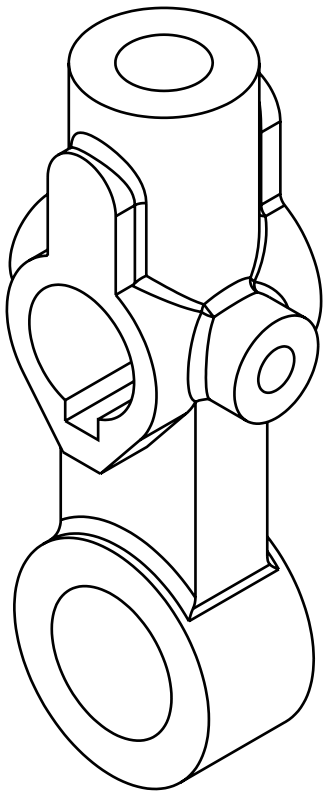

FIGURE 12.8
Idler Arm construction machine component.

c. The cores and casting manufacturing costs
d. The casting cleaning cost
e. The piece part cost

2. For the Idler Arm described in Problem 1, determine,
   a. The likely cost of the pattern
   b. The likely cost of the core box required to make the axial core
3. Figure 12.9 illustrates a Machine Bracket which is to be sand cast in stainless steel. The part is to be manufactured at a midsize automated foundry and the part can be manufactured in pairs in their standard mold size. The layout to be used is shown in Figure 12.10. The two cores required to make the transverse bores in each casting are 1.8 cm diameter, with lengths 7.4 cm and 10 cm. respectively. Note that the cores project beyond the casting to sit in core prints in the mold impression.
   The basic geometry of the part is given below:

Finished part volume $V_{fc} = 55.6$ cm^3
Part projected area $A_p = 54.8$ cm^2
Part length $L = 19.0$ cm
Part width $W = 6.0$ cm
Part depth $D = 3.0$ cm
No. of surface patches = 48[a]

[a] Allowing for repeated features.

   a. Estimate the likely cost of the pattern for the two-cavity mold (use an 85% learning curve for the repeated pattern impression, and use your estimated length and with of the envelope surrounding the pair of impressions (Figure 12.10) to estimate the cost of the plates).
   b. The likely cost of the two core boxes.

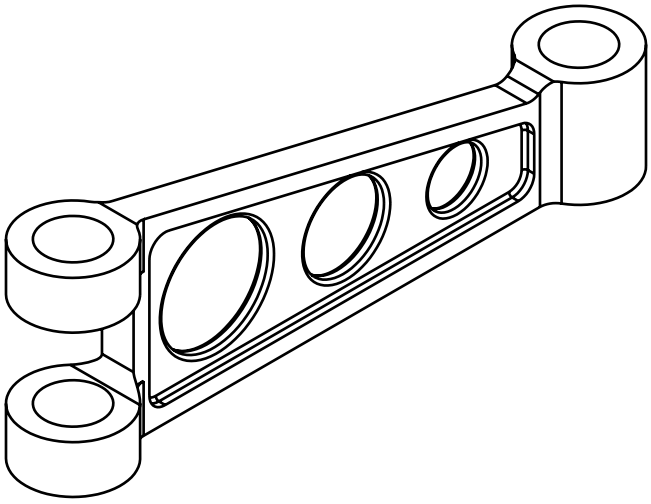

FIGURE 12.9
Machine Bracket.

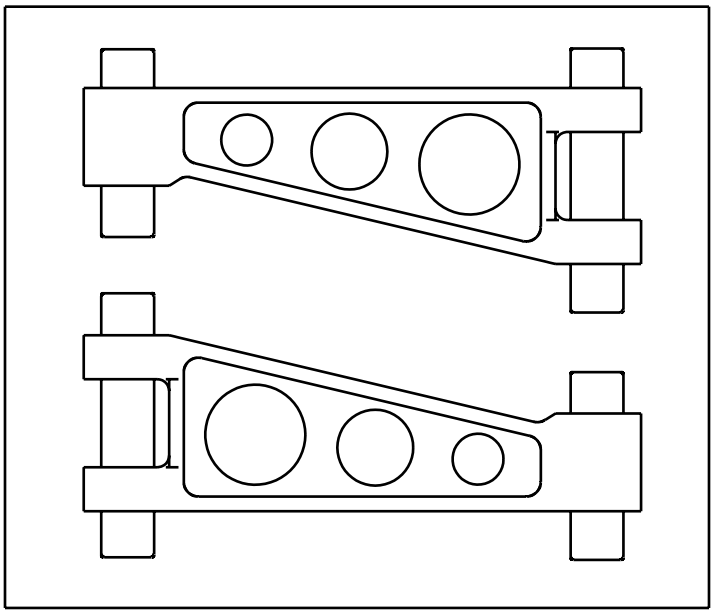

FIGURE 12.10
Two cavity layout, showing finished castings with cores in position.

4. For the Machine Bracket described in Problem 3, determine,
   a. The cost of the stainless steel in the casting.
   b. The mold and sand core costs per part (allow for the two pattern impressions per plate in appropriate equations).
   c. The cores and casting manufacturing costs
   d. The casting cleaning cost
   e. The piece part cost

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13

Design for Investment Casting

13.1 Introduction

The investment-casting process is capable of producing complex castings with tight tolerances and superior surface finish and can meet the highest performance standards, such as in aircraft jet engine applications. Other advantages of the process include the ability to cast materials that are impossible to forge and difficult to machine and to produce prototypes through direct machining of wax patterns.

Investment casting is a uniquely flexible process for making parts of high complexity, and it is therefore ideally suited to reduced part count designs—one of the main objectives of design for manufacture and assembly (DFMA).

There are two types of investment-casting processes: solid mold investment casting and ceramic shell mold investment casting. The two processes differ primarily in the way the mold is formed. In the "solid" mold process, the wax or plastic pattern is placed into a container, and mold material is poured around the pattern, solidifying into a solid block. In the "shell" process, the pattern is dipped or "invested" in the mold material, leaving a coating of uniform thickness. The coating is allowed to dry and the dipping process is repeated. The multiple coats form a hard ceramic shell mold. The ceramic shell mold process described in this chapter is the major form of investment casting for engineering applications.

13.2 Process Overview

A simplified representation of the ceramic shell mold investment-casting process is shown in Figure 13.1. The process starts with the fabrication of a wax or plastic pattern. The pattern has the same shape as the final cast part, but with dimensional allowances for the shrinkage that occurs during the casting process. Usually a number of patterns are then assembled into a cluster. The cluster includes all the necessary gates and runners for providing metal flow to each pattern in the assembly. The completed cluster is invested (dipped) into a ceramic slurry, removed, and then covered with a stucco material. Investing and stuccoing is repeated a number of times. The investing and stuccoing build up a shell around the pattern cluster. Once the ceramic shell mold is completely dry, the pattern is melted out leaving cavities in the shape of the parts. The mold is fired to reach its final strength and, while the mold is still hot, molten metal is poured into the cavity and allowed to solidify. The mold material is then knocked off the casting and the parts are separated.

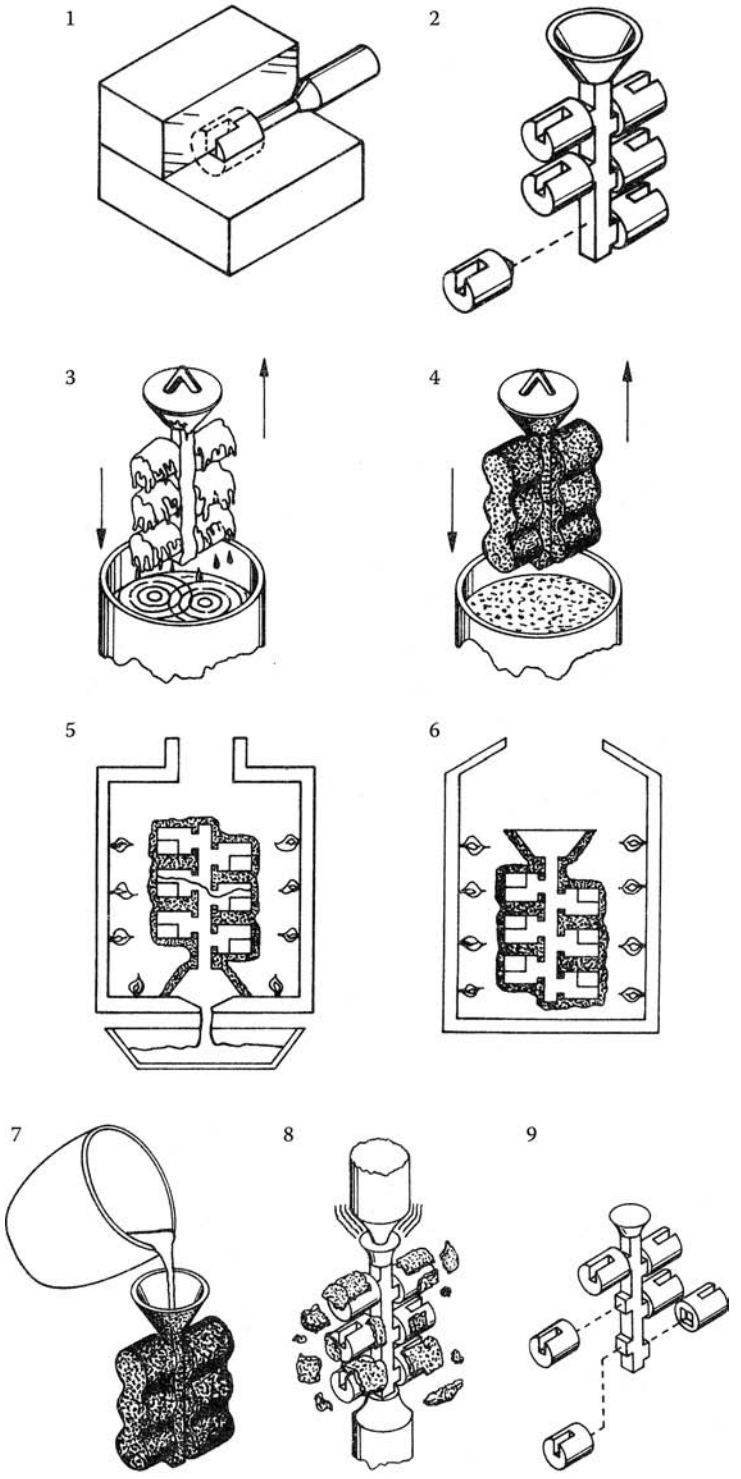

FIGURE 13.1
Simplified ceramic shell mold investment-casting process.

13.3 Pattern Materials

Patterns for investment casting are injection-molded of either wax or plastic. Paraffin and microcrystalline waxes are the most common base materials for patterns [1].

Their low melting points and low viscosity make waxes easy to mold into patterns, assemble into clusters, and melt out of shell molds without damaging the mold. Since waxes can be injected at low pressure and temperature, and have low abrasiveness, tooling costs are low.

The strength and toughness of pattern waxes can be improved by the addition of plastics; solidification shrinkage of the patterns is reduced by the addition of resins and powdered solid fillers. Other additives are used in wax blends for various purposes. Dyes are added to allow different wax formulations to be distinguished by color. Antioxidants are added to help reduce thermal degradation. Oils and plasticizers are added to adjust injection properties [1].

After wax, plastic is the next most favored material for patterns—polystyrene being the most common. Plastic patterns are strong and resist damage when extremely thin sections are required in the cast part. However, the tooling for plastic patterns is more expensive than for wax.

13.4 Pattern Injection Machines

Investment-casting patterns are usually made by injecting wax or plastic into metal molds. Wax is injected in a liquid, slush, paste, or solid form. Typical injection temperatures range from 43 to 77°C (110°F to 170°F) and injection pressures from 275 kPa to 10.3 MPa (40–1500 psi). Liquid wax injection takes place at the higher temperature and lower pressure ends of the ranges, while solid wax injection is done using lower temperatures and higher pressures. Simple equipment for wax injection consists of a pneumatic unit with a closed, heated tank of wax, as shown in Figure 13.2. The tank has a thermostat, pressure regulator, heated valve, and nozzle. Shop air provides the pressure needed. A metal mold is held to the nozzle with one hand, while the other hand operates the valve. Units of this type are usually limited to less than 690 kPa (100 psi) and only inject liquid wax. Equipment like this is used on a large variety of small parts [1].

Patterns that cannot be made on simple equipment because of size, complexity, dimensional requirements, or quantity, are made on hydraulic machines (Figure 13.3). Hydraulic machines can use higher injection pressures that improve injection time and quality. They allow the use of larger molds and higher injection pressures and are readily available in a range from 9.1 to 363 Mg (10–400 tons) clamping force [1].

Hydraulic machines with manual or semiautomatic modes of operation typically have horizontal platens. The lower platen is stationary and holds the lower half of the mold. The other platen moves vertically, holding the upper mold half, and is forced down to clamp the mold shut prior to injection of the wax. With semiautomatic machines the operation is automatic except that the pattern is removed manually. Automatic hydraulic machines typically have vertical platens. One platen is fixed while the other slides back and forth to open and close the mold, and the pattern is automatically ejected.

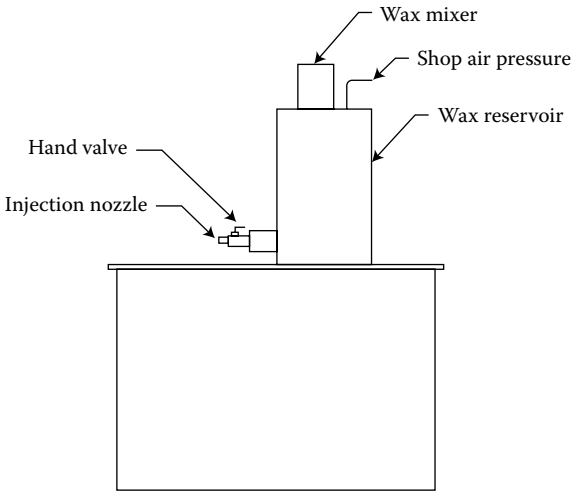

FIGURE 13.2
Simple investment-casting pattern injection equipment.

Hydraulic machines usually have a reservoir for liquid and slushy wax. The wax must be continuously mixed to keep it uniform and to keep any solids in suspension. Some facilities have central wax supplies. Machines used for paste wax injection receive their supply of wax from a removable metal cylinder containing preconditioned wax. The wax is injected as a piston forces the wax out of the cylinder. Solid wax injection uses preconditioned wax billets loaded into the machine. Both paste and solid injection machines require separate baths or ovens for preconditioning or pretempering of the wax cylinders or billets.

Polystyrene patterns are produced using standard plastic injection molding machines as described in Chapter 8.

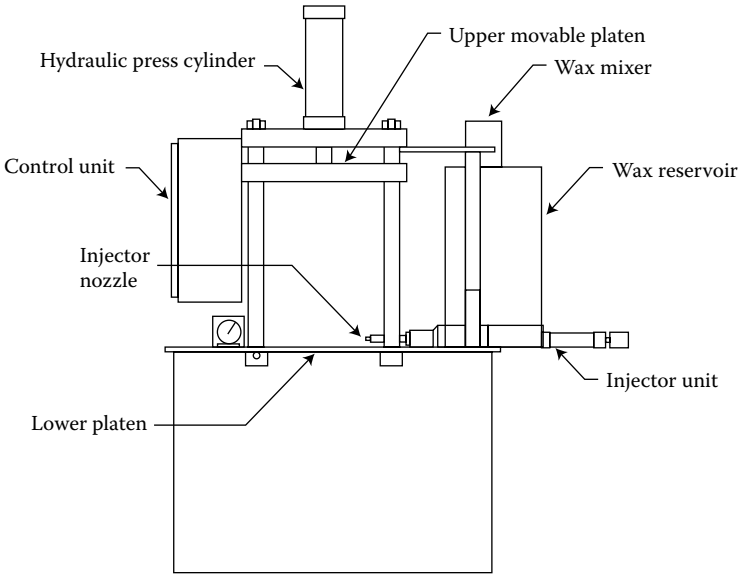

FIGURE 13.3
Hydraulic pattern injection machine.

13.5 Pattern Molds

Most molds for molding patterns are manufactured by machining the part form directly into the mold. Aluminum is the most widely used material for wax injection molds, whereas tool steel is most frequently used for plastic injection molds. Molds for wax patterns last indefinitely but those for plastic patterns wear and require replacement after 1 million cycles or so.

13.6 Pattern and Cluster Assembly

The majority of patterns are injected in one piece with gates attached. Large size or complexity may require a pattern to be made up of several pieces. The pieces may be all wax, all polystyrene, or a combination of the two. When small, delicate details are required on parts too large to be made as one-piece plastic patterns, fine plastic details may be assembled to a larger wax pattern.

Once the individual pattern assembly is complete, the metal feeding system made up of the required runners, sprue, and pouring cup is added. Smaller parts are processed in clusters when a number of patterns share the same feeding system. The number of patterns on a given cluster varies according to part size and process limitations.

Most assembly of patterns, feeding systems, and clusters is done by hand. Wax components are assembled by wax welding. This is done by melting the joining surfaces with a hot iron, spatula, or small gas flame. The two wax pieces are pressed together until the wax solidifies, welding the two components together.

Once the cluster or individual part is fully assembled, it must be cleaned. The cluster must be free of dust, loose wax, and mold lubricant. The cluster is sometimes lightly etched to promote adhesion of the ceramic mold slurry.

13.7 Ceramic Shell Mold

The cluster or single pattern assembly is dipped into ceramic slurry and then covered with stucco particles. The ceramic slurry contains very small particles and is capable of reproducing the fine detail and smooth surface finish from the pattern. The slurry also contains a binder that gives strength to the mold. The stucco particles prevent the slurry from cracking and pulling away when drying; they also help to provide adhesion between coats and help build mold thickness. Each mold layer, consisting of one slurry application followed by one stucco coat, is allowed to harden prior to adding the next layer. Layers are added until the required thickness or mold strength is reached.

The three most commonly used refractories for ceramic shell molds are silica, zircon, and aluminum silicate, and they are usually used in combination [1].

Silica is used in the form of silica glass or fused silica. It is made by melting natural quartz sand, solidifying it into glass, and then crushing it into various size particles for stucco and into fine powder for slurry mixes. Since it can be readily dissolved, it can

be easily cleaned from those cavities of finished castings that cannot be cleaned by mechanical methods. Zircon is natural sand, ground into powder for slurry mixes, and is usually used in combination with fused silica. Where used for stucco, zircon is used only for primer coats. It does not come in sizes large enough to be used as backup coat stucco. Aluminum silicates contain 42 to 72% alumina, with the balance being silica.

Slurries require the addition of a binder to give them strength. The most common binders are hydrolyzed ethyl silicate, colloidal silica, and sodium silicate [1].

Dipping, draining, and stuccoing of patterns or clusters can be done manually, robotically, with hard automation, or by a combination of the methods. Robots are increasingly being used for making shell molds [1]. They increase productivity, provide the ability to process larger parts or clusters, and produce more uniform coatings.

When dipped into the primer slurry, the cluster is manipulated in the slurry tank to guarantee that all surfaces and cavities are coated with slurry. The cluster is continually rotated and manipulated to make sure that the slurry coats the cluster evenly. After the excess slurry has drained off, the cluster is covered with stucco particles to stop any further runoff of slurry.

Stucco particles are applied by either dipping the cluster in a fluidized bed or rotating the cluster under falling particles from an overhead screen. Primer slurries have a finer refractory powder and are stuccoed with finer particles than the following backup layers. This is to provide as smooth and as detailed a representation as possible of the pattern surface and to help resist metal penetration. The primary function of backup coats is to provide the necessary strength in the mold to survive pattern meltout and metal pouring. Usually, one or two primer coats in addition to the first coat are applied. The total number of primer and backup coats is within the range of 5–15 [1].

13.8 Ceramic Cores

Cores are widely used in investment casting. The two basic categories of cores are self-forming cores and preformed cores.

Self-forming cores are formed by the mold-making process. The internal passages are already present in the wax pattern. The self-forming core is produced when the pattern is dipped into the ceramic slurry that fills the internal passages. The cavities for self-forming cores are produced by two different methods. One method is the use of core pulls in the pattern mold. The other is by using soluble wax cores placed in the pattern mold prior to wax injection. After wax is injected around the soluble wax core, the pattern is removed from the mold and the soluble core is dissolved out of the pattern. Soluble wax cores are made of solid polyethylene glycol with sodium bicarbonate or calcium carbonate used as a filler powder. The cores are usually dissolved out in an aqueous acid solution that does not attack the base wax used for the pattern body [1]. When openings are large enough to allow ceramic molding slurry complete access to internal cavity features, self-forming cores are preferred. They are used extensively in small hardware castings [1]. When access to internal features is restricted, preformed cores must be used.

Preformed ceramic cores require their own molds and are usually injection-molded in a process in which fine refractory powder is mixed with an organic vehicle and injected into hardened steel molds. The injected mixture is very abrasive and limits mold life. After forming, cores are heat treated in a two-stage process. In the first stage, the organics are

removed and in the second stage the cores are sintered to achieve their final strength and dimensions [1]. Preformed ceramic cores are usually placed in the pattern mold and wax is injected around them.

13.9 Pattern Meltout

The thermal expansion of the waxes used for patterns is many times that of the mold materials. To reduce the tendency for mold cracking, molds are heated very quickly, so that the surface of the pattern melts before the temperature of the main body of the pattern rises appreciably. As the pattern heats up and expands, the melted surface layer is squeezed out of the mold, making room for the expanding pattern and preventing the mold from cracking [1].

The primary methods used for melting patterns from molds are steam autoclave dewaxing and high-temperature flash dewaxing, with steam autoclave dewaxing being the most common method. Saturated steam with rapid pressurization to 550–620 kPa (80–90 psi) is used. Full pressure is attained in 4–7 s [1]. Molds are dewaxed in about 15 min depending on the size of the mold. The wax can be recovered for reuse.

In flash dewaxing, the mold is placed in a furnace at 870°C to 1095°C (1600°F to 2000°F). The furnace has an open bottom to allow the wax to collect outside of the furnace as it pours out of the mold. Some of the wax burns as it falls from the furnace. This means that wax reclaimed by this method is somewhat deteriorated. Polystyrene patterns are also removed from molds by this method [1].

13.10 Pattern Burnout and Mold Firing

After pattern meltout, the mold is fired to remove any remaining free or chemically bonded moisture and to burn out any remaining pattern material. Any organic material used in the slurry is burned off and the mold is sintered. Sometimes the mold is allowed to cool for inspection and a separate preheat cycle is done just prior to metal pouring. Batch- or continuous-type gas furnaces are most often used for mold firing, burnout, and preheat. Burnout and sintering temperature is between 870°C and 1095°C (1600°F and 2000°F) [1].

13.11 Knockout and Cleaning

After the casting has cooled, it must be freed from the mold. This is referred to as knockout. The mold is usually broken off using a vibrating pneumatic hammer. Shot blasting is used to remove any mold material stuck to the part surface. The blasting operation is done both manually and on automatic cycles [1].

If cores need to be removed, the entire cluster is dipped into a molten caustic bath where the cores are dissolved.

13.12 Cutoff and Finishing

After the mold has been cleaned, risers and gates must be removed. For a cluster of parts, each part must be cut from the cluster at its gates; then any separate risers need to be cut off. Materials such as aluminum, magnesium alloys, and some copper alloys are cut off using band saws. Abrasive wheels are used to cut off other copper alloys, steels, ductile iron, and superalloys. Brittle alloys may be knocked off with a hammer if notches were provided in the gates. Cutting torches are used when gates are not accessible to the other methods. After cutoff, abrasive wheels and belts are used to grind the gate stubs flush.

13.13 Pattern and Core Material Cost

There are hundreds of different wax pattern and core materials available. Table 13.1 lists material properties and costs for polystyrene and for some typical wax blends used for patterns. Table 13.2 lists the common applications for these pattern materials, and Tables 13.3 and 13.4 present the same information for core materials. The material costs given in these tables include allowances for typical order quantities and for conditioning of waxes before delivery to the wax injection machine.

The material cost for a pattern or core, C_{pm} ($), is given by

$$C_{pm} = \frac{D_{pm} M_{cp} V (1 + S_a)}{1000} \tag{13.1}$$

where

D_{pm} = density of the pattern or core material, g/cm^3
M_{cp} = pattern or core material cost per unit weight, $/kg
V = volume of the part, cm^3
S_a = volume shrinkage allowance for the cast metal.

TABLE 13.1

Pattern Material Properties

Pattern Material	Density (g/cm^3)	Thermal Diffusivity (mm^2/s)	Inject Temp. (°C)	Eject Temp. (°C)	Mold Temp. (°C)	Inject Pressure (MN/m^2)	Cost ($/kg)
Polystyrene	1.59	0.090	218	77	27	96.5	1.12
Wax 1: liquid	0.99	0.092	65	50	25	1.4–3.4	3.09
Wax 2: liquid	0.97	0.092	67	50	25	1.4–3.4	2.87
Paste	0.97	0.092	60	50	25	1.4–3.4	2.87
solid	0.97	0.092	49	48	25	2.7 min	2.87
Wax 3: liquid	1.00	0.092	68	50	25	1.4–3.4	3.17
Wax 4: liquid	1.13	0.092	64	50	25	1.4–3.4	2.45
paste	1.13	0.092	58	50	25	1.4–3.4	2.45
solid	1.13	0.092	51	50	25	2.7 min	2.45
Wax 5: liquid	1.00	0.092	64	50	25	1.4–3.4	4.74

Source: Compiled from an industry source of pattern materials and Chapter 8.

TABLE 13.2

Pattern Material Applications

Material	Description
Polystyrene	Plastic. For use in very small or fragile parts required in large quantities
Pattern wax 1	Nonfilled. Liquid injection. For thin-walled parts. Good in applications requiring cores. Good for aircraft castings requiring superior surface finish
Pattern wax 2	Nonfilled. Liquid, paste, or solid injection. For thin-walled parts. Low brittleness. Good where pattern tooling has many loose or moveable pieces. Commonly used in commercial applications
Pattern wax 3	Filled. Liquid injection. Good for patterns with fragile cores. Can be used in thin- or thick-section patterns. Good for aircraft castings requiring superior surface finish
Pattern wax 4	Filled. Liquid, paste, or solid injection. For parts with heavy sections, or thick as well as thin walls. Commonly used in commercial applications
Pattern wax 5	Nonfilled. Liquid injection jewelry wax. Superior surface finish. Easy to repair. Very flexible. May be milled or filed without chipping

Source: Compiled from an industry source of pattern materials and Chapter 8.

TABLE 13.3

Core Material Properties

Core Material	Density (g/cm^3)	Thermal Diffusivity (mm^2/s)	Inject Temp. (°C)	Eject Temp. (°C)	Mold Temp. (°C)	Inject Pressure (MN/m^2)	Cost ($/kg)
Soluble: liquid	1.00	0.092	67	50	25	1.4–3.4	3.66
solid	1.00	0.092	52	51	25	2.7 min	3.66
Silica ceramic	1.60	0.110	232	52	27	140	1.00

Source: Compiled from an industry source of core materials and Chapter 8.

TABLE 13.4

Core Material Applications

Material	Description
Soluble wax	For liquid or solid injection. Dissolved out of cluster prior to investing in ceramic slurry
Silica ceramic	Fused silica-based. For most applications. Silica can be leached out of the casting. Assumed to have a polyethylene or wax-based organic vehicle for injection

Source: Compiled from an industry source of core materials.

Typical metal shrinkage allowances, S_a, are presented in Table 13.5. It is assumed that the material in the gate and runner systems is formed from recycled wax.

EXAMPLE

The part shown in Figure 13.4 is to be cast in phosphor bronze. It has a volume of 3.326 cm^3 and two holes perpendicular to the direction of forming. These holes could be formed by side-pulls in the mold—one on each side. The cost for the type-2 liquid wax material in the pattern is

$$C_{pm} = \frac{0.97 \times 2.87 \times 3.326(1 + 0.04)}{1000} = \$0.00963$$

TABLE 13.5

Volume Allowances for Solid Contraction of Metals

Metal or Alloy	Shrinkage (%)	Metal or Alloy	Shrinkage (%)
Aluminum alloys	3	Magnesium bronze	6
Aluminum bronze	6	Copper nickel	6
Yellow brass	4	Nickel	6
Gray cast iron	3	Phosphor bronze	4
White cast iron	6	Carbon steel	5
Tin bronze	5	Chromium steel	6
Lead	8	Magnesium steel	8
Magnesium	6	Tin	6
Magnesium alloys (25%)	5	Zinc	8

Source: Adapted from Royer, A. and Vasseur, S., *Centrifugal Casting, ASM Handbook, Vol. 15, Casting*, ASM International, Metals Park, OH, 1988.

13.14 Wax Pattern Injection Cost

The first factor to be determined is the size of the injection-molding machine and, hence, the rate. The clamp force is a key factor in this determination and its estimation is covered in Chapter 8 for plastic injection molding. The data for wax injection machines is given in Table 13.6.

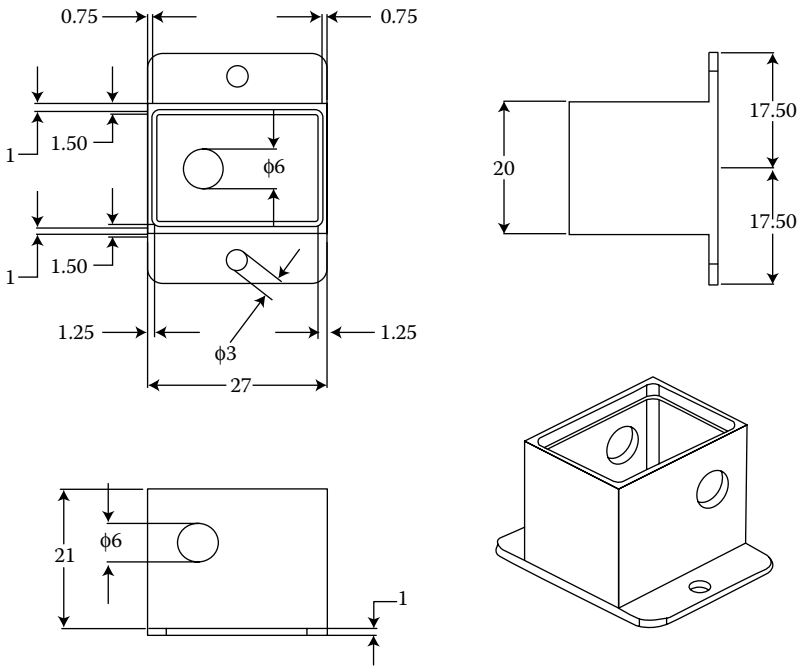

FIGURE 13.4
Sample part (dimensions in mm).

TABLE 13.6

Wax Injection Machine Data

Clamping Force (kN)	Shot Size (cm^3)	Opening Speed (cm/s)	Closing Speed (cm/s)	Maximum Clamp stroke (cm)	Maximum Flow Rate (cm^3/s)
107	1,885	2.54	2.54	38.1	82
311	1,885	2.54	2.54	51.1	82
445	1,885	2.54	2.54	51.1	82
890	18,275	3.81	3.18	863.6	82
1,334	18,375	2.54	2.54	1371.6	82
2,670	37,697	2.54	2.54	863.6	82

Source: Compiled from 1994 industry supply literature.

For plastic injection molding, it was assumed that because of the restrictions of runners and gates, the pressure in the mold is about 50% of the injection pressure. With wax injections these restrictions do not cause a significant pressure drop, and so the pressure in the mold is assumed to be equal to the injection pressure.

The total projected shot area, A_s, (cm^2), is given by

$$A_s = n_{pd} A_p (1 + P_{rv}) \tag{13.2}$$

where

n_{pd} = number of patterns (cavities) per mold
A_p = projected area of one part in the molding direction, cm^2
P_{rv} = proportion of the runner volume.

The shot size and proportion of the runner volume is assumed to be the same as that for plastic injection molding. Approximate values are given in Table 8.2.

EXAMPLE

(i) The projected area for our example part is 8.88 cm^2 and roughly extrapolating the data in Table 8.2, the proportion of runner volume would be about 60%. Assuming two parts (cavities) per mold, Equation 13.2 gives a total projected shot area of

$$A_s = 2 \times 8.88 \times (1 + 0.6) = 28.42 \text{ cm}^2$$

(ii) The recommended injection pressure P_i for liquid wax 2 is, on an average, 2.4 MN/m^2 and thus the maximum separating force, F, is given by the shot area times the injection pressure.

$$F = (28.42 \times 10^{-4}) \times 2.4 \times 10^6 \text{ N} = 6.82 \text{ kN}$$

If the available wax injection machines are those listed in Table 13.6, the smallest machine is easily large enough for our example part. This machine would take a shot size of 34 cm^3, has a clamp stroke of 20 cm, and is more than adequate.

13.15 Fill Time

Liquid wax flows easily under very low pressure; even when solidified in the mold, it flows by shearing with relative ease. Unlike plastic injection, we can assume that the flow rate remains at the maximum value of 82 cm^3/s (Table 13.6). The mold fill time, t_f (s), is given by

$$t_f = \frac{V_s}{Q_{mx}} \tag{13.3}$$

where
V_s = required shot size, cm^3
Q_{mx} = maximum wax injection flow rate, cm^3/s.

EXAMPLE

The shot size for our two-cavity mold would be about three times the pattern volume, or roughly 10 cm^3. Thus, the estimated fill time would be

$$t_f = \frac{10}{82} = 0.122\,s$$

13.16 Cooling Time

Unlike plastic injection-molded parts, which are generally thin-walled, patterns for investment casting may also be thick-walled or cylindrical. For a thin-walled pattern, the approximate cooling time given by Equation 8.5 can be used where it is assumed that heat flow is perpendicular to the part wall.

Figure 13.5 shows the three different conditions considered here. In Figure 13.5a, the thin-walled section, heat flow is perpendicular to the section, in Figure 13.5b heat flows perpendicular to the length and width of the section, and in Figure 13.5c heat flows radially from the surfaces of the cylindrical section.

The following Equations are used for the cooling time, t_c(s):
for thin-walled sections

$$t_c = \frac{h_{max}^2}{9.87\alpha} \ln \frac{1.273(T_i - T_m)}{(T_x - T_m)} \tag{13.4}$$

for thick-walled sections

$$t_c = \frac{l_s^2 w_s^2}{9.87\left(l_s^2 + w_s^2\right)\alpha} \ln \frac{1.62(T_i - T_m)}{(T_x - T_m)} \tag{13.5}$$

for solid cylindrical sections, where $L/D > 1$

$$t_c = \frac{d_{max}^2}{23.1\alpha} \ln \frac{1.6(T_i - T_m)}{(T_x - T_m)} \tag{13.6}$$

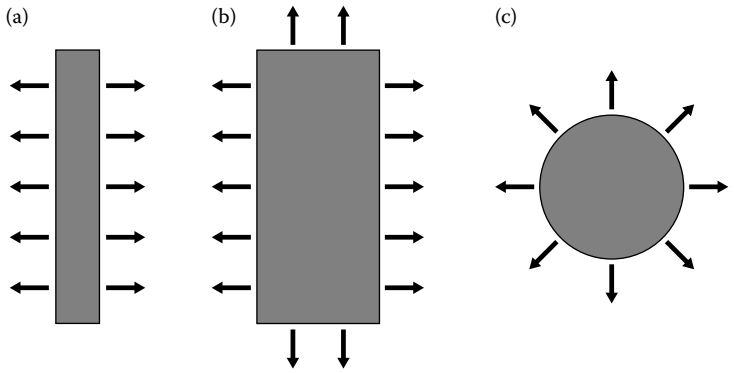

FIGURE 13.5
Cooling sections.

where
h_{max} = maximum wall thickness, mm
l_s = section length, mm
w_s = section width, mm
d_{max} = maximum section diameter, mm
α = thermal diffusivity, mm²/s
T_i = injection temperature, °C
T_m = recommended mold temperature, °C
T_x = recommended pattern or core ejection temperature, °C.

The cooling times given by these Equations can be used without correction for plastic, liquid wax, or paste wax injection. For solid wax injection, the Equations overestimate the cooling time, and correction factors of 0.46, 0.6, and 0.49 should be applied to Equations 13.4 through 13.6, respectively.

EXAMPLE

Our example part is thin-walled with a maximum thickness of 1.5 mm. Thus, the cooling time is given by

$$t_c = \left[\frac{1.5^2}{(9.87 \times 0.092)}\right] \ln\left(\frac{1.273(67-25)}{(50-25)}\right) = 1.884\,\text{s}$$

13.17 Ejection and Reset Time

The ejection and reset time for semiautomatic wax injection is handled differently for wax patterns than for plastic injection molding. The machine open and close times, t_{oc} (s), can be estimated by dividing the required stroke distance by the respective speeds given in Table 13.6 and adding a 1 s dwell time. Thus,

$$t_{oc} = (c_f h_d + c_h)\left(\frac{1}{\upsilon_c} + \frac{1}{\upsilon_o}\right) + 1 \tag{13.7}$$

where
c_f = pattern clearance factor
h_d = pattern depth, cm
c_h = hand clearance, cm
υ_c = press closing speed, cm/s
υ_o = press opening speed, cm/s.

The pattern clearance is from one to two times the thickness of the pattern and the hand clearance is about 10 cm.

For semiautomatic mold operation, the wax pattern is usually removed manually by reaching into the opening mold halves. The ejection time is the time it takes the operator to reach into the mold, pick up the wax pattern, remove the pattern, place it on the work bench, and press buttons to initiate the next cycle. It is assumed that the operator reaches into the mold as the mold still opens. It takes about 2 s for an operator to remove the pattern and initiate the machine cycle by pressing the palm buttons. If a core needs to be placed in the mold, it takes about 3 s per core of additional time. About every 10 cycles the mold is sprayed with a release agent such as silicon. This operation takes about 4 s, or 0.4 s per cycle.

The total reset time, t_r(s), for semiautomatic pattern injection can now be determined by adding the ejection time to the open and close time:

$$t_r = t_{oc} + 0.4 + (3n_c + 2)n_{pd} \tag{13.8}$$

where
n_c = number of cores per pattern to be placed in the mold
n_{pd} = number of patterns (cavities) per mold.

EXAMPLE

From Table 13.6 the press closing and opening velocities are 2.54 cm/s. We assume a pattern clearance factor of 2 to remove the 2.2 cm deep pattern from the mold. Thus, the machine open and close time is

$$t_{oc} = (2\times 2.2 + 10)\left(\frac{1}{2.54} + \frac{1}{2.54}\right) + 1 = 12.34\,\text{s}$$

and since there are two patterns and no cores in the mold, the total reset time is

$$t_r = 12.34 + 0.4 + (3\times 0 + 2)2 = 16.74\,\text{s}$$

For manual molds, the ejection time and reset time is slightly different. The mold is assumed not to be fastened to the injection machine platens. The mold is slid into place on the lower platen and against the injection nozzle. Then the operator hits the buttons to activate the injection cycle. The upper platen need only travel about a centimeter to allow the mold to slide. The open and close time is then

$$t_{oc} = 0.5\left(\frac{1}{\upsilon_c} + \frac{1}{\upsilon_o}\right) + 1 \tag{13.9}$$

Ejection of the pattern is accomplished manually for manual hand molds. First the mold halves must be separated. Any side-pull-type cores or inserts must be removed and the mold reassembled. The palm buttons can now be hit to initiate the next cycle.

To estimate the time to accomplish manual mold ejection, 15 s is allowed for sliding the mold in and out of the press, separating and replacing the mold halves, removing the part from the mold, and pressing the palm buttons. The time to remove and replace each side-pull insert is estimated at 4 s per insert. If there is a lifter-type device, 6 s is allowed. An unscrewing device is given 10 s. Silicon spray mold release is applied about once every five cycles. Equation 13.10 can be used for estimating the total reset time, t_r(s), for a manual mold with one pattern

$$t_r = t_{oc} + 15.8 + 3n_c + 4n_{sp} + 6n_l + 10n_{ud} \tag{13.10}$$

where

n_{sp} = number of side-pulls per pattern
n_l = number of lifters per pattern
n_{ud} = number of unscrewing devices per pattern.

EXAMPLE

For a hand mold, the open and close time would be

$$t_{oc} = 0.5\left(\frac{1}{2.54} + \frac{1}{2.54}\right) + 1 = 1.4\,\text{s}$$

and the total reset time, for one pattern per mold and two side-pulls, is

$$t_r = 1.4 + 15.8 + 3\times 0 + 4\times 2 + 6\times 0 + 10\times 0 = 25.2\,\text{s}$$

13.18 Process Cost per Pattern or Core

The total cycle time, t_t(s), can be found by adding together the three times: injection time, cooling time, and reset time. Thus,

$$t_t = t_f + t_c + t_r \tag{13.11}$$

Finally, the process cost per pattern or core, C_{ip} ($), is the cycle cost divided by the number of patterns per mold:

$$C_{ip} = \frac{M_i t_t}{(3600 n_{pd})} \tag{13.12}$$

where

M_i = machine and operator rate, $/h (obtained from Table 13.7 or 13.8).

The combined machine and operator rates in Tables 13.7 and 13.8 were calculated by assuming machine and operator overheads of 100%. The hourly labor rate was taken to be $11.50/h.

TABLE 13.7

Wax Injection Machine Rates

Clamping Force (kN)	Machine Cost ($)	Combined Operator and Machine Rate ($/hr)
107	31,000	30
311	43,000	31
445	51,000	33
890	83,000	38
1334	143,000	47
2670	220,000	58

Source: Compiled from 1994 industry supply literature.

EXAMPLE

The total cycle time for semiautomatic operation is

$$t_t = 0.122 + 1.884 + 16.74 = 18.75\,\text{s}$$

and for a machine and operator rate of $30/h, the process cost per pattern is

$$C_{ip} = 30 \times \frac{18.75}{(3600 \times 2)} = \$0.078$$

13.19 Estimating Core Injection Cost

The cost to inject soluble wax cores is the same as for wax patterns. Ceramic cores are different. They require higher pressures and the machines are more expensive. Machine rates are given in Table 13.8. Reset and ejection time should be handled like wax patterns. Cooling and injection times are similar to those for plastic patterns and should be estimated using the techniques for the injection of plastic parts. Ceramic cores require additional processing after injection before they can be used in a wax pattern. They must undergo a two-stage heat treatment. The first is a potentially lengthy process to remove the organic injection vehicle. The second stage is a sintering process to give the core its final strength. Ceramic cores can also have a high scrap rate. A scrap rate of between 10 and 15% can be assumed. They can break at ejection from the mold during heat treatment or handling.

TABLE 13.8

High-Pressure Ceramic Core Injection Machine Rates

Clamping Force (kN)	Machine Cost ($)	Combined Operator and Machine Rate ($/h)
667	90,000	39
1423	160,000	49

Source: Compiled from 1994 industry supply literature.

13.20 Pattern and Core Mold Cost

Methods for the estimation of the cost of plastic injection molds are presented in Chapter 8. Molds for wax pattern and cores are similar to plastic injection molds. However, because of the lower pressures and temperatures required for wax patterns and because aluminum can be used for the molds instead of steel, the cost is much lower than that of plastic injection molds.

Wax patterns can be made using semiautomatic molds or manual hand molds. For the purposes of estimating the mold base cost for wax pattern injection using semiautomatic molds, it is assumed that the mold base consists of two sets of plates made of aluminum. The mold base cost C_b (\$) can be estimated using the following equation:

$$C_b = C_{vp} + C_{fp}$$

where C_{vp} (\$) is the cost of the plates containing the core and cavity and is given by

$$C_{vp} = 0.0215 h_p A_c + 0.428 A_c n_{pl} + 14.27 h_p + 32.18 n_{pl} \tag{13.14}$$

and where C_{fp} (\$) is the cost of the ejector, riser, and stripper plates, whose thickness does not depend on the depth of the pattern:

$$C_{fp} = 0.66 A_c + 366 \tag{13.15}$$

where

A_c = projected area of the mold base, cm^2
n_{pl} = number of core and cavity plates
h_p = combined thickness of the core and cavity plates, cm.

Hand molds require only the variable plates and therefore C_{fp} is zero.

The area of the mold base, A_c, is determined by adding appropriate clearances to the length and width of the part measured in a plane perpendicular to the forming direction. We can use the same clearance value of 7.5 cm used for plastic injection molds. This clearance allows the cavity and core details to be inserted in the mold base plates. However, additional space is not required for side-pulls. These features are usually operated by pneumatic cylinders mounted on the outer mold surface. When a hand mold is used, it generally has only one cavity. Clearance at the edge of the mold is assumed to be 2.5 cm. The combined thickness of the core and cavity plates, h_p (cm), is equal to the sum of the depth of the part and the clearance required to the outer surfaces of the plates. The following Equation for h_p accounts for all types of wax dies.

$$h_p = h_d + n_{cl} h_{cl} \tag{13.16}$$

where

h_d = depth of the part, cm
n_{cl} = number of clearances required
h_{cl} = minimum clearance, cm.

Normally, the number of clearances is 2, and the minimum clearance is 2.5 cm for hand molds and 7.5 cm for semiautomatic wax injection.

EXAMPLE

The depth of our sample part is 2.2 cm. From Equation 13.16, the combined thickness of the core and cavity plates for semiautomatic wax injection is

$$h_p = 2.2 + 2 \times 7.5 = 17.2\,\text{cm}$$

The length and width of the part are 3.5 and 2.7 cm, respectively. The area of the mold base is therefore

$$A_c = (3.5 + 15)(2.7 + 15) = 327.5\,\text{cm}^2$$

The cost of the ejector, riser, and stripper plates (Equation 13.15) is

$$C_{fp} = 0.66 \times 327.5 + 366 = \$582$$

and, assuming two cavity and core plates, the cost of these (Equation 13.14) is

$$C_{vp} = 0.0215 \times 17.2 \times 327.5 + 0.428 \times 327.5 \times 2 + 14.27 \times 17.2 + 32.18 \times 2 = \$711$$

The total cost of the mold base (Equation 13.13) is

$$C_b = 582 + 711 = \$1293$$

The total thickness or height of the mold base, h_{pt} (cm), is equal to the sum of the combined thickness of all of the plates:

$$h_{pt} = h_p + h_{fp} \tag{13.17}$$

where
h_{fp} = thickness of the ejector, riser and stripper plates, cm.

The thickness of each ejector, riser, and stripper plate averages about 10 cm for semiautomatic wax dies if an ejection system is required and is zero for hand molds.

EXAMPLE

For semiautomatic wax injection the ejector, riser, and stripper plates would have a total thickness of 20 cm and the height of the mold base would be

$$h_{pt} = 17.2 + 20 = 37.2\,\text{cm}$$

Once the required size of the mold base and its cost has been established, the custom work cost can be estimated. For semiautomatic wax injection, this includes the preparation

of electrical connections, an ejection system, and pneumatic connections. For aluminum semiautomatic dies, this cost is only about 10% of the mold base cost. The cost of the mold base with custom work, C_{ab} ($), is now given by

$$C_{ab} = 1.1C_b \tag{13.18}$$

EXAMPLE

The cost of the mold base with custom work is

$$C_{ab} = 1.1 \times 1293 = \$1422$$

The cost of forming the mold base into a finished mold depends on the time it takes to perform each of the required operations. The first operation to be considered is making the shape details. This is done in a similar way to that for plastic injection molds. The following equation gives the manufacturing hours M_x required to generate the shape:

$$M_x = 0.1n_s \tag{13.19}$$

where

n_s = number of surface patches on the part.

To account for the size of the part and the removal of material, the following Equation can be used for the manufacturing hours:

$$M_{po} = 5 + 0.014A_{tp}^{1.2} \tag{13.20}$$

where A_{tp} (cm^2) is the total projected area of all parts in the mold and is given by $A_p n_{pd}$, the projected area for one part multiplied by the number of patterns in the mold.

Additional manufacturing hours are required for retractable side-pulls, internal lifters, and unscrewing devices. For semiautomatic wax molds, side-pulls require an average of about 16 h each. Since they are actuated by external pneumatic cylinders, construction is simple. There is, however, a cost for the pneumatic cylinder of about $30. For hand molds, the manufacturing time is about 8 h with no pneumatic actuator.

Internal lifters and unscrewing devices are rarely used in investment casting wax pattern molds. If they are used, it can be estimated that they require about 40 h for semiautomatic molds and 8 h for hand molds. It is estimated that actuators for lifters cost about $30 and for unscrewing devices about $50.

An ejection system is generally used for wax injection molding. When an ejection system is required, the quantity of pins is much less than that used for plastic injection. The aluminum mold material is also easier to prepare for ejector pins. The time in hours, M_e, required to make these pins and fit them to the mold is as follows:

$$M_e = 0.5A_{tp}^{0.5} \tag{13.21}$$

The adjustment factor of 0.5 is for semiautomatic wax injection.

The manufacturing hours required for different appearances or surface finishes, for required tolerance levels, and for texturing is assumed to be the same as for plastic injection

molding and is estimated using the factors presented in Tables 8.6 and 8.7 and by adding 5% of the complexity and material removal hours for textured surfaces.

For investment-casting patterns, the surface finish required is rarely better than standard opaque.

The final feature to impact manufacturing time is the shape of the parting surface. The time to make a nonflat parting surface in an aluminum die M_s (h) is

$$M_s = 0.2 f_p A_{tp}^{0.5} \tag{13.22}$$

where

f_p = parting surface adjustment factor.

The total manufacturing hours for mold making, M_{tot}, is now obtained by adding together all the individual contributing factors. The mold-making cost, C_{dm} ($), can be determined by the following equation:

$$C_{dm} = R_{ds} M_{tot} \tag{13.23}$$

where

R_{ds} = mold-making rate, $/h.

and the final cost of the mold, C_d ($) is

$$C_d = C_{dm} + C_{ab} + C_{ac} \tag{13.24}$$

where

C_{dm} = mold manufacturing cost, $

C_{ab} = cost of the mold base, $

C_{ac} = cost of standard mold components or actuators, $.

EXAMPLE

The sample part has 30 surface patches and therefore the complexity manufacturing hours (Equation 13.19) are estimated to be

$$M_x = 0.1 \times 30 = 3 \text{ h}$$

The total projected area of all parts in the mold is

$$A_{tp} = 8.88 \times 2 = 17.76 \text{ cm}^2$$

and the manufacturing hours for removal of material (Equation 13.20) are

$$M_{po} = 5 + 0.014 \times 17.76^{1.2} = 5.44 \text{ h}$$

The two side-pulls require 32 h and, for the ejection system

$$M_e 0.5 \times 17.76^{0.5} = 2.1 \text{ h}$$

From Tables 8.6 and 8.7, a tolerance of ±0.25 mm results in additional hours equal to 10% of $(M_x + M_{po})$ and a standard opaque surface finish gives additional hours equal to 15% of $(M_x + M_{po})$, that is,

$$\text{Tolerance hours} = 0.1 \times (3 + 5.44) = 0.84 \text{ h}$$

$$\text{Surface finish hours} = 0.15 \times (3 + 5.44) = 1.27 \text{ h}$$

Finally, since we have a flat parting surface there are no additional hours and the total manufacturing hours are

$$M_{tot} = 3 + 5.44 + 32 + 2.1 + 0.84 + 1.27 = 44.65 \text{ h}$$

with a mold-making rate of \$40/h this gives a mold-making cost (Equation 13.23) of

$$C_{dm} = 40 \times 44.65 = \$1786$$

The cost (C_{ac}) of two side-pulls and actuators is \$60 and the final cost of the mold (Equation 13.24) is

$$C_d = 1786 + 1422 + 60 = \$3268$$

13.21 Core Mold Cost

Soluble cores are basically wax patterns, and the cost of the molds can be estimated by using the preceding equations. Ceramic core molds are similar to plastic injection molds. The ceramic core material is injected under high pressures and temperatures. Ceramic core material is also extremely abrasive and usually requires steel molds. The cost of ceramic core molds may be estimated using the methods described for plastic injection molding in Chapter 8.

13.22 Pattern and Cluster Assembly Cost

Complex patterns may require assembly of separate pattern pieces before the pattern is complete, and this may require the use of special fixtures. These fixtures vary greatly in size and complexity depending on the pattern to be assembled. The cost of these fixtures is beyond the scope of this text, but a crude estimate can be made. It is estimated that a pattern assembly fixture costs \$300 for a small two-piece pattern and \$100 per additional piece. Sometimes features can be designed into the pattern pieces that align them for assembly, and a fixture may not be required.

The assembly operation starts with the placing of the main body of the pattern into the assembly fixture. A hot spatula is applied to the mating surface of the loose piece and the pattern piece, which is then pressed onto the main body of the pattern and held in place until the wax sets. Pattern assembly is delicate precision work. For this reason, a time of 20 s per piece is allowed. It is also assumed to take about 10 min to set up the work bench for each different type of pattern.

The pattern assembly cost, C_{tpa} ($), is given by

$$C_{tpa} = \left(\frac{W_{pa}t_{pa}}{3600}\right) + \frac{W_{pa}S_{pa}}{B_s} + \frac{C_{af}}{P_v} \tag{13.25}$$

where

W_{pa} = operator rate for pattern or cluster assembly, $/h
S_{pa} = setup time for pattern assembly, h
B_s = number of parts in the production batch
C_{af} = cost of assembly fixture, $
P_v = total production volume for a part.

and where the time required for pattern assembly, t_{pa} (s), is given by

$$t_{pa} = 20(n_{pa} - 1) + 5 \tag{13.26}$$

where n_{pa} is the number of pattern pieces to be assembled.

Occasionally, plastic pattern pieces need assembly, but this is assumed to cost the same as a wax welding operation.

EXAMPLE

In our sample part, only one pattern piece would be required. However, we can estimate the pattern assembly time for a three-piece pattern by way of illustration. Using an operator rate of $23.00/h ($11.50 plus 100% overhead), a batch size of 1000, and a life volume of 10,000, Equation 13.26 would give a pattern assembly time of

$$t_{pa} = 20(3-1) + 5 = 45\,\text{s}$$

and Equation 13.25 gives a cost of

$$C_{tpa} = 23 \times \frac{45}{3600} + \frac{23(10/60)}{1000} + \frac{400}{10{,}000} = \$0.3313$$

Once each pattern is complete, it is ready for assembly to the metal feeding system. This includes the gate (if not already part of the pattern), down runners or sprues, and a pouring basin. Large parts are often cast singly. Medium-sized and small parts are typically cast in clusters of two to hundreds of parts, all sharing the same feeding system.

Since the components of the feeding system are made of recycled wax, it is assumed that there is no raw material cost. There is some cost associated with the recovery and reprocessing of the meltout wax, but it is assumed to be small and can be included in the general operation overhead. In addition, since the feeding system component shapes are standard and wax injection molds last almost indefinitely, it is assumed that the cost of the molds used to make the standard wax extrusions and cluster bases can be spread over millions of parts and would be negligible when compared to the processing cost.

Assembly fixtures are assumed to be standard and used for many different casting patterns. The assembly operation includes the wax welding of all the patterns to the cluster base runners and the wax welding of a ceramic pouring cup or ring to the cluster base

pouring basin. A minimum of two reorientations is required during the assembly. It is estimated that a wax welding operation in cluster assembly takes about 10 s and each reorientation of the cluster base about the same. The cost of a cluster base is about $1 and a ceramic pouring cup $0.5. The time to set up the workstation for each new type of part is estimated at 7 min. With these assumptions, the total cost for cluster assembly, C_{tea} ($), is given by

$$C_{tea} = \left(\frac{W_{pa} t_{ca}}{3600}\right) + 1.5 + W_{pa} S_{ca} \tag{13.27}$$

where

S_{ca} = setup time required for the cluster to be assembled, h.

and where t_{ca} (s) is the time to assemble a cluster and is given by

$$t_{ca} = 10(n_{pc} + 3) \tag{13.28}$$

where

n_{pc} = number of parts per cluster.

13.23 Number of Parts per Cluster

The more patterns or parts that can fit onto a cluster, the less the cluster processing cost per part. The number of parts per cluster is limited by the maximum weight and size of the cluster that can be handled.

When the cluster must be manually handled, the total weight should not exceed 18 kg (40 lb), which is the maximum weight that a person can be required to handle on a regular basis. If robotic handling is used, the weight limit can be exceeded. However, for the purposes of early cost estimating, it is assumed that the weight of the dry shell mold filled with metal must not exceed 16 kg (351b).

In order to estimate the number of parts per cluster, it is necessary to have values for two ratios:

1. The casting yield, Y_d, which is the ratio of the weight of finished castings per cluster divided by the total poured weight of the metal.
2. The shell mold yield, Y_{sm}, which is the ratio of the weight of finished castings per cluster divided by the weight of the dry shell mold.

Empirical formulas based on industry data for these ratios are

$$Y_d = 0.0483(\ln W) + 0.455 \tag{13.29}$$

$$Y_{sm} = 0.148(\ln W) + 0.843 \tag{13.30}$$

where

W = weight of part, kg.

The number of parts per cluster, n_{pc}, is now given by

$$n_{pc} = \frac{16}{(W / Y_d + W / Y_{sm})} \tag{13.31}$$

EXAMPLE

The volume of our sample part is 3.326 cm^3. With a density of 8.94 g/cm^3 the weight of each part is 0.0297 kg.

The yields are

$$Y_d = 0.0483 \text{ In } 0.0297 + 0.455 = 0.285$$

$$Y_{sm} = 0.148 \text{ In } 0.0297 + 0.843 = 0.323$$

and the number of parts per cluster is

$$n_{pc} = 16/(0.0297/0.285 + 0.0297/0.323) = 81$$

The time to assemble a cluster, t_{ca}, is given by Equation 13.28 as

$$t_{ca} = 10(81 + 3) = 840 \text{ s}$$

and the total cluster assembly cost, C_{tca} from Equation 13.27 is

$$C_{tca} = 23 \times 840/3600 + 1.5 + 23 \times 7/60 = \$9.55$$

Finally, the cost per part for cluster assembly, C_{pca} (\$), is

$$C_{pca} = 9.55/81 = \$0.118$$

13.24 Pattern Piece Cost

The total cost per pattern piece, C_{tp} (\$), is the sum of the cost of injection, pattern material, setup, and the cost of the die amortized over the total product volume.

$$C_{tp} = \frac{(C_{ip} + C_{pm})}{(1 - P_{psr})} + \frac{M_i S_{ds}}{B_s} + \frac{C_d}{P_v} \tag{13.32}$$

where

C_{ip} = process cost per pattern piece, \$
C_{pm} = cost of wax per pattern piece, \$
P_{psr} = pattern piece scrap rate
M_i = injection machine and operator rate, \$/h
S_{ds} = time to set up the mold on the injection machine, h
B_s = batch size
C_d = pattern piece mold cost, \$
P_v = total production volume.

The setup time is estimated at 15 min for a semiautomatic mold and 5 min for a hand mold. These figures include the time to fasten the mold to the injection machine if necessary, adjust the shot size, and injection pressure, and remove the mold from the machine.

For estimating purposes, an average scrap rate of 5% is assumed for patterns without cores and 8% for patterns with cores.

EXAMPLE

Our sample part has only one pattern piece and no cores. With semiautomatic operation the total pattern cost is

$$C_{tp} = \frac{(0.078 + 0.00963)}{(1 - 0.05)} + 30 \times \frac{0.25}{1000} + \frac{3268}{10,000} = \$0.4265$$

13.25 Cleaning and Etching

Prior to investing the wax cluster in slurry, it must be cleaned and it is usually etched to provide a good surface for the slurry to adhere to. If there are soluble cores, these must be dissolved. For estimating purposes it is assumed that these operations can be done in one step with a single loading and unloading of the wax cluster. It is assumed that the costs of the cleaning and etching solutions and equipment are small. With a load and unload time of 8 s and an average labor rate of \$23/h, including overhead, the cost would be about \$0.06 per cluster.

13.26 Shell Mold Material Cost

After cleaning and etching the assembled pattern cluster, it is dipped with the first primer slurry coat, stuccoed, then allowed to dry before application of the next primer coat. For the purposes of cost estimation, three zircon-based primer coats are assumed, followed by four silica-based backup coats and one fused-silica seal coat, all manually applied.

The shell mold yield, Y_{sm}, is defined as the ratio of the weight of the cast parts from the cluster to the weight of the dry shell-mold. Thus, the dry weight of the shell mold, W_{sm} (kg), is given by

$$W_{sm} = \frac{n_{pc} W}{Y_{sm}} \tag{13.33}$$

where

n_{pc} = number of parts per cluster
W = weight of a single part, kg.

A detailed estimate of the material cost for a shell mold would involve knowledge of the number of primary and backup coats, the thickness and area for each, the density of the materials, and their cost per unit weight. However, for quick estimates, we can assume a cost of \$1.00/kg for shell mold material.

EXAMPLE

The weight of our sample part is 0.0297 kg, the shell mold yield is 0.323, and the number of parts per cluster is 81, giving an estimated shell mold weight of

$$W_{sm} = 81 \times 0.0297/0.323 = 7.45 \text{ kg}$$

and the shell mold would cost \$7.45.

13.27 Investing the Pattern Cluster

The cost, C_{pr} (\$), to apply the primer coats to a cluster is given by

$$C_{pr} = \frac{M_{pr}[t_{cl} + (n_{cp} - 1)t_{cp}]}{3600} \tag{13.34}$$

where

M_{pr} = machine and operator rate for primer coat application, \$/h
t_{cl} = time to apply the first primer coat, s
t_{cp} = time to apply each subsequent primer coat, s
n_{cp} = number of primer coats.

The application of the first coat is done with the most care and is estimated to take about 20 s for slurry and stucco. This includes the time to remove the cluster from a rack, dip it into the slurry tank, remove and manipulate it for even coverage, dip it into the stucco tank, and place it in the drying rack. The following two coats of slurry and stucco take about 15 s each to apply. Using these values and an operator rate of \$31.20 per hour gives a cost to apply three primer coats of

$$C_{pr} = 31.20 \times \frac{(20 + (3-1) \times 15)}{3600} = \$0.43$$

The application of backup coats is assumed to be carried out robotically. The cost, C_{bu} (\$), is given by

$$C_{bu} = \frac{n_{cb} M_{bu} t_{cb}}{3600} \tag{13.35}$$

where

n_{cb} = number of backup coats
M_{bu} = machine and operator rate for backup coat application, \$/h
t_{cb} = time to apply a backup coat, s.

Assuming a value of \$35.15 per hour for the robot, the conveyor and 50% of an operator, and a cycle time for each backup coat application of 10 s, the cost for a single backup coat is about \$0.10. If an average of five backup coats is used, the total cost for applying backup coats is

$$C_{bu} = 5 \times 35.15 \times \frac{10}{3600} = \$0.49$$

13.28 Pattern Meltout

The cost of wax pattern meltout includes the labor cost of loading and unloading the clusters into the autoclave or furnace, the cost of using the meltout unit, and the energy consumed.

The time for load and unload is estimated at about 8 s. Using an average operator rate including overhead of $23 per hour, gives a cost per cluster for load and unload of $0.05.

The machine rate for a $10,000 dewaxing furnace with an average capacity of ten clusters is about $1.52/h, assuming 100% machine overhead, a 10-year depreciation, and a 10% interest rate on the machine purchase. The cost per cluster for a 15 min cycle is, therefore, about $0.04 per cluster. Flash dewaxing with gas furnaces is reported to be only 5–10% efficient [2]. Assuming specific heats of 840 and 2890 J/kg K for silica and paraffin, respectively, melting the wax from an average size cluster requires about 10,200,000 J. With a cost of $0.60 per therm for a high-volume user (1 therm = 105,500,000 J) the average energy cost per cluster is $0.06.

13.29 Burnout, Sinter, and Preheat

Burnout, sinter, and preheat are assumed to form a single operation taking about one hour for a group often clusters in a sintering furnace. The machine rate for a sintering furnace is comparable to that for a dewaxing furnace. Therefore, the cost per cluster is about $0.15 per cluster.

The operator loads the clusters into the furnace. The unload operation is done in the foundry and is accounted for as part of the metal-pouring operation. The time to load a single cluster is estimated to be 4 s, giving a cost of $0.03 using our typical operator rate.

With a furnace efficiency of 15% and the specific heat of silica, it costs about $0.43 per cluster to bring an average size shell mold to a temperature of 1090°C. Combining the labor, machine, and energy costs, we have a total cost per cluster of $0.61 for burnout, sinter, and preheat.

13.30 Total Shell Mold Cost

The following summarizes the costs for the shell mold:

Assemble cluster	9.55
Clean and etch pattern cluster	0.06
Apply three primer coats	0.43
Apply five backup coats	0.49
Pattern meltout (dewax)	0.15
Burnout, sinter, and preheat	0.61
Shell mold material	7.45
Total	$18.74

EXAMPLE

For our sample part with 81 patterns per cluster, the shell mold cost per part, including cluster assembly, would be

$$18.74/81 = \$0.23$$

13.31 Cost for Melting Metal

The cost to melt an alloy or metal has three components energy, equipment, and labor.

Most investment casting facilities use induction furnaces to melt metal. Induction furnaces are relatively environmentally clean and efficient, do not add contaminants from combustion of fuel to the melt, and have low material losses.

For the purposes of estimating, it is assumed that induction furnaces are used. The cost of the energy used is the cost of the electricity supplied by the power company. For 1994 in the northeastern United States, the cost of power C_p for users with a demand of 500 kW or more was \$0.035 per kilowatt hour (\$/kWh) during peak hours. Equation 13.36 gives a relation for determining the cost per kilogram, C_e (\$/kg), to melt an alloy:

$$C_e = \frac{C_p E_m}{n_e} \tag{13.36}$$

where

C_p = cost of electricity, \$/kWh
E_m = minimum energy required to melt a metal, kWh/kg
n_e = efficiency of the induction furnace.

The efficiency of an induction furnace is dependent on the material to be melted and the frequency at which the furnace operates. For the purposes of cost estimating, the efficiencies given in Table 13.9 will be used. The cost of the power to melt the metal forms a relatively small portion of the material cost, and so these approximate values are adequate for estimating purposes.

The minimum energy requirements to bring a material to pouring temperature are given in Table 13.10. These figures are only approximate. Pouring temperatures may be different from one operation to the next, and differences in material composition also have an impact.

TABLE 13.9

Approximate Efficiency of Induction Melting for Various Materials

Material Group	Approximate Furnace Efficiency
Ferrous	0.80
Aluminum	0.60
Other Nonferrous	0.70

Source: Data from industry supplier of induction furnaces.

TABLE 13.10

Minimum Energy Required to Melt Alloys

Metal	Final Temperature (°C)	Energy Required (kWh/kg)	Energy Required (Btu/lb)
Aluminum bronze	1200	0.237	367
Aluminum alloy (general)	750	0.326	505
Aluminum (pure)	750	0.326	505
Brass (58% copper)	1030	0.173	268
Brass (63% copper)	1030	0.177	274
Brass (73% copper)	1080	0.183	283
Brass (85% copper)	1120	0.170	263
Brass (90% copper)	1140	0.194	300
Bronze	1100	0.185	287
Copper (pure)	1200	0.204	316
Gold (pure)	1150	0.066	102
Gray iron	1500	0.390	604
Iron (pure)	1600	0.391	605
Lead (pure)	450	0.023	35.6
Magnesium (pure)	700	0.332	514
Malleable Iron (black)	1550	0.395	612
Malleable Iron (white)	1550	0.405	627
Cu 70%-Mn 30%	1030	0.193	299
Nickel (pure)	1600	0.341	528
Silver (pure)	1050	0.107	166
Spheroidal iron	1550	0.400	620
Steel (general)	1600	0.393	609
Stainless steel	1650	0.405	627
Zinc (pure)	500	0.093	144
Tin (pure)	400	0.037	57.3

Source: Data from industry supplier of induction furnaces.

EXAMPLE

The alloy for our sample part is phosphor bronze. The furnace efficiency, n_e, from Table 13.9 is 0.7 and the minimum energy for melting, E_m, is 0.185 kWh/kg. Thus, the cost of energy to melt the metal ready for pouring is

$$C_e = 0.035 \times \frac{0.185}{0.7} = \$0.00925/\text{kg}$$

The equipment cost, C_f ($), for a complete induction melting unit, including furnace, power supply, and installation, can be determined from Equation 13.37. This equation should only be used for furnaces with a capacity range of from 100 to 4000 kg.

$$C_f = 100{,}000 \log\left(S_z^{1.64/851}\right) \tag{13.37}$$

where

S_z = size of the furnace in kilograms of capacity for iron, kg.

EXAMPLE

If the furnace for our sample part has an iron capacity of 250 kg, then the cost of the furnace is

$$C_f = 100,000 \log(250^{1.64/851}) = \$100,269$$

The costs given by Equation 13.37 are for high-quality coreless induction furnaces. They are more expensive than some of the cheaper units used by many small investment casters, but they meet strict European guidelines for shielding, have a high initial purchase price, but have longer life with lower overall maintenance and operating cost.

It has been estimated that a furnace can be charged manually at about 1500 kg of iron per hour. Induction furnaces can be set with automatic melting cycles and require only about 4 min an hour to set up and monitor.

Some additional labor is required to check and certify the composition of the melt. Many investment casters purchase certified alloy from suppliers in the form of billets, bars, or ingots. Induction melting allows them to melt this metal with little compositional change in the material. However, if scrap runners and gates are to be remelted, the metal composition changes after repeated melting. If the foundry does not have the capacity to test metal composition, readjust it to within specification, and certify it, then they must sell their scrap after a limited number of melts. Sometimes only one melt can be allowed for critical applications. It is assumed here that a metallurgist is available and can test, adjust, and recertify the metal composition in about 10 min per melt. This assumption allows the recovery of all gates and runner scrap for remelting unlimited number of times.

The national average labor rate for foundry workers is about $13.50 per hour. The rate for the metallurgist is assumed to be about $18 per hour. Labor overheads are estimated at 100%. The amortization period for the furnace is assumed to be 10 years at an interest rate of 10%. Machine overheads are estimated at 100%. Machine overhead in this case includes maintenance such as changing the refractory liner and power cables. It does not include power, as that is determined separately by material type.

The data in Table 13.11 are for iron. Different materials have different densities, and the weight of each material that a furnace can hold varies. Each furnace can hold a certain volume. The volume capacity is assumed constant for a given furnace. The weight of a particular material that a furnace can hold can be determined by comparing its density with iron. The machine cost, C_{mf} ($/kg), for a particular alloy can be determined by

TABLE 13.11

Machine Rates for Induction Furnaces

Furnace Size (kg of Iron)	Furnace Cost Buy and Install ($)	Machine Rate with Overhead ($/h)	Furnace Cycle Time (h)	Machine Cost per Cycle ($/cycle)	Machine Cost per kg Iron ($)
2000	250,000	38	1.6	61	0.031
1000	200,000	30	1.4	51	0.041
500	150,000	23	1.2	28	0.056
250	100,000	15	1.2	18	0.072
150	64,000	10	1.1	11	0.073

TABLE 13.12

Operator Rates for Induction Furnaces

Furnace Size (kg of iron)	Labor Cost per Melt Cycle ($)	Labor Cost per kg Iron ($/kg)
2000	34	0.017
1000	21	0.021
500	15	0.030
250	12	0.048
150	11	0.070

multiplying the cost per kilogram of iron by the ratio of the density of iron to the desired alloy as shown in Equation 13.38:

$$C_{mf} = C_{mi}\left(\frac{\rho_i}{\rho_a}\right) \tag{13.38}$$

where

C_{mi} = cost of the furnace per kilogram of iron, $/kg
ρ_i = density of iron, g/cm^3
ρ_a = density of the alloy, g/cm^3.

Most investment casters use furnaces under 500 kg capacity. If it is assumed that the average furnace size is 250 kg, Equation 13.38 reduces to Equation 13.39 for a density of iron of 7.08 g/cm^3:

$$C_{mf} = \frac{0.51}{\rho_a} \tag{13.39}$$

EXAMPLE

If an average-sized furnace of 250 kg capacity for iron is used and the density of phosphor bronze is 8.94 g/cm^3, Equation 13.39 gives the cost of using the induction furnace per kg of the alloy:

$$C_{mf} = \frac{0.51}{8.94} = \$0.057/\text{kg}$$

The data in Table 13.12 are also for iron. It is assumed that the pouring rate is relatively constant, and so differences in density have less effect on the labor time required for pouring. Density differences should also not affect the monitoring and certification of the melt. Charge time may be affected. If it is assumed that the same number of equally sized billets of different weights is handled, then the labor time to charge a furnace should not be dramatically different for different alloys. For the purposes of estimating, it is assumed that the labor time to charge a furnace per cycle is the same regardless of the material. The values in Table 13.12 for the cost per cycle for iron can, therefore, be used for all materials. The typical furnace size for investment casting is about 250 kg. The labor cost per kilogram for any material is estimated as $0.048/kg.

13.32 Raw Base Metal Cost

As investment casters often handle many different alloys, they often do not have the volume to refine metal from raw scrap. They usually buy their metal in the grade in which they intend to cast the final part. Some investment casters do have the capacity to make adjustments to the melt and bring the melt within specification for certain materials, but for the purposes of estimating it is assumed that an alloy is purchased from a supplier already certified to the final part material specification. The raw metal cost is therefore the purchase price of the alloy from the supplier.

13.33 Ready-to-Pour Liquid Metal Cost

The cost of liquid metal that is ready to pour may be found by adding together the melting cost and the raw alloy cost. The molten metal cost, C_m (\$/kg), is the sum of the cost of energy, the cost of the machine, the cost of the labor, and the cost of raw material:

$$C_m = C_e + C_{mf} + C_{ml} + C_{rm} \tag{13.40}$$

where

C_e = energy cost per kilogram for melting metal, \$/kg
C_{mf} = cost of the furnace per kilogram of alloy, \$/kg
C_{ml} = cost of labor per kilogram of alloy, \$/kg
C_{rm} = cost of the raw alloy, \$/kg.

Since labor cost is assumed to be constant regardless of the alloy and the furnace size is estimated as 250 kg, Equation 13.40 can be written as follows:

$$C_m = C_e + C_{mf} + C_{rm} + 0.048 \tag{13.41}$$

EXAMPLE

For the raw material cost of phosphor bronze of \$1.764/kg, the cost of ready-to-pour liquid metal is

$$C_m = 0.00925 + 0.057 + 1.764 + 0.048 = \$1.878/\text{kg}$$

13.34 Pouring Cost

For the purposes of estimating, it is assumed that pouring is a four-worker operation and that they can pour about 1500 kg/h. Using an average foundry rate for foundry workers of \$27/h, including 100% overhead, gives a cost per kilogram for pouring of

$$C_{mp} = \$0.072/\text{kg}$$

13.35 Final Material Cost

The final material cost is the cost of the poured material less the value of the scrap recovered after cutoff. Gates and runner are assumed to be returnable to the melt. When returned in this fashion they replace raw purchased material kilogram for kilogram. When material cannot be returned to the melt and must be sold back to the supplier, it is sold back at a reduced value. For the purposes of estimating, unless known to be otherwise, it is assumed that scrap is returned to the melt.

Only a portion of the total weight poured goes to making the final part. Some of the material is lost during melting and some during cutoff. During melting with an induction furnace, losses are often less than 1%. For the purpose of estimating, it is assumed that total metal losses are about 2%. The remainder of the metal that does not go into the part weight is taken up by the gates and runners for return to the melt. The ratio of the part weight to the poured metal weight is defined as the casting yield. Casting yield for investment casting can be as low as 10% to as high as 90%.

Equation 13.42 gives the relation for final part material cost per kilogram, C_{mat}, given the preceding assumptions and simplifications:

$$C_{mat} = \frac{[C_m + C_{mp} - V_{sc}(1 - P_l - Y_d)]}{Y_d} \tag{13.42}$$

where

$$Y_d = \frac{n_{pc} W}{W_{pr}} \tag{13.43}$$

and where

C_m = unpoured liquid metal cost, \$/kg
C_{mp} = pouring cost, \$/kg
V_{sc} = value of scrap, \$/kg
P_l = metal loss rate
Y_d = casting yield
n_{pc} = number of parts per cluster
W = weight of a single part, kg
W_{pr} = weight of material poured into a single mold, kg.

Casting yield can vary greatly from part to part. Casting yield varies because of the part weight and shape. Two parts of the same weight can have different casting yields, due to their shape. One part may require extra gates, longer runners, and multiple risers. In investment casting, the casting yield can also be affected by the number of parts per cluster and the particular type of process used. Material can also have an effect on casting yield. A material such as aluminum with a broad freezing range may require more risering and gating than an identical part made from a ferrous alloy.

Equation 13.29 was developed for estimating casting yield, Y_d, as a function of the part weight only. This relation does not take into account the shape of the part. Also, the data available was for steel alloy parts and for traditional shell mold investment casting.

EXAMPLE

Equation 13.29 gave a casting yield of 0.285, or 28.5%.
If the value of scrap is \$0.7/kg, the final part material cost is

$$C_{mat} = \frac{\left(1.878 + 0.072 - 0.7 \times (1 - 0.02 - 0.285)\right)}{0.285} = \$5.14/\text{kg}$$

giving a metal cost per part of $5.14 \times 0.0297 = \$0.153$

13.36 Breakout

At this point in the process, the shell mold has lost much of its strength and is often cracked and fragmented. Breaking out the solidified metal cluster from the shell mold is usually accomplished with a pneumatic hammer. The cluster is placed in a fixture that contacts the top of the cluster at the pouring cup and the bottom of the cluster at a central down runner or sprue. The machine cycle is started with the pressing of palm buttons. The pneumatic hammer strikes the cluster at the pouring cup, and the shell mold breaks away.

The cost of pneumatic breakout is assumed to include a setup cost to adjust the machine to the specific size cluster and a labor cost for the operation of the machine. The machine for this operation is relatively inexpensive, and the cost of the machine is assumed to be small when compared to the cost of the operator. The cost of the machine is included in the general overhead. The cost per cluster, C_{bo} (\$), for pneumatic breakout is given by Equation 13.44:

$$C_{bo} = C_{nh} + \frac{C_{ns} n_{pc}}{B_s} \tag{13.44}$$

$$C_{nh} + \frac{t_{nh} R_{nh}}{3600} \tag{13.45}$$

$$C_{ns} + S_{nh} R_{nh} \tag{13.46}$$

where

C_{nh} = operator cost per cluster for a cycle of the pneumatic hammer, \$
C_{ns} = cost of setting up the pneumatic hammer for the correct size of cluster, \$
n_{pc} = number of parts per cluster, \$
B_s = number of parts per production batch
t_{nh} = cycle time for pneumatic hammer breakout, s
R_{nh} = operator rate for breakout, \$/h
S_{nh} = setup time for a pneumatic hammer, h.

The setup time for the breakout machine is estimated at about 5 min. The cycle time includes load and unload time for a cluster of about 10 s and a machine cycle of 3 s for a total cycle time of 13 s. If the burdened operator rate is estimated at \$25.00 per hour, assuming

a base wage of $11.50 per hour with 100% overhead and accounting separately for vacations, holidays, and sick days, Equation 13.44 can be reduced to Equation 13.47:

$$C_{bo} = 0.09 + \frac{2.08 n_{pc}}{B_s} \tag{13.47}$$

EXAMPLE

We have 81 parts per cluster and a batch size of 1000. Thus, the cost per cluster for breakout is

$$C_{bo} = 0.09 + 2.08 \times \frac{81}{1000} = \$0.259$$

13.37 Cleaning

Most of the shell mold is removed during breakout. Some mold material remains trapped in crevices and holes. This remaining material is removed either by blasting equipment or by being dissolved off by a caustic bath. If ceramic cores were used or deep holes are present, leaching out of the ceramic in a caustic bath is probably required.

The costs for batch cleaning in a blasting cabinet and cleaning using a caustic bath are handled similarly. The operator is assumed not to have to be present during either cleaning cycle. The machines are assumed to run unattended during their operation, and the cycle is controlled by a simple timer. The material cost for blast media or caustic is assumed to be small and is included in the general overhead along with the cost of the blasting cabinet and the leaching tanks. No setup of any kind is assumed necessary for these operations. This reduces the cost estimate of these operations to a simple loading and unloading of a cluster. Using the preceding wage rate and a cycle time for loading and unloading of 10 s, the cost for either a blast-cleaning operation or a leaching operation is estimated to be

$$C_{cl} = \$0.07 \text{ per cluster}$$

13.38 Cutoff

The cutoff cycle is assumed to include a setup cost, a material (or tool wear) cost, and an operator cost. The cost of the machine, usually either a band saw for softer nonferrous materials or an abrasive cutoff wheel for harder materials, is assumed to be small and is included in the general overhead. A detailed cost analysis taking into account the life and cost of the specific cutting tool, the part material and size, and the gate cross-section should be possible, but the data for such an analysis were not available. Given the lack of available data, only a crude estimate for cutoff cost can be attempted. Equation 13.48 gives an estimate for the cost, C_{co} ($), of cutoff per cluster. The type of material is not taken into account in the cutoff time estimate even though this would have an effect. The cost of wear on the

band saw blade or abrasive cutoff wheel is roughly estimated as equal to the labor cost of the operation:

$$C_{co} = C_{cf} + C_{tw} + \frac{C_{fs} n_{pc}}{B_s} \tag{13.48}$$

$$C_{cf} = \frac{t_{co} R_{co}}{3600} \tag{13.49}$$

$$C_{fs} = S_{co} R_{co} \tag{13.50}$$

$$t_{co} = t_{cl} + (t_{cg} + t_{gp}) n_{gp} n_{pc} + (t_{sc} + t_{so}) n_{so} \tag{13.51}$$

where
C_{co} = total cost per cluster of cutoff, $
C_{cf} = operator cost per cluster for cutoff, $
C_{tw} = cost of cutoff tool wear per cluster, $
C_{fs} = cost of setting up the cutoff machine for a specific cluster, $
n_{pc} = number of parts per cluster
B_s = number of parts per production batch
t_{co} = cycle time for cutting off all the parts from a cluster, s
R_{co} = operator rate for the cutoff operation, $/h
S_{co} = setup time for a cutoff operation, h
t_{cl} = time to load a cluster for cutoff, s
t_{cg} = time to cut through a single gate, s
t_{gp} = time to reposition the cluster from one gate to the next, s
n_{gp} = number of gates per part
t_{sc} = time to make a supplemental cut through runner or sprue, s
t_{so} = time to reposition cluster from one supplemental cut to the next, s
n_{so} = number of supplemental cuts per cluster.

The same operator rate of $25.00 per hour used for breakout is assumed for cutoff. The setup time, S_{co}, is also estimated at about 5 min. The time to load the cluster, t_{cl}, is estimated at 4 s. The time to cut through a single gate, t_{cg}, is crudely estimated by Equation 13.52

$$t_{cg} = \frac{w^2}{m_{rc}} \tag{13.52}$$

where
m_{rc} = cutoff rate, cm^2/s
w = thickness of the gate, cm.

An average removal rate is estimated at 0.2 cm^2/s.

Although size and weight of the part probably have an effect, it is estimated that it takes about 2 s for the operator to position the cluster between gate cuts. This is actually a conservative number, since the parts are often in a straight line making positioning between gate cuts very fast.

Supplemental cuts are those cuts that do not free a part from the cluster, but make access to the gates for the cutoff saw possible or just easier. These cuts are usually through the runners in the cluster, which are usually thicker than the gates. It is estimated that a supplemental cut takes three times as long as it takes to cut through a gate stub. Since the cluster is more difficult to handle before these cuts are made, positioning the cluster between each supplemental cut is also assumed to take three times as long as positioning the cluster for a gate cut. Equation 13.53 can now be written by combining Equations 13.51 and 13.52 and substituting estimated values for cutting and positioning time:

$$t_{co} = 4 + (5w^2 + 2)(n_{gp}n_{pc} + 3n_{so}) \tag{13.53}$$

The number of supplemental cuts can only be crudely estimated, since very little data was available. The number of these cuts is in part dependent on the process envelope, size of part, and other process-specific factors. It is assumed here that the number of supplemental cuts can be estimated from the part weight alone and is between one and six cuts. Equation 13.54 assumes a simple linear relation between part weight and the number of supplemental cuts:

$$n_{so} = \text{INT}(-0.7W + 6.5) \quad \text{if } W > 7, \quad \text{then } n_{so} = 1 \tag{13.54}$$

where

n_{so} = number of supplemental cuts (rounded off to nearest whole number)
W = weight of a single part, kg.

EXAMPLE

Equation 13.54 gives an estimate for the minimum number of supplemental cuts:

$$n_{so} = \text{INT}(-0.7 \times 0.0279 + 6.5) = 6$$

Assuming a single gate thickness of 0.5 cm, Equation 13.53 gives the cycle time for cutting off all the parts from the cluster:

$$t_{co} = 4 + (5 \times 0.5^2 + 2)(1 \times 81 + 3 \times 6) = 325.8 \text{ s}$$

giving an operator cost per cluster of

$$C_{cf} = 325.8 \times \frac{25}{3600} = \$2.26$$

The cost of setup is

$$C_{fs} = \left(\frac{5}{60}\right) \times 25 = \$2.08$$

and the total cost per cluster for cutoff is

$$C_{co} = 2.26 + 2.08 \times \frac{81}{1000} = \$2.43$$

Summing the costs per cluster for breakout, cleaning, and cutoff we get 0.259 + 0.07 + 2.43 = $2.76, with a cost per part of 2.76/81 = $0.034.

Finally, the total cost of the part, rounded to three decimal places, can be summarized as follows:

Metal 0.153
Pattern, (including tooling) 0.427
Shell mold 0.230
Breakout, clean, cut-off 0.034
and the total cost is $0.844.

It should be noted that this analysis has not included the costs of grinding the gate stubs flush, straightening (if required), inspection, or heat treatment.

13.39 Design Guidelines

Investment casting offers greater freedom in design than any other metal forming operation. Accurate and intricate castings can be made from alloys that melt at high temperature. Parts can be cast to such close tolerance that little or no machining is required [3].

The investment-casting process was previously known as the "lost wax" process and has been in use for thousands of years. Its advantage over other casting processes is its ability to produce very complex castings with fine details. However, except for very small production quantities, the wax or plastic patterns are produced by injection molding. Therefore, guidelines similar to those for injection molding apply. These guidelines apply to the pieces of the pattern that are used to make up the final pattern shape. Thus, the pattern piece must be easily removable from its mold and the main wall should have a uniform thickness, which minimizes distortion by facilitating even cooling throughout the pattern piece.

In addition, the principles of good sand casting design also apply to investment casting. For example, nonfunctional mass should be minimized to assist in providing sufficient gating to "feed" the part. Also, uniform wall sections with generous radii and fillets assist in metal flow and reduce stress concentrations.

Separate cores can add significantly to the cost, as well as bosses and undercuts. The minimum section ranges from 0.25 to 1 mm depending upon the metal to be cast. The maximum section is approximately 75 mm.

Castings range from 0.5 g to 100 kg in weight, but the investment-casting process is best for parts that weigh less than 5 kg.

A flat parting plane for each pattern piece helps to minimize the cost.

PROBLEMS

1. Using the example in this Chapter, estimate the pattern cost (including tooling cost per part) if the parts are of the same material and geometric shape but are twice the size in terms of the linear dimensions (i.e., eight times the volume). Assume use of the same injection molding machine for the wax pattern and one cavity per mold.

2. Using the example in this Chapter, estimate the cost of metal per part if the parts are of the same material and geometric shape but are twice the size in terms of the linear dimensions (i.e., eight times the volume).
3. Using the example in this Chapter, estimate the cost of the shell mold per part (not including the pattern cost) if the parts are of the same material and geometric shape but was twice the size in terms of the linear dimensions (i.e., eight times the volume).
4. Using the example in this Chapter, estimate the cost of breakout, cleaning and cut-off if the parts are of the same material and geometric shape but are twice the size in terms of the linear dimensions (i.e., eight times the volume).
5. For the example in this Chapter, what would be the savings if the two side holes were eliminated? Would you consider that it would be less expensive to produce the holes by machining after casting?

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14

Design for Hot Forging

14.1 Introduction

Hot forging, also referred to as drop forging, is a process that can be used to produce a wide variety of parts in most metals. Forgings are produced in sizes ranging from a few millimeters maximum dimension up to 3 m or more in some cases. The principles and practices of hot forging have been established since the nineteenth century, but improvements have obviously been made in equipment, lubricants, and the ability to process the more difficult to forge materials since that time. The basic procedure for hot forging is relatively straightforward. Metal stock in the form of either a bar or a billet is first heated into the hot working temperature range to improve ductility. Then the material is squeezed or hammered in a series of tool steel dies to convert the stock into the finished shape. Excess material in the form of flash is produced as a necessary part of forging, and the final processing stage is to remove the flash to yield the finish forged part. Hot forging is a near net shape process, but all forgings require some subsequent machining, in particular for surfaces that must locate with other surfaces during the final assembly of a product.

14.2 Characteristics of the Forging Process

Most forgings require a series of forming stages, called preforms, to convert the initial stock material into the finish-forged shape. The number of preforms required depends on several factors, including the overall shape, shape complexity, and material of the part. Forging complexity is increased by several features, including:

- The presence of thin sections in the part
- Large changes in cross-sectional area of the part
- Part shapes that require the die parting line to be cranked (Figure 14.1).

14.2.1 Types of Forging Processes

The main types of basic forging processes are referred to as open-die and closed-die forging. In open-die forging a series of relatively simple dies is used to form the final forging incrementally with a large number of blows. This process is largely a more automated version of the old blacksmith-type operations that have been used for centuries. The discussion in this chapter does not include open-die forging, since the process is used to form

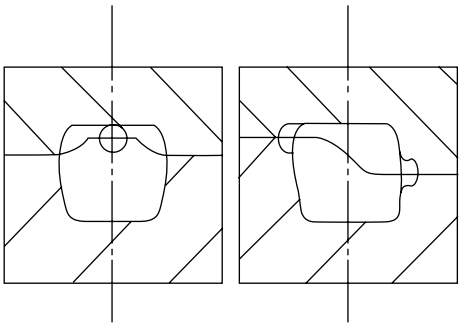


FIGURE 14.1
Forging requiring a cranked parting line.

relatively crude final shapes, but discussion is devoted to closed-die forging, which is used for the manufacture of a wide range of part shapes.

In closed-die forging, a series of shaped dies is used to convert the initial stock into the finish-forged shape. The term "closed-die" forging is something of a misnomer, as the die cavities are not completely closed and material in the form of flash flows out at the die parting line during the final stages of forging. This flash is a critical part of the forging process, and proper control of the flash is essential to ensure die filling. Within closed-die forging, two other terms are used: blocker forgings and precision forgings. Blocker forgings, compared to conventional forgings, have thicker sections and more generous radii. They are termed blocker forgings, because the performing shape prior to the finishing impression is traditionally called a blocker.

Blocker forgings are easier to form than equivalent conventional forgings, requiring fewer forming stages and lower loads. They are used sometimes when small quantities of parts are required, to reduce die costs, or in difficult-to-form materials, when it is hard to obtain thin sections or there are other problems. Blocker forgings require more subsequent machining to reach the final part shape than conventional forgings.

Precision forgings are parts formed with thinner sections and closer tolerances than equivalent conventional forgings, that is, nearer to net shape. Such forgings require careful processing, and peak loads during the final forming stages are 2.5–3 times higher than those experienced for equivalent conventional forging (see Section 14.7). Thus, larger equipment and more precise die-to-die positioning is required. Although the term precision forging implies closer precision than is normally obtained for any material, in practice precision forgings are more often produced in light alloys (aluminum alloys, magnesium alloys, etc.) than in other materials.

14.3 Role of Flash in Forging

The flash produced during closed-die forging is scrap material and may in many cases have a volume that is more than 50% of the final part volume. The amount of flash produced increases with the complexity of the part. However, the production of flash is a necessary part of the process, and its control is essential to ensure good die filling, particularly for tall, thin shape features. Figure 14.2 [1] shows the deformation that takes place during the

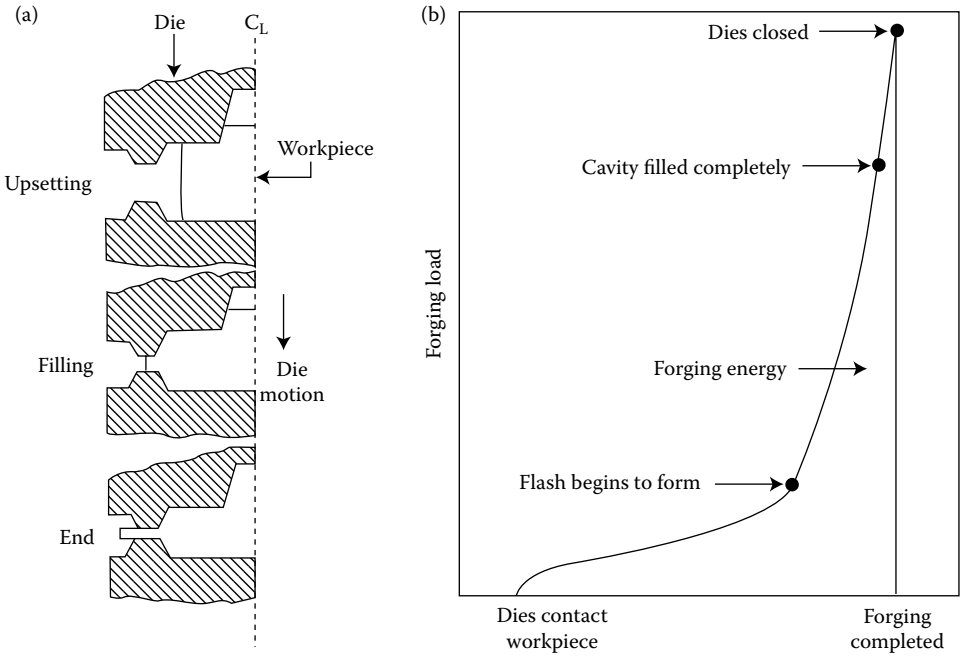


FIGURE 14.2
(a) Forging of a simple axisymmetric part, (b) Load variation during the stroke for forging the part. (Adapted from Kalpakjian, S. and Schmid, S. *Manufacturing Processes for Engineering Materials*, 5th Ed., Prentice-Hall, Englewood Cliffs, NJ, 2007.)

forging of a relatively simple axisymmetrical forging. At the onset of deformation the initial stock material (billet) is upset, and the corresponding forging load is relatively low. Upsetting-type deformation is the most natural form of deformation between dies and the material flows sideways, to form a flattened shape. However, if material is to be forced to move into the extremities of the die cavity, this sideways material flow must be restricted. This is the role of flash formation. A narrow flash land around the split line of the dies restricts the sideways flow of the material. In the final stages of die closure, material is extruded through the flash land into the flash gutter around the forging cavity. As the deformation proceeds, the narrowing gap between the flash lands begins to restrict the sideways flow of material, through increased friction and other forces. The forging load begins to rise and the pressure inside the die increases. This increased pressure causes material to flow backwards in the direction of die closure and into the extremities of the die cavity. At the final stage of die closure, the forging load reaches its peak and this corresponds to complete die filling. At this point, the last part of the flash is squeezed through the flash land. The selection of appropriate values for the flash land geometry (gap and width) is critical to good die filling during forging, without excessive forging loads and cavity pressures.

14.3.1 Determination of the Flash Land Geometry

Figure 14.3 shows a typical arrangement for the flash land and the flash gutter on a forging. The gutter must be large enough to accommodate the flash produced. The choice of the appropriate width and thickness of the flash land is an important part of the forging

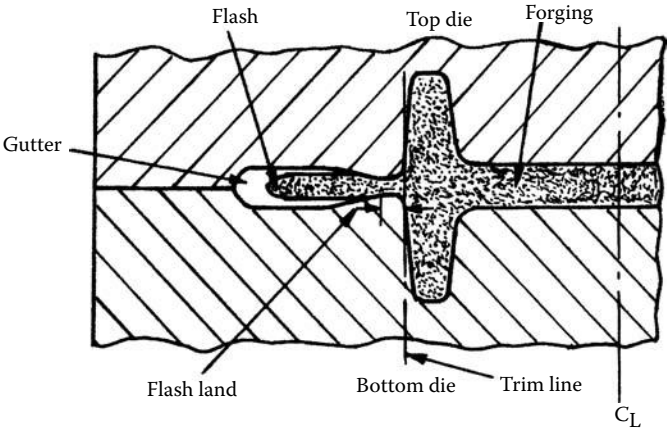


FIGURE 14.3
Flash land and flash gutter configuration.

process design. If the geometry is wrong, the dies may not fill completely or the forging loads may become excessive. In addition, the projected area of the flash in the flash lands is usually included in the total projected area of the part for estimation of the forging loads required and therefore is a determining factor in equipment selection for processing. Determination of the flash land dimensions has been based on experience with forgings of a similar type. As a result there are a number of empirical formulas available for the flash land geometry, and a selection of these is given in Table 14.1 [2].

The first two formulas take no account of the forging complexity and the third formula is based on a limited number of axisymmetric forgings. The fourth and fifth formulas are based on statistical analysis for a large number of forgings and have been shown to be reliable [2,8], each giving similar results. The fourth formula is used here for the cost estimation procedures described below, because it is simpler to evaluate. This formula is based on data for steel forgings, but it is assumed to be applicable to all materials and is used in the following form in which the main input variable is part volume, V, as opposed to part weight.

$$\text{Flash thickness, } T_f = 1.13 + 0.0789V^{0.5} - 0.000134V \tag{14.1}$$

$$\text{Flash land ratio, } \frac{W_f}{T_f} = 3 + 1.2e^{-0.00857V} \tag{14.2}$$

TABLE 14.1

Selected Empirical Formulas for Flash Land Geometry

Reference	Flash Thickness, T_f (mm)	Flash Land Ratio, W_f/T_f
Brachanov and Rebelskii [3]	$0.015A_p^{0.5}$	—
Voiglander [4]	$0.016D + 0.018A_p^{0.5}$	$63D^{0.5}$
Vierrege [5]	$0.017D + 1/(D+5)^{0.5}$	$30/[D\{1 + 2D^2/(h(2r+D))\}]^{0.33}$
Neuberger and Mockel [6]	$1.13 + 0.89W^{0.5} - 0.017W$	$3 + 1.2e^{-1.09W}$
Teterein and Tarnovski [7]	$2W^{0.33} - 0.01\,W - 0.09$	$0.0038ZD/T_f + 4.93/W^{0.2} - 0.2$

A_p, forging projected area (mm^2); W, forging weight (kg); D, forging diameter (mm); Z, forging complexity factor.

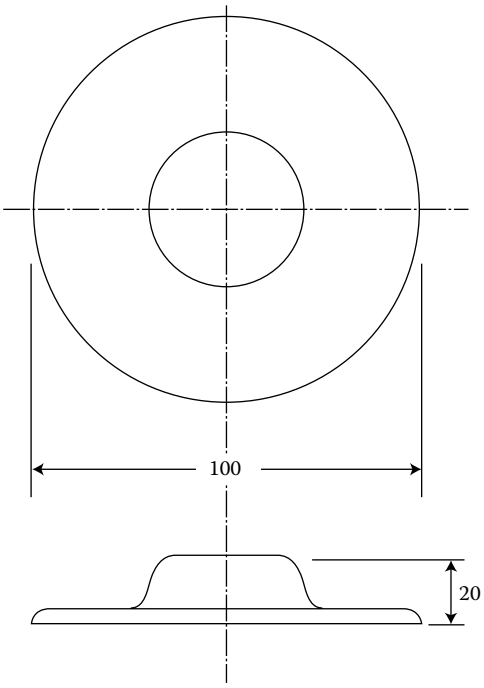


FIGURE 14.4
Steel forging for sample calculations.

This formula is used to determine the area of the flash during forging. The land width, W_f is multiplied by the length of the flash line of the finish forging die (perimeter of the part, P_r).

EXAMPLE

Figure 14.4 shows simple steel forging that will be used to illustrate the subsequent calculations in this chapter. The basic data for this part are as follows:

Part volume $V = 49.9$ cm^3
Projected area $A_p = 78.6$ cm^2
Perimeter $P_r = 31.4$ cm

For this part the flash parameters can be obtained from Equations 14.1 and 14.2.

$$T_f = 1.13 + 0.0789\ (49.9)^{0.5} - 0.000134\ (49.9) = 1.68 \text{ mm}$$
$$W_f/T_f = 3 + 1.2e^{-0.00857(49.9)} = 3.78$$

From this, W_f is $3.78 \times 1.68 = 6.35$ mm, and the projected area of the flash land is $0.635 \times 31.4 = 19.9$ cm^2.

14.3.2 Amount of Flash

Costs for the material in forging are determined by the weight of the finished forging and any material wasted in processing the part. Material losses result mainly from the flash

produced during forging, but further losses may occur due to scale formation for those materials that oxidize significantly during heating and, for hammer forgings, due to bar ends, and so on. Estimation of the flash for a particular forging is difficult and is usually based upon experience with the manufacture of forgings of a similar type. The amount of flash produced varies with the shape of the part, and there are two basic systematic approaches to estimating the amount of flash that have been utilized.

1. Statistical data giving average ratios of the gross to net weight of forgings for different classes of part and weight are used. This approach has been utilized in different forms by Morgeroth [9], Kruse [10], and the FIA [11] for steel forgings.
2. The use of average values of the flash amount per unit length of the flash line for different weights of forging (e.g., Refs. [8] and [12]).

For the estimating procedures described in this chapter, the second of these approaches has been used. Table 14.2 shows data relating the flash weight per unit length of flash line for different weights of forging. This data has been recommended by the United Kingdom National Association of Drop Forgers and Stampers (NADFS) and has been found to be reliable by companies who use it for flash estimation [8]. These data are for the forging of steel and it has been assumed that the equivalent volume is produced in other materials. This equivalent volume of flash can be obtained by dividing by the density of steel. An expression has been fitted to these data to enable the volume of flash per unit length of flash line to be estimated, and this relationship is as follows:

The volume of flash per unit length of flash line, V_{fl}, is given by

$$V_{fl} = 0.1234V^{0.5}\ \text{cm}^3/\text{cm} \tag{14.3}$$

EXAMPLE

For the part shown in Figure 14.4 the volume of flash per centimeter of flash line from Equation 14.3 is $V_{fl} = 0.1234\ (49.9)^{0.5} = 0.87\ \text{cm}^3/\text{cm}$ or the total volume of flash generated is $0.87 \times 31.4 = 27.3\ \text{cm}^3$.

TABLE 14.2

Flash Weight per Unit Length of Flash Line for Steel Forgings

Forging Weight (kg)	Flash Weight (kg/cm of Periphery)
Less than 0.450	0.0047
0.450–2.273	0.0063
2.273–4.545	0.0098
4.545–6.818	0.013
6.818–11.364	0.0168
11.364–22.727	0.0223
22.727–45.455	0.0324
Above 45.455	0.0477

Source: Adapted from Choi, S.H. and Dean, T.A. *International Journal of Machine Tool Design and Research*, 24, pp. 105–119, 1984.

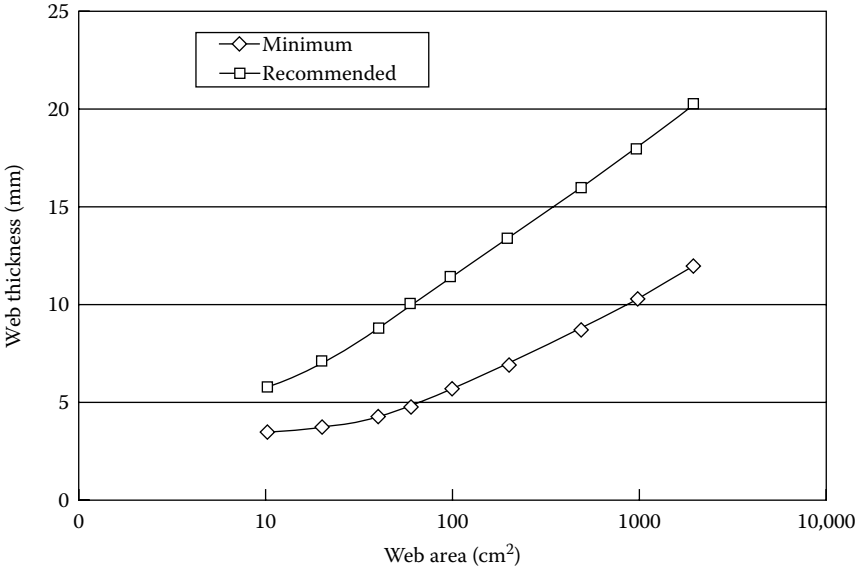


FIGURE 14.5
Web thickness related to projected area. (Adapted from Thomas, A. *Die Design*, Drop Forging Research Association, Sheffield, UK, 1980.)

14.3.3 Webs in Forgings

Webs are thin sections with a large projected area in the direction of die closure. Webs are often designed into the parts for strength and other reasons, often accompanied by peripheral ribs. These webs add considerably to the load requirements during forging operations because of the large die contact areas, which increase cooling rates, friction, and so on. If the finished part has through holes to be forged in, then these must be filled with webs at the die parting line and then these webs are removed by shearing (piercing) during the flash removal process. The material in these webs is additional waste material and adds to the material cost per part.

The appropriate thickness of the webs is dependent on the projected area of the holes to be filled, as shown in Figure 14.5, from which the following relationship is obtained:

$$\text{Web thickness } T_w \text{ (mm)} = 3.54\ A_H^{0.227}, \tag{14.4}$$

where A_H *is* the area of the holes in square centimeters.

14.4 Forging Allowances

Parts produced by hot forging require machining on surfaces that locate with other parts in a final product. Thus, the detailed shape features of a forging are developed from the required-machined part by adding various allowances to the machined surfaces, although some of these allowances also form part of the forging design for surfaces that would not be machined. Figure 14.6 shows the cross-section of a simple forging, which is assumed to

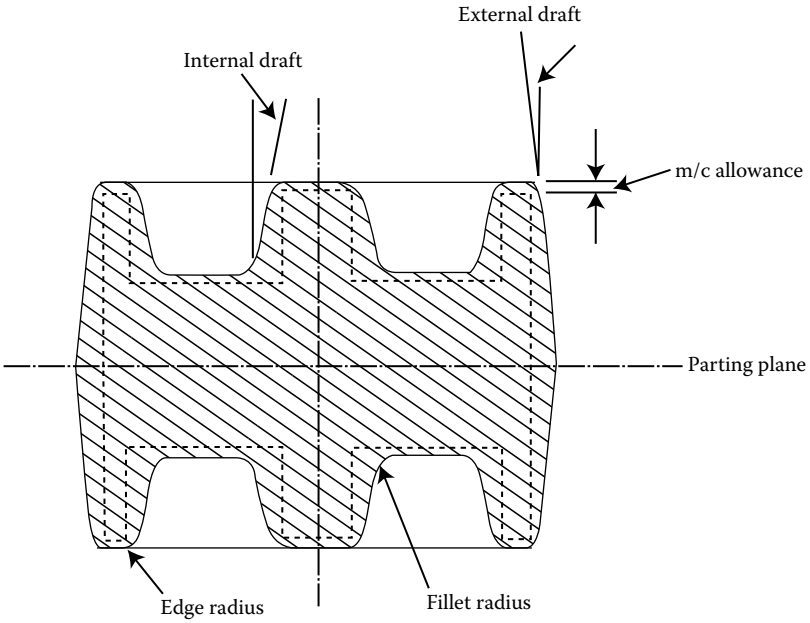


FIGURE 14.6
Forging allowances for finish machining and draft.

be machined all over. The first allowance added to the machined surface is a finish or machining allowance. This amount is in addition to any dimensional tolerances and must be sufficient to result in a clean surface after finish machining. The allowance for machining is dependent on several factors, but particularly on the amount of oxidation that results from heating the part up to the forging temperature. The level of oxidation is dependent on the material type and on the overall size of the forging. Figure 14.7 shows typical finish allowances for different materials [13].

Draft is an angle allowance added to surfaces parallel to the direction of die closure to facilitate release of the part from the die after forging. In general, draft allowances on inside surfaces are greater than those on outside surfaces because of the tendency of the part to shrink onto projections in the die as cooling takes place. Table 14.3 gives recommended values of draft angles for both presses and hammers [2].

Finally, all edges and corners in the part must have radii added. These radii are necessary to aid material flow and ensure good die filling. In addition, sharp corners in dies can lead to premature die failure due to fracture as a result of associated stress concentrations, high stresses, and so on. Table 14.4 shows typical recommendations for edge and fillet radii for different materials. In general, larger radii are recommended for the more difficult-to-forge materials.

14.5 Preforming during Forging

In practice, very few forgings are produced in the one stage indicated in Figure 14.2. This usually results in excessive amounts of flash to ensure die filling and/or large die loads.

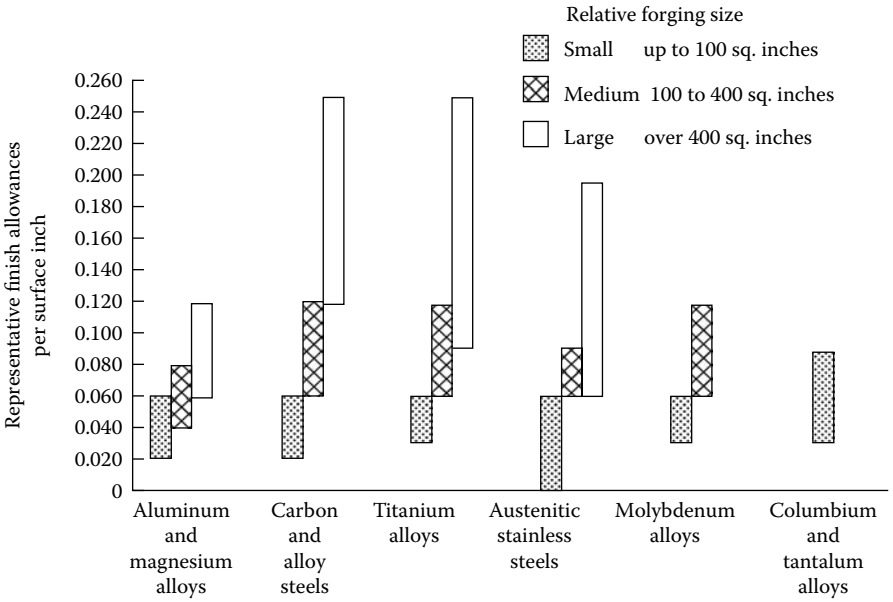


FIGURE 14.7
Finish machining allowances for different materials. (Adapted from Jensen, J.E. *Forging Industry Handbook*, FIA, Cleveland, 1970.)

TABLE 14.3

Draft Allowances for Forgings

	Hammer Dies		Press Dies	
Materials	**External**	**Internal**	**External**	**Internal**
Steels				
Aluminum alloys	5–7°	7–10°	3–5°	5–7°
Titanium alloys				
Ni-based alloys				
Tolerances in all cases	±1°	±1°	±1°	±1°

Source: Adapted from Thomas, A. *Die Design*, Drop Forging Research Association, Sheffield, UK, 1980.

TABLE 14.4

Typical Minimum Edge and Fillet Radii for Rib/Web Type Forgings

Material	**Corner Radius (mm)**	**Fillet Radius (mm)**
Aluminum alloys	2.3	9.7
Low alloy steels	3.0	6.4
Titanium alloys	4.8	12.7
Nickel-based superalloys	6.4	19.0
Iron-based superalloys	4.8	17.0
Molybdenum	4.8	12.7

Source: Adapted from Jensen, J.E. *Forging Industry Handbook*, FIA, Cleveland, 1970.

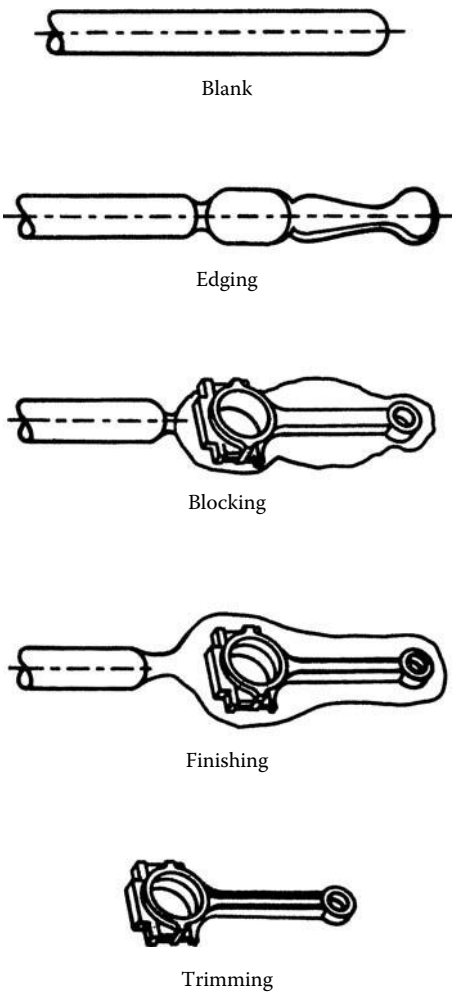


FIGURE 14.8
Typical forging sequence for a connecting rod. (Adapted from. Kalpakjian, S. and Schmid, S. *Manufacturing Processes for Engineering Materials*, 5th Ed., Prentice-Hall, Englewood Cliffs, NJ, 2007.)

Thus, in most cases, a series of preforming operations are necessary to gradually bring the stock material closer to the finished shape before the last forming stage in the finishing die cavity (finisher). The number and type of preforming operations depend largely on the finished forging shape. Figure 14.8 shows a typical sequence for a simple connecting-rod forging [1].

In most cases, the starting point of forging is a simple shape—either a length of round or square section bar or a billet cut off from bar stock. The object of preforming is to redistribute the stock material to correspond more closely to the finished shape. The design of preforms is still something of a "black art," relying heavily on the skills of experienced personnel. Progress has been made in the application of finite-element and upper-bound plasticity analyses to the design of preforms, but this is still a subject of research [14,15].

Most flat or compact forgings start from billets and can usually be produced in two to four forming stages. The first forging stage is usually a simple die, which may just be flat

faces, called a buster or scale-breaking die. The purpose of this die is to do some initial flattening of the billet, largely to remove the scale produced by oxidation during heating. For simple shapes, the material may then be forged in the finishing die. However, for most parts one or two more preforming stages are necessary. The preform prior to finishing is called a blocker (sometimes called a semifinisher or in the United Kingdom a molding impression). The blocker is essentially a smoothed-out version of the finisher with thicker sections and larger radii. There are some well-accepted design rules for blocker cross-sections [16]. Figure 14.9 [17] shows some typical blocker sections relative to finisher cross-sections. If the final part has thin and/or tall features (thin ribs and webs), then a preblocker may also be required and this will have thicker sections and larger radii than the blocker.

For long parts, the starting point is usually the heated end of a bar of material of constant cross-section. The initial preforming stages are relatively simple open-die forging operations, the purpose of which is to distribute the material along the length of the forging to correspond more closely to the mass distribution of the finished part. This is achieved by using relatively simple dies called fullers, followed by a die called an edger (or in the United Kingdom a roller die). Figure 14.10 [17] shows a typical sequence for forging a connecting rod. Fullers are used to elongate and draw down the bar stock as appropriate. Fullers have crowned faces and the stock is placed between the dies, with one or two blows taking place. The stock is then rotated through 90° and the process is repeated. Usually, only one

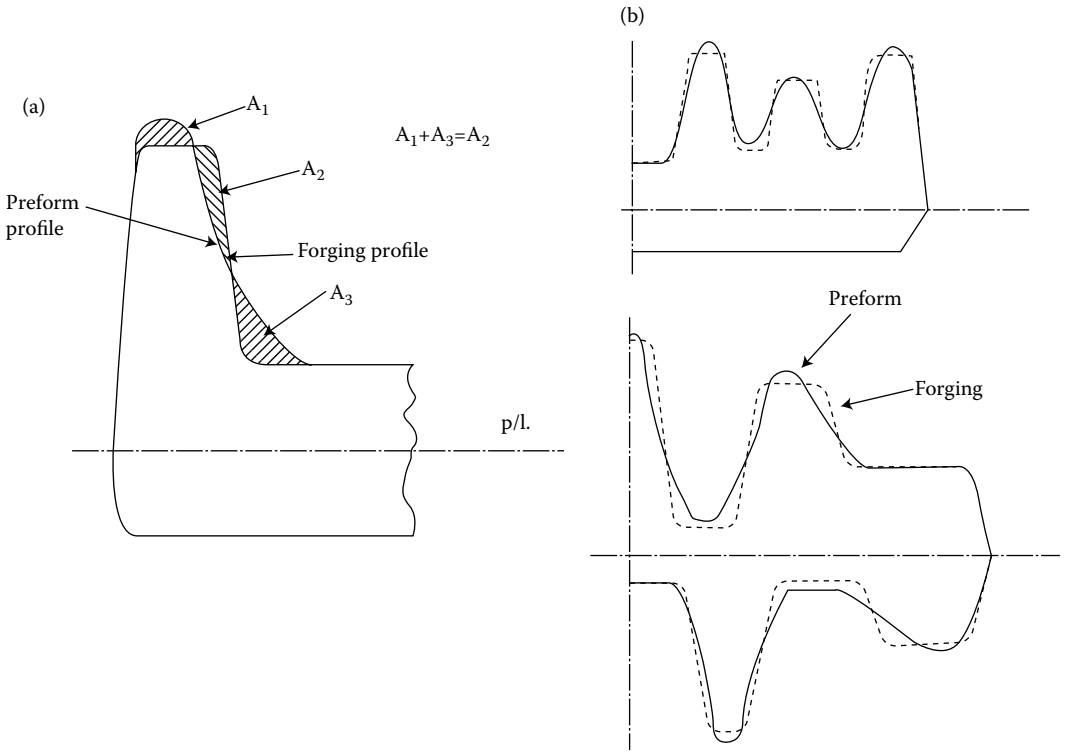


FIGURE 14.9
Typical blocker cross-sections compared to the finish forging cross-sections. (a) General design procedure, (b) Sample cross-sections. (Adapted from Biswas, S.K. and Knight, W.A. *International Journal of Production Research*, 14, pp. 23–49, 1976.)

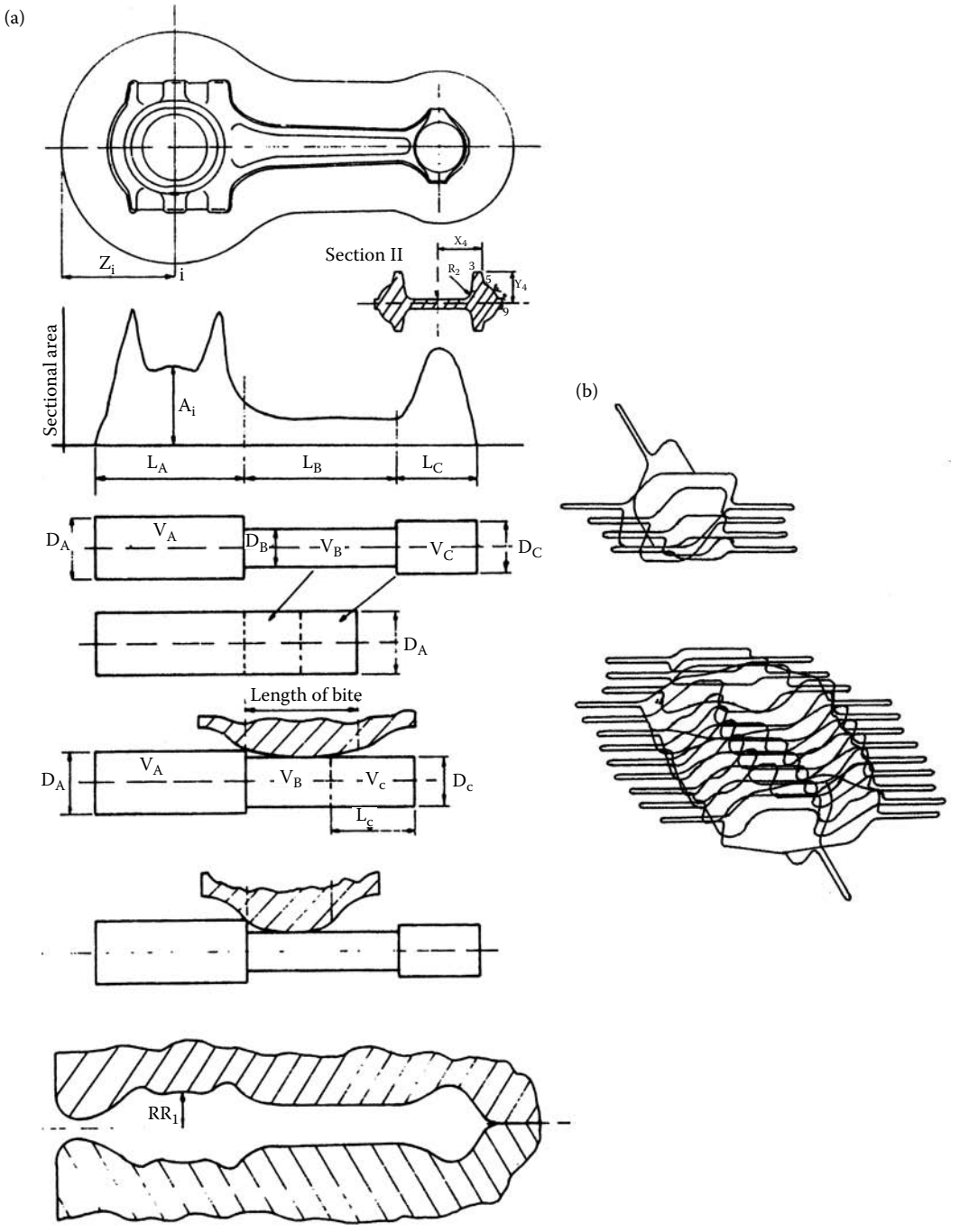


FIGURE 14.10
Forging sequence design for a connecting rod. (a) Mass distribution stages, (b) Blocker cross-sections. (Adapted from Biswas, S.K. and Knight, W.A. *International Journal of Production Research*, 14, pp. 23–49, 1976.)

fuller stage is used, but if there are two or more major changes in the cross-sectional area along the length of the part, more than one fuller may be used. After fullering, the edger or roller die is used to smooth out the stock material and to further elongate it somewhat.

For the connecting-rod example in Figure 14.10, after two fullering stages and one edger die, the result is a dumbbell shape, with approximately round cross-sections and with an axial mass distribution similar to the finished shape. These initial mass-distribution-preforming stages can be done on reducer rolls, which use a series of shaped rolls to elongate and draw down the bar stock. Reducer rolls are sometimes used in conjunction with mechanical presses for higher productivity.

Following these initial mass-distribution-preforming stages, the cross-sections of the part are then formed to correspond to the finished shape. For simple shapes this may be done directly in the finishing cavity, but usually a blocker die is used, and for forgings with very thin sections a preblocker may also be required. The usual reason to include a blocker forging stage is to increase the life of the finishing-die impression before resinking is necessary. Whether a blocker die is required is usually decided based on experience with similar parts and on the total quantity of forgings required. For simple forgings no blocker impression may be needed. Chamouard [16] gives recommendations for the use of blocker impressions for rib/web-type forgings, based on the rib height to rib thickness ratio. A blocker impression is recommended when this ratio exceeds 2.5.

Blocker forging cross-sections are essentially smoothed-out versions of corresponding sections in the finished forging, with thicker sections and larger radii. The blocker sections are designed by modifying the corresponding finished sections, using empirically established design rules. For a connecting-rod forging several transverse sections along the length of the part would be selected, together with radial sections at the ends (Figure 14.10). From these sections corresponding blocker sections are developed, and these define the shape of the blocker die impression. For rib/web-type cross-sections, blocker sections have been developed using logarithmic curves, based on the recommendations of Chamouard [16].

If the final forging has bends in the longitudinal axis, a bending operation is added to the sequence. In this case the mass-distribution-preforming stages (fullers and edgers) are developed with the axis of the part straightened out, followed by the bending impression. Any blocker stages are carried out on the bent stock, and again the corresponding die is developed from cross-sections of the finishing impression.

14.5.1 Die Layout

As seen above, several die impressions are needed to process a hot forging completely. For small and medium-sized hammer forgings these impressions are laid out on a single die block. Figure 14.11 shows two typical examples [18]. For larger forgings, the various stages may be carried out on separate machines with reheating of the forging stock between stages. For press forgings, the various die impressions may be machined into one die block or into separate die inserts attached to the machine bed.

For multiple impression dies, the various impressions must be laid out on the die surface to enable successful forging with a minimum-sized die block. The die block depth should be sufficient to enable several resinks of the cavities as wear occurs. A number of factors must be taken into account in the layout of die impressions, including the minimum spacing between cavities, which depends among other things on the cavity depth. In general, the finisher and blocker impressions are placed in the center of the die block, with the

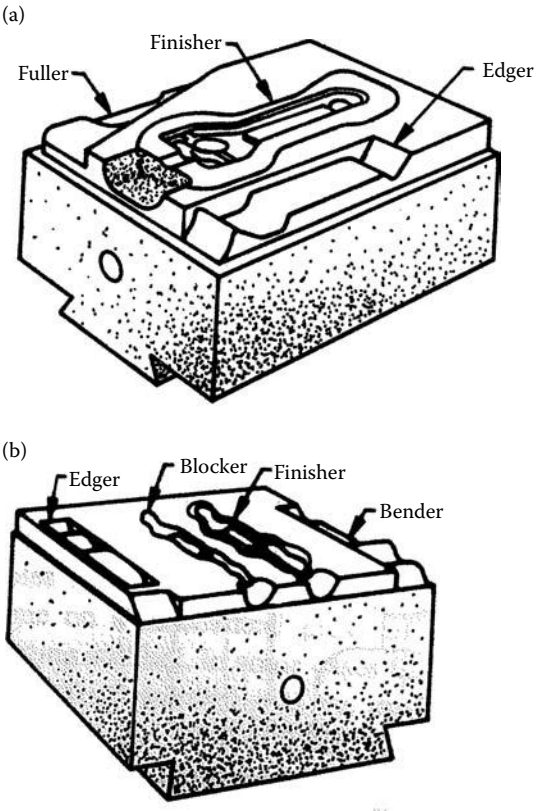


FIGURE 14.11
Typical multi-impression hammer forging dies. (Adapted from American Society of Metals, *Metals Handbook: Metalworking-Bulk Forming*, Vol. 14, Part A, ASM, Cleveland, 2005.)

fullers to one side and the edger and/or bending die to the other (Figure 14.12). The finisher is positioned such that the center of loading corresponds to the dowel pin that is used to position the dovetails on the back of the die on the hammer bed. If more than one forging is to be made at once, the finisher and blocker impressions can sometimes be nested to conserve space. The fuller dies are usually inclined at 10–15° across the left-hand corner of the die block, again to conserve space. For the purposes of estimating die block size, the following cavity-spacing rules, derived from data provided by Thomas [2], can be used:

- Cavity depth $d_c = 0.5T$, where T is the part thickness
- Cavity spacing $S_d = 3.1(d_c)^{0.7}$
- Cavity edge distance $S_e = 3.4(d_c)^{0.76}$
- Die block depth = $5d_c$

Die locks or registers are provided on some dies to prevent mismatch during forging for parts with cranked parting lines. Die locks absorb the side loads produced, but add to the size of the die block and increase the machining costs of the die blocks. Figure 14.13 shows a typical die lock configuration. To be effective, the die lock must engage just before the top die comes into contact with the forging stock. An overlap of 10–12 mm is recommended, and to allow adequate strength the width of the lock should be at least 1.5 times the depth [1].

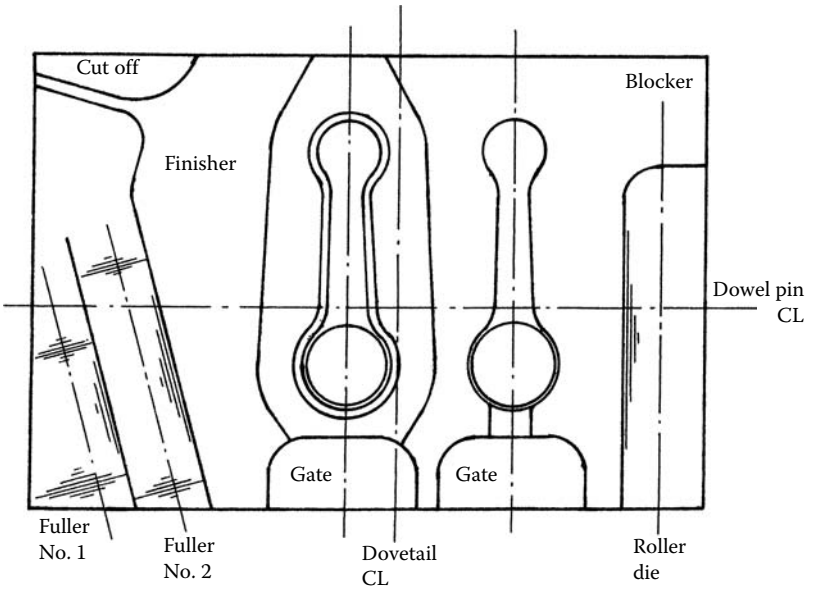


FIGURE 14.12
Die layout for hammer forging die. (Adapted from Biswas, S.K. and Knight, W.A. *International Journal of Production Research*, 14, pp. 23–49, 1976.)

If the die parting line is only marginally cranked, a die lock may not be required, but for the purposes of the classification of forgings below it is assumed that locked dies are necessary for forgings with cranked parting lines.

14.6 Flash Removal

The final stage in hot forging is the removal of the flash to yield the finish forging. The flash removed is scrap material and can be more than 50% of the material used for some

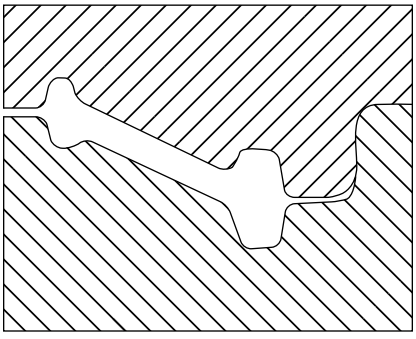


FIGURE 14.13
Typical die lock configuration. (Adapted from Thomas, A. *Die Design*, Drop Forging Research Association, Sheffield, UK, 1980.)

forgings. The flash is usually removed with a trimming die, which shears the flash off at the parting line of the forging. The webs in any through-holes are also pierced out at the same time. Flash trimming is usually done on a mechanical press adjacent to the main forging machine, with the forging still hot. In some cases, flash trimming may be done later when the part is cold. The operation and the dies used are similar for both hot and cold flash trimming, but the press loads are higher for cold flash trimming. The flash may also be removed by a machining operation, such as band sawing, but this is slow and relatively expensive. Consequently, band sawing should only be considered for small quantities of parts or for some larger forgings.

Trimming and piercing dies have a shearing edge corresponding to the parting line of the forging. The complexity is therefore increased by the need for a cranked parting line. The corresponding punch forces the forging through the trimming die to remove the flash, and the design of the punch must be such that this can be achieved without distortion or damage to the forged part.

14.7 Classification of Forgings

A number of classification schemes for forgings have been developed over the years [19]. These range from relatively simple pictorial systems to quite complex numerical coding schemes. The general objective has been to indicate forging complexity in some way in order to relate this difficulty to different aspects of the forging process design. Several early systems were proposed to systematically provide data on typical gross to net weights for different forging types for estimating purposes [9–11].

A relatively complex classification and coding scheme was used in a *Design for Forging Handbook* [20], in order to indicate general forging costs [21]. This classification scheme covered the presence of individual shape features of the forging such as holes, depressions, bosses, ribs, and so on. Parts were allocated to different classes dependent on the presence of these features. For the purposes of the current procedure a more simplified approach based not on the presence of specific features, but on numerical evaluations of complexity, is used [12]. Parts are first divided into main classes determined by the overall dimensions of the rectangular envelope that encloses the part (Figure 14.14). For long forgings with a bent axis this envelope is determined after the part has been straightened out. This initial broad classification divides parts according to the basic sequence of operations required for processing.

Class 0: Compact Parts ($L/W \leq 2.0$, $L/T \leq 2.0$) (Figure 14.15)

The basic sequence of operations for this class is

Scale break (buster)

Blockers (one or two)

Finisher

Clip and pierce to remove flash and webs for through-holes

The forging complexity for this class is increased by the presence of

Thin sections

Cranked die split lines

Forged in side depressions

<table>
<tr><td>First digit</td><td colspan="2">Description</td></tr>
<tr><td>0</td><td colspan="2">Compact parts
$L/W \le 2, L/T \le 2$</td></tr>
<tr><td>1</td><td colspan="2">Flat parts
$L/W \le 2, L/T > 2$</td></tr>
<tr><td>2</td><td rowspan="2">Long parts
$L/W > 2$</td><td>Main axis straight</td></tr>
<tr><td>3</td><td>Main axis bent</td></tr>
</table>

L = Envelope length
W = Envelope width
T = Envelope thickness
$L \ge W \ge T$

FIGURE 14.14
Forging classification, allocation of first digit.

Class 1: Flat Parts ($L/W \le 2.0$, $L/T > 2.0$) (Figure 14.15)

The basic sequence of operations for this class is

Scale break (buster)
Blockers (one or two)
Finisher
Clip and pierce to remove flash and webs in through-holes

The forging complexity for this class is increased by the presence of

Thin sections
Ribs and webs
Cranked die split lines
Forged in side depressions

Classes 2 and 3: Long Parts ($L/W > 2.0$) (Figure 14.16)

The basic sequence of operations for these classes is

Fullers (one or two)
Edger (roller)
Bender (for bent parts)
Blockers (one or two)
Finisher
Clip and pierce to remove flash

In some cases, passes through reducer rolls may replace the first two stages. The forging complexity for these classes is increased by the presence of

Large changes in cross-sectional area

Second digit	Description	
0	Parting line flat	No side Depressions
1	Parting line not flat	
2	Parting line flat	Side Depressions
3	Parting line not flat	

FIGURE 14.15
Allocation of second digit for compact and flat parts.

Thin sections
Ribs and webs
Cranked die split lines

EXAMPLE

For the part shown in Figure 14.4, $L = W = 100$ mm and $T = 20$ mm. Thus, $L/W = 1$ and $L/T = 5$. The first digit is 1 (flat part). There are no side depressions and the parting line is flat, and so the second digit is zero (Figure 14.15).

14.7.1 Forging Complexity

Two numerical indications of forging complexity are used: the shape complexity factor and the number of surface patches in the part.

14.7.1.1 Shape Complexity Factor

This factor is a modification of that used in the European tolerance standards for forgings to indicate complexity [22], that is

$$\text{Complexity factor } F_{\text{fc}} = \frac{\text{Volume of rectangular envelope for part}}{\text{Part volume}} = \frac{LWT}{V}$$

Second digit	Description
0	Parting line flat
1	Parting line not flat

FIGURE 14.16
Allocation of second digit for long parts.

For bent parts, the axis is straightened before this complexity factor is calculated. This factor indicates in a general way the amount of deformation necessary within specific classes of forging, as the presence of thin sections and large changes in cross-sectional area result in increased values of this complexity rating. For the example part shown in Figure 14.4, $F_{fc} = 4.00$.

14.7.1.2 Number of Surface Patches in the Part

This rating is similar to the counting procedure for surface patches used for cost estimation for injection molded parts as outlined in Chapter 8. The number of surface patches that make up the shape in the upper and lower cavities is counted. All standard surface elements, such as planes, cylinders, cones, and so on, are given equal rating, but free form or sculptured surface elements are counted equal to four standard surface patches. This number is a measure of the forging complexity that indicates the presence of more complex shape features. For example, a multiribbed part has increased numbers of surface elements present relative to a simpler forging.

14.8 Forging Equipment

Hot forgings can be produced on a variety of equipment, including mechanical and hydraulic presses, friction screw presses, and hammers. This forging equipment can be divided into two basic types: work-restricted and stroke-restricted machines. In work-restricted machines, the amount of deformation that can be achieved during each stroke or blow of the machine is limited by the energy or maximum force available. If the energy or force capacity is less than is required to deform the part, then more than one stroke or blow is needed. Machines that fall into this category are hammers, friction screw presses, and hydraulic presses. In stroke-restricted machines the amount of deformation that can be done is fixed by the stroke of the machine. If sufficient force or energy to carry out the operation is not available, then the machine stalls and a larger machine should be used. Mechanical presses fall into this category, as a crank or eccentric determines the amount of ram movement.

Hammers are the most common types of machine used [23], and the basic technology of forging hammers was developed in the eighteenth century. The choice of forging equipment depends on a number of factors, including part size and complexity, material, and the quality of the parts to be produced. Hammers are often preferred for small to medium batches because of quicker tool setups and lower overheads. They are also used for elongated and branch-type forgings, because die areas can be provided for the larger number of preform dies required for such shapes. Additionally, mechanical presses are not available in very large load capacities, so, for large forgings, hammers or large hydraulic presses must be used.

14.8.1 Gravity Drop Hammers

Gravity drop hammers [18] are the oldest type of forging equipment available. The principle of operation is that the moving die block (tup) is raised by a lifting mechanism and then released, so that it falls onto the fixed die attached to the anvil. The amount of deformation that can be carried out is determined by the potential energy of the moving die

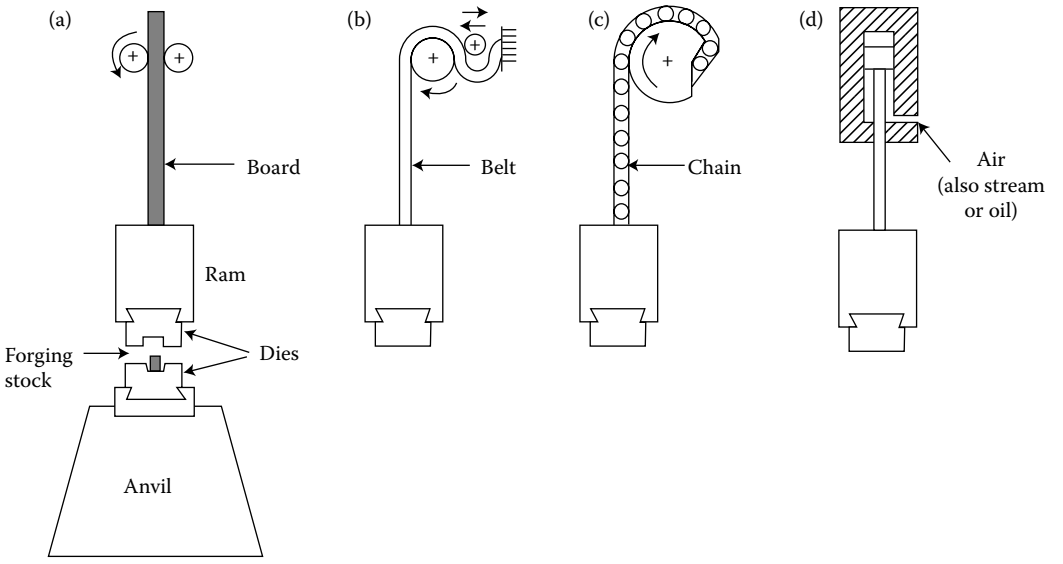


FIGURE 14.17
Schematic of various types of drop hammer: (a) Board hammer, (b) Belt hammer, (c) Chain hammer, (d) Airlift hammer. (Adapted from Kalpakjian, S. and Schmid, S. *Manufacturing Processes for Engineering Materials*, 5th Ed., Prentice-Hall, Englewood Cliffs, NJ, 2007.)

block at its maximum height. This potential energy is converted into kinetic energy as the die block falls and is then dissipated in the deformation of the workpiece. Various lifting mechanisms are used, including frictional means with boards, band brakes or belts, or a lifting cylinder employing steam, compressed air, or hydraulic fluid (Figure 14.17). These machines are available in a range of blow energies from 0.6 kN m (60 kg m) to 400 kN m (40,000 kg m).

14.8.2 Double Acting or Power Hammers

These machines [18] are similar to gravity hammers in that a lifting cylinder raises the moving tup, but power is also applied to the downward-moving tup to increase the energy capacity. Energy ratings for similar tup weights are considerably more than for gravity hammers, and the die closing speeds are higher also. Power comes from double-acting steam, compressed air, or hydraulic cylinders. Double-acting hammers are manufactured in a range of energy ratings from 3 kN m (300 kg m) to 825 kN m (82,500 kg m).

14.8.3 Vertical Counterblow Hammers

In these machines, two tups with nearly equal masses are driven by double-acting cylinders toward each other and impact in the center of the machine. More energy is dissipated in the workpiece than in the foundations and subsoil compared to single-acting hammers. Very high-energy capacities are available in the largest machines, with ranges from 30 kN m (30,000 kg m) to 2000 kN m (200,000 kg m).

14.8.4 Horizontal Counterblow Hammers

These machines are also called impacters and two rams are actuated by double-acting cylinders. The heated stock is positioned vertically between the dies by an automatic transfer mechanism. Energy ranges from 4 kN m (400 kg m) to 54 kN m (5400 kg m) are typical.

14.8.5 Mechanical Presses

In mechanical presses [18], a crank, knuckle joint, scotch yoke, or moving-wedge mechanism is used to apply a vertical squeezing motion between the upper moving die and a lower fixed die. Figures 14.18a and b show typical mechanical press mechanisms. In general, the guidance of the two dies is better than in hammers, and so improved die matching is possible. Press ratings from 3 to 140 MN (300–14,000 tons) are available. Thus, mechanical presses are not available for the largest of parts processed by forging.

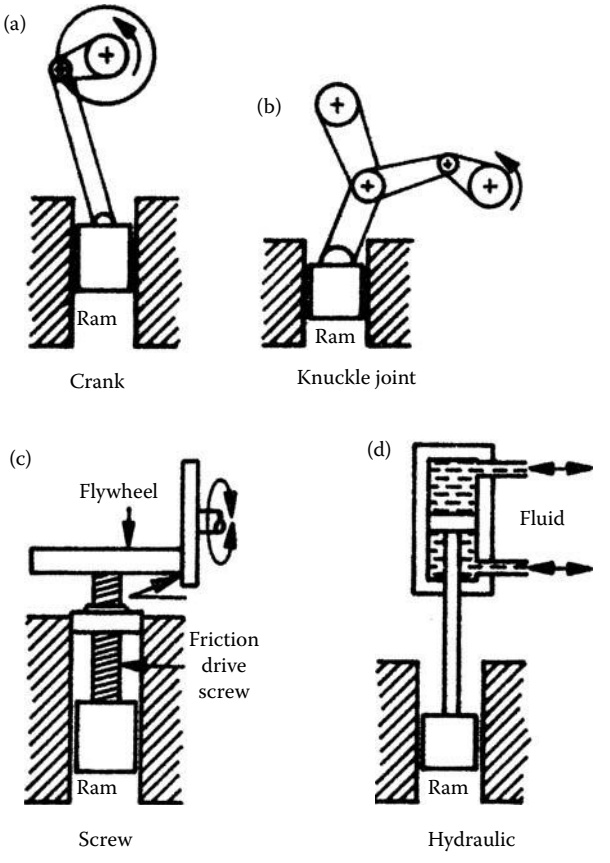


FIGURE 14.18
Schematic of various types of forging press mechanisms: (a) Crank press, (b) Knuckle joint press, (c) Friction screw press, (d) Hydraulic press. (Adapted from Kalpakjian, S. and Schmid, S. *Manufacturing Processes for Engineering Materials*, 5th Ed., Prentice-Hall, Englewood Cliffs, NJ, 2007.)

14.8.6 Screw Presses

In screw presses [18], the upper ram and die are connected to a large vertical screw that can be rotated by a flywheel, so that the ram can move up and down relative to the fixed die in the bed of the machine (Figure 14.18c). The ram has a limited amount of energy for each stroke; thus, multiple blows are usually employed similar to hammers. Screw presses are available in ratings from 0.63 to 63 MN (63–6300 tons).

14.8.7 Hydraulic Presses

Hydraulic presses [18] are available in a wide range of sizes up to the largest at 50,000 tons or more capacity. The moving die is attached to a ram actuated by a large hydraulic cylinder (Figure 14.18d). Various strokes, forces, and closing speeds can be obtained on hydraulic presses. In some cases, hydraulic presses are fitted with auxiliary horizontally moving rams, and these enable side depressions to be forged into some parts, although this is not done to a great extent.

14.8.8 Choice of Forging Machine Type

In general, whether to use hammers or presses depends on a number of factors, but some guidelines exist [23].

Circular or ring forgings in steels are particularly suited to crank presses until the dimensions of the forgings result in loads in excess of the range of mechanical presses, when power or counterblow hammers become necessary.

Asymmetrical and branched forgings tend to be produced on hammers, as more total die area is required than is available on mechanical presses of appropriate load capacity.

Large circular forgings are manufactured using hammers because of the large force requirements.

Close-to-form blade-type forgings tend to be made using screw presses or with wider tolerances on hammers.

Thin-plate-type forgings with edge ribs, together with light alloy precision forgings are usually produced on hydraulic presses.

Smaller batch sizes tend to be made on hammers rather than presses.

TABLE 14.5

Some Comparative Data for Forging Equipment

Hammers	Maximum Blow Energy (kJ)	Die Closing Speed (m/s)
Gravity drop	47–120	3–5
Power drop	1150	4.6–9
Counterblow	1220	4.6–9
Impacter	34	10–17
Presses	Force (MN)	—
Mechanical	2.2–143	0.06–1.5
Screw	1.3–280	0.5–1.2
Hydraulic	2.2–623	0.03–0.8

Source: Adapted from Wick, C. ed., *Tool and Manufacturing Engineers Handbook: Forming*, 2nd Ed., Society of Manufacturing Engineers, Detroit, August, 2003.

14.8.9 Comparisons of Forging Equipment

Table 14.5 [24] shows some comparative data for the different types of forging equipment. As can be seen, die-closing speeds are significantly higher for hammers compared to presses. This has relevance for the forging of strain rate-sensitive materials. Table 14.6 shows the ranges of the different types of forging equipment available. The different machines are compared based on their maximum deformation energy capacity. However, this comparison is not related to the energy available per blow or stroke of the machine, but is based on the energy requirements for parts typically processed on the size of machine indicated. The relative comparisons between machines are derived from ratios presented in Dallas [24] and other reports. The ratings at the top of each column are those normally used in industry, with hammers usually rated by the weight of the tup and presses by the load capacity in tons. As can be seen, mechanical presses are not usually available above 14,000 tons capacity; thus, large forgings must be produced on either hammers or hydraulic presses, with the largest restricted to counterblow hammers or large hydraulic presses.

Figure 14.19 shows typical average usable blow or stroke rates for forging equipment. These data are largely based on data from Scott and Wilson [23], with some supplementary calculations from Dallas [24]. These blow rates are not the maximum obtainable from the equipment, but are typical usable blow rates, which reflect such factors as the time taken to manipulate the part between impressions. As can be seen, mechanical presses are capable of the highest usable blow rates for smaller parts, which is why they are preferred for higher productivity situations for parts that are appropriate. For large parts, the usable blow rates become comparable for the various types of equipment, because the time taken to manipulate the forgings between blows becomes dominant rather than the blow rate capabilities of the machines. These curves enable estimates of the forging cycle times to be made once an appropriate machine has been chosen.

Figure 14.20 shows data on the cost per operation for different types of forging equipment relative to the cost of a 1000 lb power hammer [25]. In this context, operation means forging stage (i.e., blocker, finisher, etc.). The data have been collected from a variety of industry sources and also reflect the fact that on average hammers utilize two or three times the number of blows per forming stage as is used on presses, for which only one per operation is assumed. Figure 14.21 [26] shows some combined curves for the data in Figure 14.20. The curve for hammers is a combination of the data for all types of hammers. In the upper range of energy capacities, the curve corresponds to counterblow hammers and at the lower ranges to power hammers. The curve for mechanical presses ends at the point of intersection with the curve for hydraulic presses. These curves can be used to estimate forging processing costs once the number of forging stages has been established.

14.9 Classification of Materials

A wide variety of materials can be used for forging, but by far the largest proportion of parts produced is from carbon and alloy steels, with a significant number also made from light alloys. Table 14.7 shows a general classification of materials used in hot forging [11,20]. These material classes are arranged roughly in increasing order of forging difficulty. However, there is considerable overlap in these classes. For example, many high-strength aluminum alloys are more difficult to process than steels. An increase in forging difficulty is represented by increased forging load requirements and usually reduced die life. In

TABLE 14.6

Equivalent Capacities of Presses and Hammers

Maximum Energy		Hydraulic Presses, Rating	Counterblow Hammers, Rating	Power Hammers, Rating	Mechanical Presses, Rating	Gravity Ddrop Hammers, Rating	Friction Screw Presses, Rating
(ft lb)	(kg m)	(tons)	(kg m)	(lb)	(tons)	(lb)	(tons)
3850	533	170	450	455	210	1000	170
5870	812	260	650	680	320	1500	250
8830	1200	400	1000	910	475	2000	390
11,000	1540	400		1000	600	2200	490
11,320	1570	550		1130	660	2500	500
14,200	1960	680		1360	820	3000	620
16,700	2310	750	2000	1500	900	3300	730
19,400	2690	900		1800	1080	4000	850
21,700	3000	935	2500	1870	1120	4100	950
22,500	3120	1000		2000	1200	4400	990
24,700	3420	1125		2250	1350	5000	1050
26,200	3630		3000				1150
28,500	3950	1250		2500	1500	5550	1250
30,000	4160	1350	3500	2700	1620	6000	1520
34,400	4770	1,500	4000	3000	1800	6600	1600
41,600	5770	1800		3600	2160	8000	1830
46,000	6370	2000	5500	4000	2400	8800	2020
52,000	7200	2250	6000	4500	2700	10,000	2290
58,000	8030	2500		5000	3000		2590
70,000	9700	3000	8000	6000	3600		3080
86,800	12,000	3700	10,000	7400	4400		3800
94,000	13,000	4000		8000	4800		4180
118,000	16,000	5000	13,000	10,000	6000		5000
138,000	19,100	5850	16,000	11,700	7000		6060
142,000	19,600	6000		12,000	7200		6220
173,000	23,900	7300	20,000	14,600	8700		7590
220,000	27,120	8300	25,000	16,600	10,000		9650
240,000	32,200	10,000	32,000	20,000	10,600		10,220
300,000	41,500	12,500	13,650	25,000	13,650		
361,500	50,070	15,000	40,000	30,000			
425,000	59,000	17,500		35,000			
	60,330	18,000		36,000			
484,000	67,036	20,000	50,000	40,000			
546,800	75,500		63,000				
610,000	84,500	25,000		50,000			
694,400	95,800		80,000				
738,000	102,00	30,000					
868,000	120,200	35,000	100,000				
1,280,000	172,000	50,000	144,000				

Source: Adapted from Knight, W.A. and Poli, C. *Design for Forging Handbook*, University of Massachusetts, Amherst, MA, 1982; Wick, C. ed., *Tool and Manufacturing Engineers Handbook: Forming*, 2nd Ed., Society of Manufacturing Engineers, Detroit, August, 2003; and Leone, J.L. *Relative Forging Costs Analysis and Estimation*, MS Thesis, University of Massachusetts, Amherst, MA, 1983.

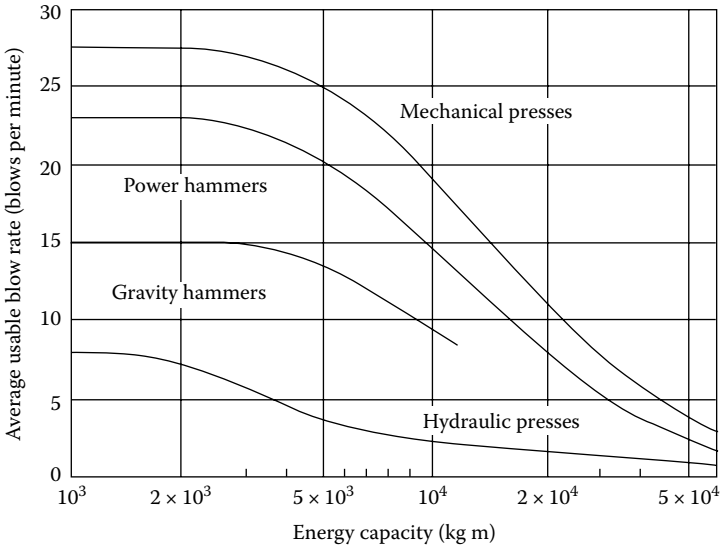


FIGURE 14.19
Average usable blow rates for forging equipment. (Adapted from Knight, W.A. *International Journal of Advanced Manufacturing Technology*, 7, pp. 159–167, 1992.)

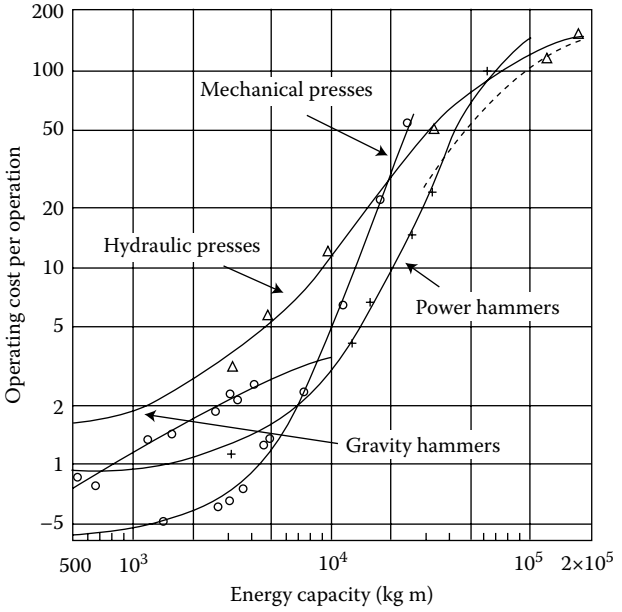


FIGURE 14.20
Operating cost per operation relative to 1000-lb power hammer. (Adapted from Leone, J.L. *Relative Forging Costs Analysis and Estimation*, MS Thesis, University of Massachusetts, Amherst, 1983.)

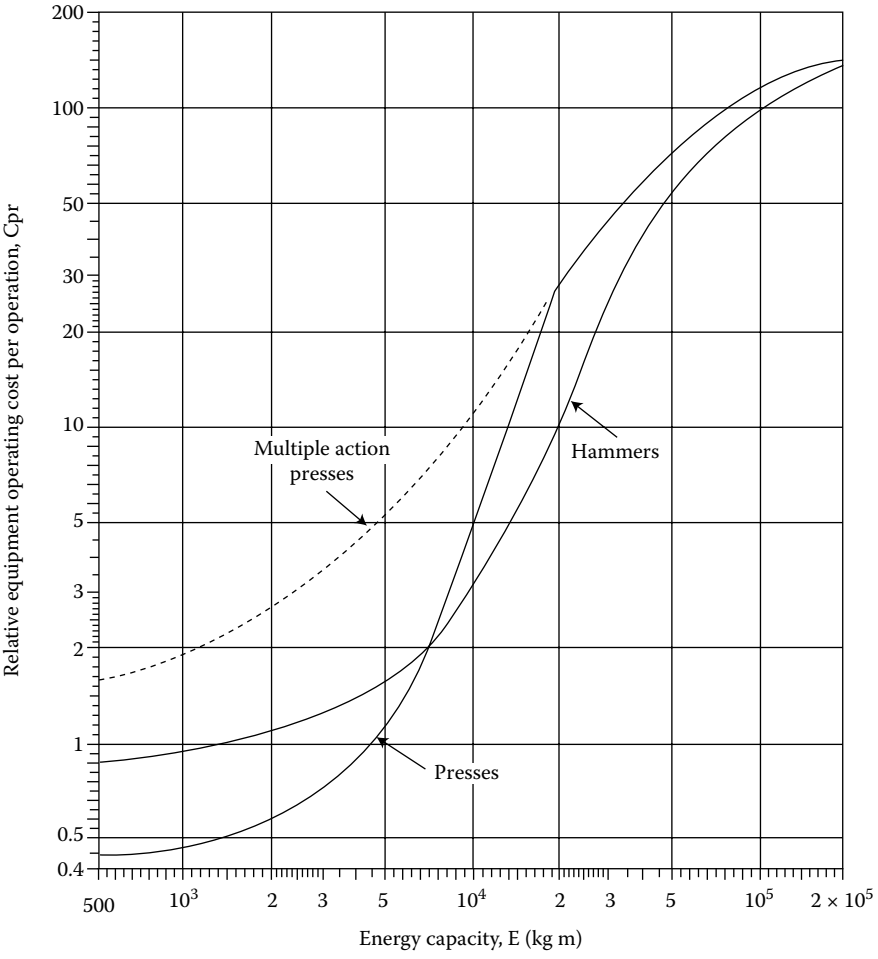


FIGURE 14.21
Relative operating cost per operation for forging equipment. (Adapted from Knight, W.A. and Poli, C.R. *Machine Design*, January 24, pp. 94–99, 1985.)

addition, for the more difficult to deform materials it may be impossible to obtain very thin sections (ribs and webs), and consequently the end product must be less close to net shape than for the easier to forge materials. Thus, so-called precision forgings are usually associated only with light alloy materials.

Table 14.7 contains two factors that are used in cost estimating procedures described later. The first of these is a load factor α_m that gives the approximate deformation energy per unit area required for a relatively simple shape in the specific material. The second factor is a material die life factor β_m, which represents the approximate reduction in die life for the forging of similar shapes in different materials.

14.10 Forging Costs

Figure 14.22 shows the breakdown of the average forging costs for hot forgings found in industry [27]. Material costs usually make up around 50% of forging costs, and of this

TABLE 14.7

Classification of Forging Materials

Class	Materials	Load Factor, α_m(kg-m/mm^2)	Die Life Factor, βm
0	Aluminum alloys		
	Group A	0.054	1.0
	Group B	0.087	1.0
	Magnesium alloys	0.065	1.0
1	Copper and copper alloys	0.065	1.0
2	Carbon and alloy steels		
	Group A	0.065	1.0
	Group B	0.076	0.8
	Group C	0.087	0.7
	Group D	0.098	0.6
3	Ferritic and martensitic stainless steels	0.109	0.3
	Tool steels	0.109	0.3
	Maraging steels	0.109	0.3
4	Austenitic stainless steels	0.130	0.3
	PH stainless steels	0.141	0.3
	Nickel alloys of iron	0.130	0.3
5	Titanium and titanium alloys		
	α and α/β alloys	0.163	0.2
	β alloys	0.195	0.2
6	Iron-based superalloys	0.152	0.2
7	Cobalt-based superalloys	0.195	0.2
8	Nickel-based superalloys	0.220	0.1
9	Niobium (Columbium) alloys	0.195	0.1
	Molybdenum alloys	0.217	0.1
	Tantalum alloys	0.124	0.1
	Tungsten alloys	0.260	0.1
	Beryllium	0.065	0.5

Source: Adapted from Knight, W.A. and Poli, C. *Design for Forging Handbook*, University of Massachusetts, Amherst, MA, 1982.

material, a significant proportion is waste material in the form of flash, scale losses, and so on. Die costs represent about 10% of forging costs and the remainder includes direct labor, equipment operating costs, and overhead costs. For the purposes of early cost estimating, three main cost elements are considered.

1. Material costs, including flash and scale losses.
2. Equipment operating costs, including labor, heating costs, ancillary equipment, and overhead.
3. Die costs, including initial tooling costs and maintenance and resinking costs.

Each of these will be considered in more detail in the following discussion. The early costing procedure described for hot forging is currently restricted to parts produced on

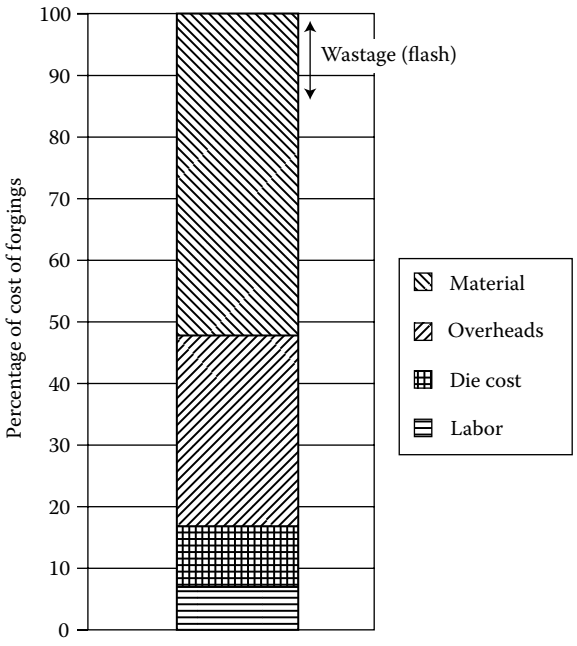


FIGURE 14.22
Breakdown of average costs for hot forging. (Adapted from Hobdell, A.C. and Thomas, A. Approaches to cheaper forgings, *Metal Forming*, 36(1), p. 17, 1969.)

hammers and forging presses using conventional dies. Preforming carried out on forging rolls is not considered, nor are such processes as ring rolling and hot upset forging.

14.10.1 Material Costs

The material costs for a forged part are determined as follows:

$$\text{Material cost } C_{\text{mat}} = C_{\text{m}}\rho\left[(V + P_{\text{r}}V_{\text{fl}} + A_{\text{H}}T_{\text{w}})\left(1 + \frac{S_{\text{sl}}}{100}\right)\right], \tag{14.5}$$

where
C_{m} = cost per unit weight of material
ρ = part density
V = the part volume
P_{r} = length of the flash line (perimeter of part)
V_{fl} = flash volume per unit length of flash line (Equation 14.3)
A_{H} = area of through holes
T_{w} = web thickness recommended (Equation 14.4)
S_{sl} = scale loss for material, %.

EXAMPLE

For the part shown in Figure 14.4 the following data are available:

Part volume $V = 49.9$ cm^3
Flash volume per length of flash line $V_{fl} = 0.87$ cm^3/cm
Length of flash line $P_r = 31.4$ cm
There are no through holes
Assuming that $C_m = 1.1$ \$/kg, $\rho = 7.86$ g/cm^3, and $S_{sl} = 5\%$, then
$C_{mat} = 1.1 \times 7.86[(49.9 + 31.4 \times 0.87)\ 1.05]/1000 = \$0.43$ per forging

14.10.2 Equipment Operating Costs

The production cost per piece is basically expressed as

$$C_{pr} = \frac{M}{R_p} \tag{14.6}$$

where M is the operating cost per unit time of the equipment and R_p is the production rate (pieces per unit time). The operating cost per unit time, M, includes direct labor, ancillary equipment for handling and heating, and not just the operating cost of the main press or hammer used for the forging. It is usual for a separate press to be used for the trimming of the flash and piercing, and this is usually a mechanical press. The costs for this are determined separately. Thus, the operating cost of the equipment used is given by

$$C_{pr} = \frac{MN_b}{B_r} \tag{14.7}$$

where N_b is the number of blows or strokes required to form the part and B_r is the effective blow or stroke rate of the press or hammer used. It should be noted that the number of strokes is usually equal to the number of operations if a mechanical or hydraulic press is used. For work-restricted machines such as hammers, several blows per operation are usually used, the average being between two and three blows per operation in general. This assumption has been used for generating the data in Figure 14.21.

Thus, the operating costs of the equipment are dependent on the equipment selected for the forging and its effective stroke or blow rate. The required equipment must be selected based on the load or energy required for shaping the part. A variety of methods are available for estimating the load needed for a specific forging [18,24,28–32], including some relatively complex plasticity analyses. For the purposes of early cost estimation, it has been decided to modify the procedure outlined in the *ASM Handbook* [18]. The plan area of the forging (including area of the flash in the flash lands) is multiplied by a material factor to give the energy capacity of the hammer required to forge the part. Variations of this approach are generally used by estimators in industry to determine the appropriate equipment to be used. However, the load or energy required for a forging is influenced by the

shape complexity of the part in addition to the material being forged. Thus, for the purpose of this early cost-estimating system, the following is used:

$$\text{Energy capacity } E_f = A_p \alpha_m \alpha_s \tag{14.8}$$

where
A_p = the projected part area including flash
α_m = material load factor (Figure 14.7)
α_s = shape load factor.

Once the energy capacity of the required equipment is known, a specific piece of equipment can be selected from Table 14.6 and the relative operating cost per operation determined from Figure 14.21.

The material load factor is obtained from the material classification given in Table 14.7. The shape load factor reflects the increased load required to finish-forge more complex shapes. This factor is obtained from the classification scheme described above (Figures 14.14

Forging data:

	Forging shape complexity factor, F_{fc}							
Second digit	≤ 1.5		> 1.5 and ≤ 2.5		> 2.5 and ≤ 5.0		>5.0	
0	1.6 2	0.95	1.7 3	0.9	1.9 3	0.75	2.2 4	0.55
1	1.6 2	0.7	1.7 3	0.6	1.9 3	0.5	2.2 4	0.3
2	1.6 2	2	1.7 3	0.6	1.9 3	0.5	2.2 4	0.3
3	1.6 2	0.65	1.7 3	0.5	1.9 3	0.45	2.2 4	0.25

Key: Shape load factor, α_s, upper left
Shape die life factor, β_s, upper right
Number of forging operations, N_{op}, lower left

Forging operations required:

	Number of forging operations, N_{op}		
	2	3	4
Scale break, n_{sb}	1	1	1
Blocker, n_{bk}	0	1	1
Semifinisher, n_{sf}	0	0	1
Finisher, n_{fs}	1	1	1

Bender, $n_{bnd} = 0$; Edger, $n_{edg} = 0$; Fuller stage 1, $n_{f1} = 0$; Fuller stage 2, $n_{f2} = 0$

FIGURE 14.23
Data for compact forgings, Shape Class 0.

Forging data:

	Forging shape complexity factor, F_{fc}							
Second digit	≤ 1.5		> 1.5 and ≤ 3.0		> 3.0 and ≤ 6.0		>6.0	
0	1.0 2	1.0	1.25 3	0.75	1.4 3	0.45	1.6 4	0.3
1	1.05 2	0.9	1.3 3	0.7	1.45 3	0.4	1.65 4	0.3
2	1.0 2	1.0	1.25 3	0.75	1.4 3	0.45	1.6 4	0.3
3	1.05 2	0.9	1.3 3	0.7	1.45 3	0.4	1.65 4	0.3

Key: Shape load factor, α_s, upper left
Shape die life factor, β_s, upper right
Number of forging operations, N_{op}, lower left

Forging operations required:

	Number of forging operations, N_{op}		
	2	3	4
Scale break, n_{sb}	1	1	1
Blocker, n_{bk}	0	1	1
Semifinisher, n_{sf}	0	0	1
Finisher, n_{fs}	1	1	1

Bender, $n_{bnd} = 0$; Edger, $n_{edg} = 0$; Fuller stage 1, $n_{f1} = 0$; Fuller stage 2, $n_{f2} = 0$

FIGURE 14.24
Data for flat forgings, Shape Class 1.

through 14.16). Figures 14.22 through 14.26 show the data associated with the classification. The appropriate shape load factor, α_s, is given in the upper left of each classification block. The other data include the shape die life factor, α_s (upper right), and the number of forging operations required, N_{op} (lower left). Shown in the lower part of these figures are the specific operations required for each value of N_{op}.

14.10.3 Examples of Equipment Selection

Figures 14.27 through 14.29 [12] show comparisons of the forging equipment capacities determined by this procedure, compared to the actual equipment used for a range of forgings in different classes. As can be seen, the correlation is generally good, except for the case of precision forgings in light alloy materials, where a factor of 2–2.5 is necessary to give the required result (parts F and M in Figure 14.27). Thus, for the purposes of early cost estimating, the basic calculation is applied to conventional forgings and this value increased by 2.5 for precision forging and multiplied by a factor of 0.9 for blocker-type forgings, to reflect the lower loads required in this case.

Forging data:

	Forging shape complexity factor, F_{fc}							
Second digit	≤ 2.0		> 2.0 and ≤ 5.0		> 5.0 and ≤ 10		>10	
0	1.0	0.9	1.1	0.85	1.2	0.75	1.3	0.6
	3		4		5		6	
1	1.2	0.65	1.3	0.6	1.45	0.5	1.7	0.35
	2		3		3		4	

Key: Shape load factor, α_s, upper left
Shape die life factor, β_s, upper right
Number of forging operations, N_{op}, lower left

Forging operations required:

	Number of forging operations, N_{op}			
	3	4	5	6
Fuller stage 1, n_{f1}	0	1	1	1
Fuller stage 2, n_{f2}	0	0	1	1
Edger, n_{edg}	1	1	1	1
Blocker, n_{bk}	1	1	1	1
Semifinisher, n_{sf}	0	0	0	1
Finisher, n_{fs}	1	1	1	1

Bender, $n_{bnd} = 0$; Scale break, $n_{sb} = 0$

FIGURE 14.25
Data for long straight forgings, Shape Class 2.

14.10.4 Forging Processing Costs

Once the appropriate forging equipment type and size and the forging complexity have been determined, the processing cost for the forging can be estimated. Equation 14.7 can be modified into the form

$$C_{pr} = \frac{C_{op}N_{op}}{N_c} \tag{14.9}$$

where
C_{op} = the forging equipment cost per operation
N_{op} = the number of operations required
N_c = the number of identical forgings per cycle.

The forging equipment operating cost per operation, C_{op}, is obtained from

$$C_{op} = C_{ro}C_{1000} \tag{14.10}$$

where C_{ro} is the relative cost per operation compared to a 1000 lb power hammer, obtained from Figure 14.21, and C_{1000} is the operating cost per operation of a 1000 lb power hammer.

Forging data:

	Forging shape complexity factor, F_{fc}							
Second digit	≤ 2.0		> 2.0 and ≤ 5.0		> 5.0 and ≤ 10		>10	
0	1.05 4	0.9	1.15 5	0.85	1.25 6	0.75	1.4 7	0.5
1	1.25 4	0.65	1.35 5	0.6	1.5 6	0.5	1.7 7	0.35

Key: Shape load factor, α_s, upper left
Shape die life factor, β_s, upper right
Number of forging operations, N_{op}, lower left

Forging operations required:

	Number of forging operations, N_{op}			
	4	5	6	7
Fuller stage 1, n_{f1}	0	1	1	1
Fuller stage 2, n_{f2}	0	0	1	1
Bender, n_{bnd}	1	1	1	1
Edger, n_{edg}	1	1	1	1
Blocker, n_{bk}	1	1	1	1
Semifinisher, n_{sf}	0	0	0	1
Finisher, n_{fs}	1	1	1	1

Scale break, $n_{sb} = 0$

FIGURE 14.26
Data for long bent forgings, Shape Class 3.

EXAMPLE

For the sample part shown in Figure 14.4 the following data are available:

Projected area = 78.6 cm^2
Projected area of flash land = 19.9 cm^2
Material load factor = 0.065 kg m/mm^2 (Table 14.7)
Shape classification number = 10
Forging complexity factor = 4
Shape load factor = 1.4 (Figure 14.23)
Number of operations = 3 (Figure 14.23)
The equipment energy capacity required, E_f, is given by Equation 14.8:
$E_f = (78.6 + 19.9) \times 100 \times 0.065 \times 1.4 = 896$ kg m

From Table 14.6 this part will require a power hammer rated at just below 1000 lb or a mechanical press of about 450 tons. From Figure 14.21, the relative operating cost per operation for a hammer of this size is 0.95. Thus, assuming the processing cost per operation for a 1000 1b power hammer is $0.15, then the processing cost per forging would be

$$C_{pr} = 0.95 \times 0.15 \times 3 = \$0.42 \text{ per forging}$$

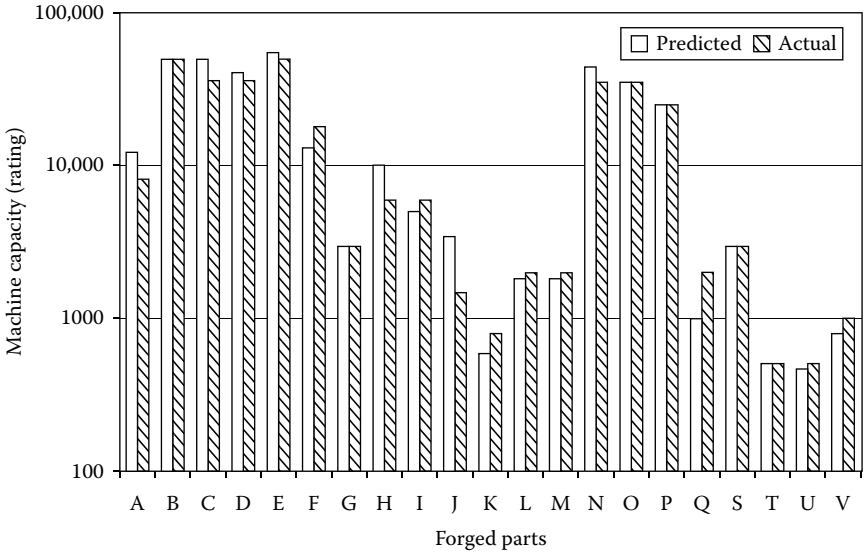


FIGURE 14.27
Comparison between predicted and actual forging equipment capacities for flat, round forgings. (Adapted from Knight, W.A. *International Journal of Advanced Manufacturing Technology*, 7, pp. 159–167, 1992.)

14.10.5 Forging Machine Setup Costs

The forging press or hammer must be set up prior to each batch of forgings produced. The setup cost per forging is given by

$$C_{set} = \frac{T_{set} M}{B_s} \tag{14.11}$$

where T_{set} is the setup time and B_s is the batch size. Based on data available for average setup times for forging equipment [31], a relationship between setup time and forging equipment capacity of the following form can be found:

$$T_{set} = 0.3925(E_f)^{0.28} \text{ h} \tag{14.12}$$

where E_f is the energy capacity in kg-in. determined from Equation 14.8.

EXAMPLE

For the sample part in Figure 14.4, the required energy capacity has been determined to be 896 kg m. Thus, the corresponding setup time from Equation 14.12 is $0.3925(896)^{0.28} = 2.6$ h. Assuming an operating cost rate, M, of \$85/h and a batch size of 10,000 forgings, the setup cost per forging becomes $85 \times 2.6/10{,}000$, which gives \$0.02. This is small, but increases significantly for small batch quantities.

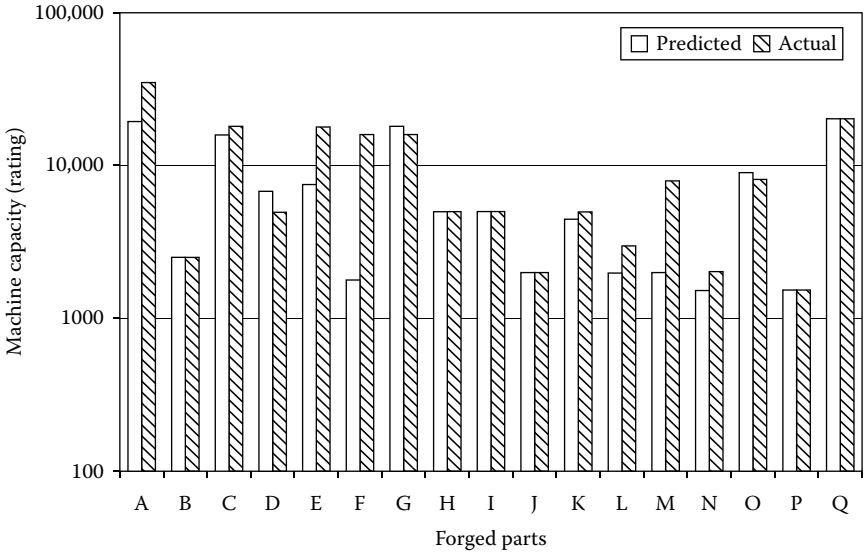


FIGURE 14.28
Comparison between predicted and actual forging equipment capacities for flat, nonround forging. (Forgings F and M are precision forgings in aluminum alloy.) (Adapted from Knight, W.A. *International Journal of Advanced Manufacturing Technology*, 7, pp. 159–167, 1992.)

14.11 Forging Die Costs

Several factors contribute to the die cost per piece, including:

1. The initial tooling costs
2. The total number of forgings to be produced or the expected life of the tools
3. The costs of tool refurbishing and/or resinking, together with the number of resinks possible

These factors are influenced by the complexity of the forging and the material used.

14.11.1 Initial Die Costs

The approach adopted for estimating the initial die cost is as follows:

1. Determine the die material costs.
2. Estimate the number of hours required for machining the tooling and dies, including all hand finishing and other factors.

There is one die cavity for each operation in the forging sequence, but some of the initial dies are relatively simple in form. There is a difference in practice between the use of presses and hammers in forging. For hammer forgings it is most usual to utilize multi-impression die blocks manufactured as one piece. In some circumstances the finishing cavity may be inserted into the die block, but this is often a result of resinking after the initial cavity

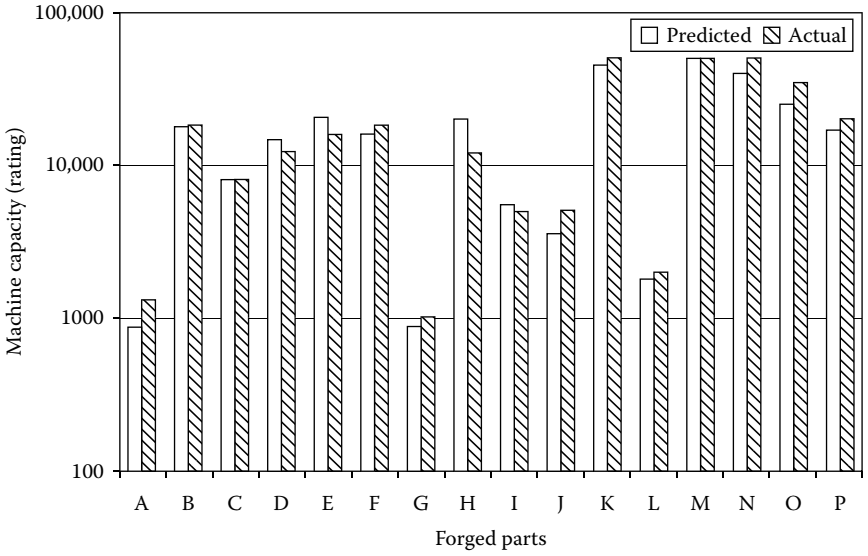


FIGURE 14.29
Comparison between predicted and actual forging equipment capacities for long forging. (Adapted from Knight, W.A. *International Journal of Advanced Manufacturing Technology*, 7, pp. 159–167, 1992.)

becomes worn. Hammer forging preforming operations include fullering, edging, bending, and so on. On presses, it is more normal to use separate die inserts for each operation, which are mounted into standard die containers on the press bed. The preforming stages are busters, preblockers, and so on. Thus, the tool material requirements are different for presses and hammers, but the complexity considerations for machining the main cavities are similar.

14.11.2 Estimation of Costs for Multi-Impression Forging Dies

The procedure adopted for determining the initial die costs is a modification of that given by the Forging Industry Association (FIA) for forging estimating [11]. Based on the plan area of the forging, the type of forging, and complexity as expressed as the number of surface patches in the cavity shape, the number of hours to machine each die type required is determined. The size of the die blocks can be estimated based upon the guidelines used in industry.

14.11.2.1 Die Material Costs

The die material costs are determined from the number of die cavities required and the dimensions of the part, using industry guidelines for such factors as the spacing between die impressions [2]. The number of forging impressions N_{imp} is given by

$$N_{\text{imp}} = n_{\text{bd}} + n_{\text{bk}} + n_{\text{sf}} + n_{\text{fin}} + n_{\text{sb}} \tag{14.13}$$

where the appropriate values are obtained from the forging classification data given in Figures 14.23 through 14.26.

Similarly, the number of fuller dies

$$N_{fl} = n_{f1} + n_{f2} \tag{14.14}$$

The equivalent bar diameter for long parts or for other types of part when more than one forging per cycle are produced, D_{bar}, is given by

$$D_{bar} = \left(\frac{4 d_{ave} W_{plt}}{\pi} \right)^{0.5} \tag{14.15}$$

where d_{ave} is the average cavity depth and W_{plt} is the platter width. The average cavity depth, d_{ave}, is given by $d_{ave} = V/A_p$. The platter width is equal to the width of the part if only one forging per cycle is to be produced. Otherwise, the platter width and length need to be determined taking into account any nesting of the part shapes that may be possible.

The width of the die block, W_{blk}, is given by

$$\begin{aligned} W_{blk} &= n_{edg}(D_{bar} + 19) + (N_{imp} - 1)S_d \\ &\quad + N_{imp} W_{plt} + 2S_e + N_{fl}(D_{bar} + 19)\cos\psi_{fl} \end{aligned} \tag{14.16}$$

where W_{plt} is the platter width and ψ_{fl} is the angle of the fullers to the die face, usually 15°. The length of the die block, L_{blk}, is given by

$$L_{blk} = L_{plt} + 2S_e \tag{14.17}$$

but if locked dies are required to counteract lateral forces from cranked parting lines, then a further S_e is added to the die block length to accommodate the counter lock. The length and width of the platter, L_{plt} and W_{plt} are equal to the part length, L, and the part width, W, respectively, if only one part per cycle is produced. However, if more than one part per cycle is produced, then appropriate values of L_{plt} and W_{plt} should be assigned, taking into account any nesting of the part profiles that may be possible.

The die block depth, T_{blk}, is assumed equal to 5 times the cavity depth, d_c. Then the cost of the die block material, C_{dmat}, is given by

$$C_{dmat} = 2C_t L_{blk} W_{blk} T_{blk} \rho_t \tag{14.18}$$

where C_t is the cost of tool steel per unit weight and ρ_t is the density of tool steel.

EXAMPLE

For the part shown in Figure 14.4, the calculations of die material costs are as follows. For this part, $n_{bd} = 0$, $n_{bl} = 1$, $n_{sf} = 0$, $n_{fin} = 1$, $n_{edg} = 0$, $n_{sb} = 1$, and $n_{fl1} = n_{fl2} = 0$ (Figure 14.24). Therefore, $N_{imp} = 3$ and $N_{fl} = 0$. The width of the platter is equal to the width of the part = 100 mm, if only one part per cycle is produced. For the part, the cavity spacing $S_d = 3.1(10)^{0.7} = 15.5$ mm and the cavity edge distance, $S_e = 3.4(10)^{0.76} = 19.6$ mm (Section 14.5). Consequently, the width of the die block is given by Equation 14.16 as

$$W_{blk} = 2 \times 15.5 + 3 \times 100 + 2 \times 19.6 = 370 \text{ mm}$$

The length of the die block is $L_{blk} = 100 + 2 \times 19.6 = 140$ mm and the block thickness $T_{blk} = 100$ mm. Assuming the cost of tool steel is \$20 per kilogram and the density of tool steel is 7.9 g/cm^3, then the die material cost for this part is

$$C_{dmat} = 2 \times 20 \times 7.9(5 \times 14 \times 37)/1000 = \$818.$$

14.11.2.2 Multi-Impression Die Manufacturing Costs

The cost of manufacturing multi-impression dies is determined by estimating the number of hours required to manufacture the dies and then multiplying this by a die manufacturing hourly rate. The procedure used is modification of the FIA estimating procedure [11]. The total time to manufacture the die set is the sum of the times corresponding to the various steps in the procedure.

i. *Block Preparation Time*. The time for initial preparation of the die block is given by

$$T_{prep} = T_{bt} + 0.0078 W_{blk} L_{blk} \text{ h} \tag{14.19}$$

where T_{bt} is the base time, which is equal to 4 h if the forging complexity factor F_{fc} is less than 2.0, 5 h for F_{fc} between 2.0 and 6.0, and 6 h for F_{fc} greater than 6.0. The die block width and length are given in centimeters.

EXAMPLE

For the sample part in Figure 14.4, $T_{bt} = 5$ h as $F_{fc} = 4$. Then T_{prep} is determined as $5 + 0.0078 \times 37 \times 14 = 9$ h.

ii. *Layout Time*. The time for laying out the die block is given by

$$T_{lay} = 0.008 N_c^m A_p F_{fc} S_c S_{lk} \text{ h} \tag{14.20}$$

where N_c is the number of forgings per cycle, S_c is the cavity standard, S_{lk} is the lock standard, and m is the multicavity index—usually taken as 0.7. The lock standard, S_{lk}, is 1.0 for parts for which the die split line is in one plane and 1.5 if the split line is not in one plane. The cavity standard, S_c, is

$$S_c = 0.6(n_{fn} + n_{sf}) + 0.4(n_{sb} + n_{blk} + n_{bnd} + n_{edg} + n_{f1} + n_{f2}) \tag{14.21}$$

EXAMPLE

For the sample part $S_{lk} = 1$, as the split line will be flat. In Equation 14.21, $n_{fn} = n_{sb} = n_{blk} = 1$ and all other terms are zero; thus, S_c becomes 1.4. The projected area of the part is 78.6 cm^2. Therefore, the layout time is given as

$$T_{lay} = 0.008 \times 78.6 \times 4 \times 1.4 = 3.52 \text{ h}$$

iii. *Milling Time*. The time for milling the die cavities is obtained from

$$T_{mill} = 0.155 N_{mill}^m A_p S_{ml} S_c S_{lk} \tag{14.22}$$

where S_{ml} is the milling standard given by

$$S_{ml} = K(6.45M_s)^b \quad \text{or} \quad 0.2, \quad \text{whichever is greater} \tag{14.23}$$

Here M_s is the number of surface patches per unit projected area, N_{sp}/A_p and

$$K = 0.9(1-\exp(-0.0098d_{ave}))$$

$$b = 0.4 + 0.7\exp(-0.0039d_{ave})$$

EXAMPLE

For the sample part the following data are available: Number of surface patches, N_s, is 7 and therefore $M_s = 7/78.6 = 0.089$. The average depth, d_{ave}, is given by V/A_p and equals 49.9/78.6 or 6.35 mm. Thus, $K = 0.9[1 - \exp(-0.0098 \times 6.35)] = 0.0543$ and $b = 0.4 + 0.7\exp(-0.0039 \times 6.35) = 1.083$. These give a milling standard of 0.03, which is less than 0.2; thus, $S_{ml} = 0.2$. Thus, the milling time $T_{mill} = 0.155 \times 78.6 \times 0.2 \times 1.4 = 3.41$ h.

iv. *Bench Work Time*. The bench work time, t_{bw}, on the dies is given by

$$T_{bw} = N_c^m S_{bn} S_c S_{lk}, \tag{14.24}$$

where S_{bn} is the bench standard, which depends on the forging complexity and average cavity depth. The benchwork factor, $F_{ins} = (A_p/6.54 + 0.5N_s)$ and $S_{bn} = B_0 + 0.26(F_{ins}-15)$. The constant B_0 depends on the average depth, d_{ave}, as follows:

$$d_{ave} \le 12.7 \text{ mm } B_0 = 0.056d_{ave}$$

$$d_{ave} > 22.86 \text{ mm } B_0 = 4.5 + (0.04d_{ave} - 0.9)2.19$$

$$d_{ave} > 12.7 \text{ and } \le 22.86 \; B_0 = 0.5 + (0.04d_{ave} - 0.35)7.27$$

EXAMPLE

For the example part $d_{ave} = 6.35$ mm. Thus $B_0 = 0.056 \times 6.35 = 0.356$. Also, $A_p = 78.6$ cm^2 and $N_s = 7$. From this, $F_{ins} = (78.6/6.6.54 + 0.5 \times 7) = 15.52$ and $S_{bn} = 0.356 + 0.26(15.52 - 15) = 0.49$. Thus, the benchmark time is $0.49 \times 1.4 = 0.69$ h.

v. *Planing Time*. The block planning time

$$T_{pl} = 0.008T_{cav}^{1.5} \tag{14.25}$$

where the cavity time $T_{cav} = T_{lay} + T_{mill} + T_{bw}$.

EXAMPLE

The block planing time for the example part $T_{pl} = 0.008(5.3 + 3.41 + 0.69)^{1.5}$, or 0.23 h.

vi. *Dowel Time*. The dowel time, T_{dl}, is 3 h if the die material volume is less than 4260 cm^2, or else is 4 h.

EXAMPLE

For the example part the total volume of the die material is 10,350 cm^3; thus, $T_{dl} = 4$ h.

vii. *Flash Gutter Time*. The time to machine flash gutters on the die cavities

$$T_{fl} = \frac{N_c P_r}{635} \quad \text{or } 0.8\,\text{h} \quad \text{whichever is the larger} \tag{14.26}$$

In this expression, P_r is the forging outside perimeter in millimeters.

EXAMPLE

For the example part, $T_{fl} = 314/635 = 0.49$ h and therefore T_{fl} is 0.8 h.

viii. *Edger Time*. If an edger die is required, the time for manufacture is T_{edg} and is given by

$$T_{edg} = n_{edg} L \left(\frac{D_{bar}}{25.4 + 1} \right) 0.005 \tag{14.27}$$

No edger is required for the example part.

ix. *Finish-Polish Time*. The time to finish-polish the dies cavities, T_{pol}, is given by

$$T_{pol} = N_c \left[1 + (F_{fc} - 1)0.6 \right] \tag{14.28}$$

EXAMPLE

For the example part $F_c = 4$, and therefore $T_{pol} = (1 + (4 - 1)0.6) = 2.8$ h.

The total die-manufacturing time is the sum of the above times and consequently the die-manufacturing cost is

$$C_{dman} = C_{man}(T_{prep} + T_{lay} + T_{mill} + T_{bw} + T_{pl} + T_{dl} + T_{fl} + T_{edg} + T_{pol}) \tag{14.29}$$

The total initial die-manufacturing costs are thus

$$C_{DIE} = C_{dmat} + C_{dman} \tag{14.30}$$

EXAMPLE

Assuming a die-manufacturing cost rate of \$45 per hour, then for the example part $C_{dman} = 45(9 + 3.51 + 3.41 + 0.69 + 0.23 + 4 + 0.8 + 0 + 2.8) = \$1100$.

Thus, the total initial die cost is $C_{DIE} = \$1100 = \$1918$.

14.12 Die Life and Tool Replacement Costs

The life of hot forging dies is relatively short, and therefore it is necessary to include in the estimating procedure a consideration of the expected tool life and a general strategy for

tool replacement and refurbishing. The life of the finishing cavity particularly is determined by the complexity of the forging and the material being forged. For example, the same shape produced by different materials results in different die lives. This can be accommodated by the use of the material die life factor, β_m, and typical values for these are given by the FIA [12], as shown in Table 14.7.

Similarly, the life of the tools is reduced as the complexity of the forging (thinner sections, ribs, etc.) is increased. This reduction is accommodated by the shape die life factor, β_s, which is obtained from the classification of forgings described above. Using these factors, die costs are determined by specifying a typical die replacement and refurbishing strategy for a relatively simple forging in low carbon steel. For such a part, the die life would be, say, 40,000 pieces, with up to five resinks of the main die cavity possible. Subsequent to this, a new tool set is assumed necessary. For other parts, it is assumed that this basic tool life and the periods before refurbishing is reduced by the die life factors for material and shape complexity. The die resink quantity, Q_{rs}, is determined by

$$Q_{rs} = Q_{rb}\beta_s\beta_m \tag{14.31}$$

where Q_{rb} is the basic resink quantity (say 40,000), β_s is the shape die life factor, and β_m is the material die life factor. Thus, the total die life, L_D, is given by

$$L_D = (N_{rs} + 1)Q_{rs}N_c \tag{14.32}$$

where N_{rs} is the number of resinks possible, say 5.

The cost of each resink, C_{rs}, is assumed to be equal to

$$C_{man}\left[0.9(T_{mill} + T_{bw} + T_{fl}) + T_{pol}\right] \tag{14.33}$$

If the total number of forgings required (life volume), Q_{lv}, is greater than the total die life, then the forging die cost per part, C_D, is given by

$$C_D = \frac{(C_{DIE} + (N_{rs} + 1)C_{rs})}{L_D} \tag{14.34}$$

However, if the life volume is less than the total die life, then the number of resinks required, n_{rs}, will be $Q_{lv}/(Q_{rs}N_c)$ and then the forging die cost per part would be

$$C_D = \frac{(C_{DIE} + n_{rs}C_{rs})}{Q_{tv}} \tag{14.35}$$

EXAMPLE

For the part $\beta_s = 0.45$ (Figure 14.24) and $\beta_m = 1.0$ (Table 14.7). The resink quantity, $Q_{rs} = 40{,}000 \times 0.45 \times 1.0 = 18{,}000$. From this the total die life will be, from Equation 14.32, $L_D = (5 + 1)$ 18,000 = 108,000 parts. The cost of each resink is $C_{rs} = 45[0.9(3.41 + 0.69 + 0.23) + 0.2.8] = \$301$. Thus, assuming a total required quantity of 25,000 forgings, then from Equation 14.35, the die cost per part is $(1918 + 301 \times 25{,}000/18{,}000)/25{,}000 = \$0.09$ per forging.

14.13 Costs of Flash Removal

14.13.1 Flash Removal Processing Costs

After the main forging processes, the flash must be removed to yield the finished forging. This is usually carried out on a mechanical press, with a purpose-built trimming die and punch. If possible, any webs in through-holes are pierced out at the same time. For small quantities of parts and for large forgings the flash may be removed by a bandsaw or a similar machining method, but this is generally time-consuming and more expensive. In order to determine the processing costs for flash trimming, the required size of the trimming press must be estimated, and this is determined from the load needed to shear the flash at the parting line. The trimming load, F_{trm}, is given by

$$F_{trm} = (T_f P_r + T_w P_w) Y_s N_c 1.15 \tag{14.36}$$

where P_w is the perimeter of the through holes and Y_s is the equivalent shear stress of the material of the forging. The constant of 1.15 is used to give a factor of safety of 15%. The equivalent yield stress is usually taken to be 70% of the UTS of the material. For cold trimming the room temperature UTS should be used and for hot forming the UTS should be assumed to be the material flow stress at an appropriate strain rate.

Once the trimming load is known, the energy equivalent for the mechanical press can be determined as

$$E_f = 0.096 F_{trm}^{0.98} \text{ kg m} \tag{14.37}$$

From this the relative cost per operation can be determined from Figure 14.20, and multiplying this by the operating cost per operation for a 1000 1b hammer gives the trimming cost, which should be divided by the number of forgings per cycle to result in the trimming cost per part.

There is a small setup cost for flash trimming. This can be determined in the same manner as for the main forging equipment, following the procedure outlined in Section 14.10.5.

EXAMPLE

For the example part the perimeter of the part is 31.4 cm and the flash thickness is 1.68 mm. For hot trimming of mild steel the material flow stress is approximately 97 MPa. Thus from Equation 14.36 the trimming load, F_{trm}, is given by

$$F_{trm} = 314 \times 1.68 \times 0.7 \times 97 \times 1.15 = 41{,}191 \text{ N}$$

From this equation, (14.37) gives $E_f = 3197$ kg m, which from Figure 14.21 results in a trimming cost relative to the cost per operation of a 1000 1b hammer of 0.73. Thus, assuming that the cost per operation of a 1000 lb hammer is \$0.15, then the trimming cost per part is $0.73 \times 0.15 = \$0.11$.

14.13.2 Tooling Costs for Flash Removal

The procedure for determining the tooling costs for trimming is modified from the FIA estimating procedure [11]. First, the material required for the tools is estimated. The trimming die material volume, V_{trd}, is given by

$$V_{trd} = 1.2 L_{plt} W_{plt} \frac{T}{2} \tag{14.38}$$

The trimming punch material volume, V_{trp}, is given by

$$V_{trp} = L_{plt} W_{plt} T \tag{14.39}$$

From these the trimming tool material cost, C_{trm}, is determined as

$$C_{trm} = (V_{trd} + V_{trp}) \rho_t C_t \tag{14.40}$$

EXAMPLE

For the example part $L_{plt} = W_{plt} = 10$ cm and the part thickness is 2 cm. From these $V_{trd} = 120$ cm^3 and $V_{trp} = 200$ cm^3. Assuming the cost of tool steel is \$20/kg and the density is 7.9 gm/cm^3, the material cost of the trimming tools is

$$C_{trm} = 20 \times 7.9 \times 320/1000 = \$50.6$$

The time to manufacture the trimming die, T_{td}, is given by

$$T_{trd} = T_{int} + (A_0 + M_p A_{tb} + T_{lk}) N_c \text{ h} \tag{14.41}$$

where

T_{int} = initial time allowance hours (4 for cold trim and 5 for hot trim)
A_0 = base time, h
M_p = block area factor, cm^2
A_{tb} = die block area, cm^2
T_{lk} = addition for locked forging dies, h.

The values of A_0, M_p, and T_{lk} are obtained from Table 14.8, for different values of the parting line profile complexity factor, F_c, where this is determined by

$$F_c = \frac{P_r}{2(\pi A_p)^{0.5}} \tag{14.42}$$

The number of hours required for the trim punch manufacture is estimated from

$$T_{tp} = (0.004 A_{pb} + 0.33) + 0.05 + \left[\frac{(A_{pb} - A_p N_c)}{6.56}\right] + \left[\frac{(P_r - P_w)}{2.54} + 14 F_c - 13\right] N_c F_{lck} + 0.005 N_c A_p F_{fc} \tag{14.43}$$

TABLE 14.8

Data for Estimating Trim Die-Manufacturing Times

Profile Complexity, F_c	Base Time, A_0 (h)	Block Area Factor, M_p (h/cm^2)	Locked Die Addition, T_{lck} (h)
1.0–1.5	0.62	0.0143	2
1.5–1.8	2.52	0.0146	3
>1.8	5.08	0.0168	0
>1.8 + die lock	8.86	0.0203	0

where A_{pb} is the punch block area, given by L_{plt} W_{plt}, and F_{lck} is a lock factor equal to 0.06 unless the die split line is cranked, in which case the factor is 0.065. The total initial trim tooling cost is

$$C_{trim} = (T_{td} + T_{tp})C_{man} + C_{trm} \tag{14.44}$$

The trim die life, L_{trm}, is given by $L_{trm} = L_{tbas}\beta_m N_c$, and from this the trim tool cost per part is C_{trim}/L_{trm} or C_{trim}/Q_{lv} if the life volume required, Q_{lv}, is less than L_{trm}.

EXAMPLE

For the example part the profile complexity factor, F_c, is 1.0 as the forging profile is circular. Thus, from Table 14.8, $A_0 = 0.62$ h, $M_p = 0.0143$ h square centimeters and the forgoing dies are not locked so $T_{lck} = 0$. From these, assuming hot trimming, the manufacturing time for the trimming die is

$$T_{td} = 5 + (0.62 + 0.0143 \times 78.6) = 6.74 \text{ h}$$

The value of F_{lck} is 0.06 and hence the time for manufacturing the trimming punch becomes

$$T_{tp} = (0.004 \times 100 + 0.33) + 0.05 + [(100–78.6)/6.56 + 14 - 13]0.06 + 0.005 \times 78.6 \times 4 = 2.61 \text{ h}$$

Thus, the total cost of the flash trimming tools is

$$C_{trim} = 45[6.74 + 2.61] + 50.6 = \$472$$

Assuming a lifetime production quantity of forgings, Q_{lv}, of 25,000, then the trimming tool cost per part \$472/25,000 = \$0.02 per part.

14.14 Other Forging Costs

There are some additional small costs associated with forging.

14.14.1 Billet Preparation

For most forging operations, there is a small additional cost for billet preparation. For long parts, the forging may be made directly from the heated end of an appropriate length of bar stock. For other types, an appropriate billet must be cut off from bar stock. This can be achieved by several methods, including sawing, abrasive cutoff, and cold shearing, which

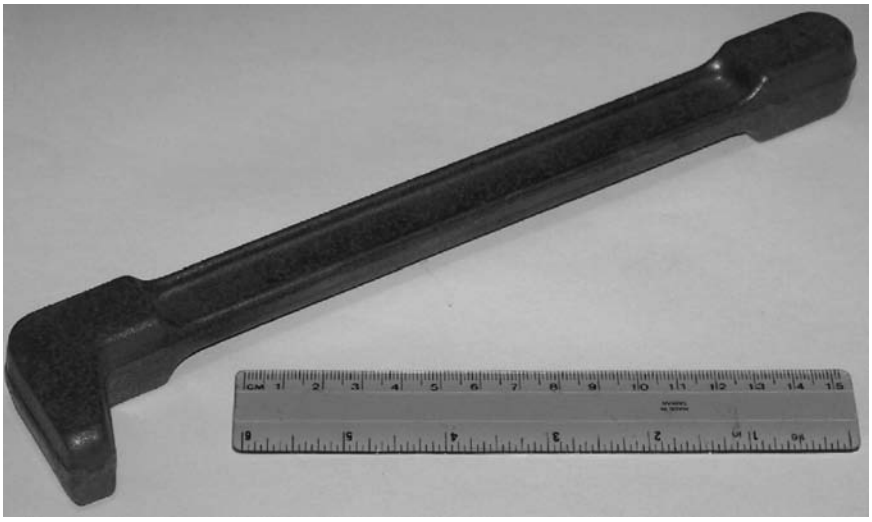
involves the least waste material. Cold shearing is usually carried out on a mechanical press, and the cost of processing can be calculated following a procedure similar to that for flash trimming described in Section 14.13.1. Since standard tools are used, the tool cost per part is very small.

14.14.2 Billet Heating Costs

The costs for heating the billet or bar end to the appropriate forging temperature can be estimated by determining the energy costs for heating. These can be obtained by multiplying the billet weight by the material specific heat and the required temperature rise. For small forgings, this cost is relatively small, but for large forgings that may require several reheats between operations the heating costs may become significant.

PROBLEMS

The sample forgings (A, B, and C) shown in Figures 14.30 through 14.32 are used for the following problems.



Part Data	
Material	Medium carbon steel
Material cost ($/kg)	1.00
Material density, ρ (g/cm^3)	7.83
Length, L (mm)	254
Width, W (mm)	51
Thickness, T (mm)	23
Part volume, V (cm^3)	43
Projected area, A_p (cm^2)	48
Outer perimeter, P_r (mm)	594
Number of surface patches	30

FIGURE 14.30
Sample forging A.

Part Data	
Material	304 Austenitic stainless stl.
Material cost ($/kg)	4.0
Material density, ρ (g/cm^3)	7.97
Length, L (mm)	83
Width, W (mm)	83
Thickness, T (mm)	20
Part volume, V (cm^3)	28
Projected area, A_p (cm^2)	47
Outer perimeter, P_r (mm)	320
Area of throughhole, A_H, (cm^3)	16
Perimeter of throughole, P_w (mm)	145
Number of surface patches	30

FIGURE 14.31
Sample forging B.

14.1 For sample forging A shown in Figure 14.30 determine the following:
- a. The flash thickness
- b. The flash land width
- c. The projected area of the flash land
- d. The volume of the flash for this forging
- e. The gross weight of the forging
- f. The material cost for this forging

14.2 For sample forging B shown in Figure 14.31 determine the following:
- a. The flash thickness
- b. The flash land width
- c. The projected area of the flash land
- d. The volume of the flash for this forging
- e. The web thickness needed for the through hole in this part
- f. The gross weight of the forging
- g. The material cost for this forging

Part Data	
Material	Medium carbon steel
Material cost ($/kg)	1.00
Material density, ρ (g/cm^3)	7.83
Length, L (mm)	76
Width, W (mm)	50
Thickness, T (mm)	50
Part volume, V (cm^3)	65
Projected area, A_p (cm^2)	34
Outer perimeter, P_r (mm)	240
Area of through hole, A_H, (cm^3)	5
Perimeter of throughole, P_w (mm)	80
Number of surface patches	50

FIGURE 14.32
Sample forging C.

14.3 For sample forging C shown in Figure 14.32 determine the following:
- a. The flash thickness
- b. The flash land width
- c. The projected area of the flash land
- d. The volume of the flash for this forging
- e. The web thickness needed for the through-hole in this part
- f. The gross weight of the forging
- g. The material cost for this forging

14.4 For sample forging A shown in Figure 14.30 determine the following:
- a. The classification of the forging
- b. The complexity factor, F_{fc}, of the forging
- c. The sequence of forging operations for this part

d. The equivalent energy capacity, E_f, of the forging equipment needed for this forging
e. An appropriate size of forging hammer to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.
f. An appropriate size of mechanical press to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.

14.5 For sample forging B shown in Figure 14.31 determine the following:
a. The classification of the forging
b. The complexity factor, F_{fc}, of the forging
c. The sequence of forging operations for this part
d. The equivalent energy capacity, E_f, of the forging equipment needed for this forging
e. An appropriate size of forging hammer to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.
f. An appropriate size of mechanical press to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.

14.6 For sample forging C shown in Figure 14.32 determine the following:
a. The classification of the forging
b. The complexity factor, F_{fc}, of the forging
c. The sequence of forging operations for this part
d. The equivalent energy capacity, E_f, of the forging equipment needed for this forging
e. An appropriate size of forging hammer to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.
f. An appropriate size of mechanical press to produce this forging and the estimated forging cost per part, assuming that the operating cost per operation of a 1000 lb power hammer is \$0.15.

14.7 For the forging A shown in Figure 14.30, assuming that the part is produced using multi-impression dies on a hammer, determine the following:
a. The estimated initial cost of the forging dies assuming a die-manufacturing rate of \$50 per hour.
b. The die cost per part assuming a life volume of 200,000.

14.8 Repeat question 14.3 assuming two identical forgings are made at the same time. You will need to nest the parts together to form a suitable forging platter. Some of the data determined in question 14.1 may be needed to complete the calculations.

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