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Engineering and Technology

Seventh Edition

Serope Kalpakjian
Steven R. Schmid

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Manufacturing Engineering and Technology

SEVENTH
EDITION
IN SI UNITS

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To the memory of

Margaret Jean Kalpakjian

"And ever has it been known that love knows not its own depth until the hour of separation."

Khalil Gibran

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Preface

In preparing the seventh edition of this book, our goal continues to be to provide a comprehensive and state-of-the-art manufacturing engineering and technology textbook, with the additional aims of motivating and challenging students in studying this important engineering discipline. As in the previous editions, the book attempts to present a broad overview, emphasizing a largely qualitative coverage of the science, technology, and practice of manufacturing. We have included detailed descriptions of the fundamentals of manufacturing processes, operations, and the manufacturing enterprise.

The book continues to address the various challenges and issues in modern manufacturing processes and operations, ranging from traditional topics such as casting, forming, machining, and joining processes, to advanced topics such as the fabrication of microelectronic devices and microelectromechanical systems and nanomanufacturing. The book provides numerous examples and case studies, as well as comprehensive and up-to-date coverage of all topics relevant to modern manufacturing, as a solid background for students as well as for professionals.

New to This Edition

In response to the suggestions by several of our colleagues and their students, numerous changes have been made to this edition of the book:

- Recognizing the proliferation of intelligent phones and the intention of Internet browsing ability in these phones and tablet devices, *QR Codes* have been introduced with this edition. Each QR Code is a link to a video solution to problems or a manufacturing process video. See sample QR Code to the right.
- The 56 video solutions are complete, step-by-step solution walkthroughs of representative problems from the text. The problems featured in video solutions provide additional assistance for students with homework or in preparing for an exam or quiz.
- The 65 manufacturing videos provide students with real-world context and allow students to watch an interactive demonstration of relevant issues or problem-solving strategies.

  Please note: Users must download a QR code reader to their smartphone or tablet. Data and roaming charges may also apply.
- Wherever appropriate, *illustrations* and *examples* have been replaced with newer ones to indicate recent advances in manufacturing.
- To provide a better perspective of the topics covered, the text now contains more *cross-references* to other relevant chapters, sections, tables, and illustrations in the book.
- The *questions* and *problems* and *projects* for class discussions, at the end of each chapter have been significantly expanded.
- The *bibliographies* at the end of each chapter have been thoroughly updated.

Video Solution 1.1 Calculating the Number of Grains in a Ball Bearing

- Every attempt has been made to ensure that *figures* and *tables* are placed on the same page as they are referenced in the text; this has been made possible by rearranging the page layout, including the use of margins on the pages.
- An *eText* version of this edition, and *videolinks* are provided on the web at www.pearsonhighered.com/kalpakjian.
- A *Solutions Manual* is, as always, available for use by instructors.

The text has been thoroughly edited and updated, as can be noted by page-by-page comparison with the previous edition. Specific revisions in the book include:

1. Expansion of the discussions regarding carbon in its useful forms, such as nanotubes and graphene (Section 8.6)
2. Expansion of product design considerations for manufacturing processes (various chapters)
3. Servo presses for forging and sheet-metal forming (Section 14.8)
4. Hot stamping of sheet metals (Section 16.11)
5. Expanded discussion on sintering, material properties, explosive compaction, roll densification, and combustion synthesis in powder metallurgy (Chapter 17)
6. Discussion of laser-engineered net shaping and self-replicating machines in rapid prototyping (Chapter 20)
7. Through-the-tool cooling systems in machining (Section 22.12)
8. Electrolytic laser MicroJet and Blue Arc machining (Chapter 27)
9. Immersion and pitch splitting lithography (Section 28.7)
10. MolTun (Section 29.3.4) and an expanded discussion of MEMS devices (Chapter 29)
11. Visual sensing (Section 37.7)
12. Production flow analysis (Section 38.8)
13. Development of MTConnect (Section 39.7)
14. Energy consumption in manufacturing (Section 40.5)

Audience

As in the previous editions, this seventh edition has been written for students in mechanical, manufacturing, industrial, aerospace, metallurgical and materials, and biomedical engineering programs. The book is also appropriate for use in associate degree programs at junior and community colleges. It is hoped that by studying this book, students will begin to appreciate the critical role of manufacturing engineering and technology in our daily lives and professional activities, and also view it as an academic subject that is as exciting, challenging, and as important as any other engineering discipline.

We would be very grateful for comments and suggestions from instructors and students regarding the nature and contents of the large number of topics presented in this book, as well as informing us of any errors in the text and in the illustrations that may have escaped our attention during the preparation of this text. Please send your comments or suggestions to Steven R. Schmid, schmid.2@nd.edu or to Serope Kalpakjian, kalpakjian@iit.edu.

Translations

Various editions of this book and our other textbook, *Manufacturing Processes for Engineering Materials*, are available in Chinese, Korean, Spanish, Italian, and German.

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It gives us great pleasure to acknowledge the assistance of the following colleagues in the preparation and publication of this edition of the book: K. Scott Smith, University of North Carolina at Charlotte; Steven Hayashi, General Electric Corp.; James Adams, Metal Powder Industries Federation; Timotius Pasang, Auckland University of Technology, New Zealand; Miguel Sellés Cantó, Escola Politècnica Superior d'Alcoi, Universitat Politecnica de València, Spain; and Megan McGann and Holly Weiss, University of Notre Dame. We also acknowledge Kent M. Kalpakjian, Micron Technology, as the original author of Fabrication of Microelectronic Devices (Chapter 28), and would like to thank Flora Derminjan, Micron Technology, and Vahagn Sargsyan, Carl Zeiss Nano Technology Systems, for reviewing this chapter for this edition. Thank you also to the reviewers for this edition: Keng Hsu, University of Illinois at Urbana-Champaign; Wayne Hung,Texas A&M University; Stephen Jenkins, Wor-Wic Community College; Edward Red, Brigham Young University; David Veazie, Southern Polytechnic State University; Yan Wang, Worchester Polytechnic Institute; and Y. Lawrence Yao, Columbia University.

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We are happy to present below a cumulative list of all those individuals who generously have made numerous contributions to various editions of our two books.

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Professor Kalpakjian has received the *Forging Industry Educational and Research Foundation Best Paper Award* (1966), the *Excellence in Teaching Award* from the Illinois Institute of Technology (1970), the *ASME Centennial Medallion* (1980), the *SME International Education Award* (1989), a *Person of the Millennium Award* from IIT (1999), and the *Albert Easton White Outstanding Teacher Award* from ASM International (2000); the *SME Outstanding Young Manufacturing Engineer Award* for 2002 was named after him. Professor Kalpakjian is a life fellow of ASME, fellow of SME, fellow and life member of ASM International, fellow emeritus of The International Academy for Production Engineering (CIRP), and a past president and founding member of the North American Manufacturing Research Institution/SME. He is a high honors graduate of Robert College (Istanbul), Harvard University, and the Massachusetts Institute of Technology.

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About the Adaptor

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General Introduction

CASE STUDIES:

I.1 What is Manufacturing?

As you begin to read this chapter, take a few moments to inspect various objects around you: mechanical pencil, light fixture, chair, cell phone, and computer. You soon will note that all these objects, and their numerous individual components, are made from a variety of materials and have been produced and assembled into the items that you now see. You also will note that some objects, such as a paper clip, nail, spoon, and door key, are made of a single component. As shown in Table I.1, however, the vast majority of objects around us consist of numerous individual pieces that are built and assembled by a combination of processes called **manufacturing**. This is well illustrated by the tractor shown in Fig. I.1, with several components and their materials highlighted.

The word *manufacture* first appeared in English in 1567, and is derived from the Latin *manu factus*, meaning "made by hand." The word *manufacturing* first appeared in 1683, and the word *production*, which is often used interchangeably with the word *manufacturing*, first appeared sometime during the 15th century.

Manufacturing is concerned with making products. A manufactured product may, in turn, itself be used to make other products, such as (a) a large press, to shape flat sheet metal into automobile bodies; (b) a drill, for producing holes; (c) industrial sewing machines, for making clothing at high rates; and (d) machinery, to produce an endless variety of individual items, ranging from thin wire for guitars and electric motors to crankshafts and connecting rods for automotive engines.

Items such as nails, bolts, screws, nuts, washers, and paper clips are *discrete products*, meaning individual items. By contrast, a spool of wire, metal or plastic tubing, and a roll of aluminum foil are *continuous products*, which are then cut into individual pieces of various lengths for specific purposes.

Because a manufactured item typically begins with raw materials, which are then subjected to a sequence of processes to make individual products, it has a certain value. For example, clay has some value as mined, but when made into a product such as cookware, pottery, an electrical insulator, or a cutting tool, value is *added* to the clay. Similarly, a nail has a value over and above the cost of the short piece of wire or rod from which it is made. Products such as computer chips, electric motors, medical implants, machine tools, and aircraft are known as *high-value-added* products.

A Brief History of Manufacturing. Manufacturing dates back to the period 5000–4000 B.C. (Table I.2), thus it is older than recorded history (which dates to the Sumerians around 3500 B.C.). Primitive cave drawings, as well as markings on clay tablets and stone, needed (a) some form of a brush and some sort of pigment, as in the prehistoric cave paintings in Lascaux, France, estimated to be 16,000 years old; (b) some means of first scratching the clay tablets and then baking them, as in cuneiform scripts and pictograms of 3000 B.C.; and (c) simple

TABLE I.1

Approximate Number of Parts in Products	
Common pencil	4
Rotary lawn mower	300
Grand piano	12,000
Automobile	15,000
Boeing 747–400	6,000,000

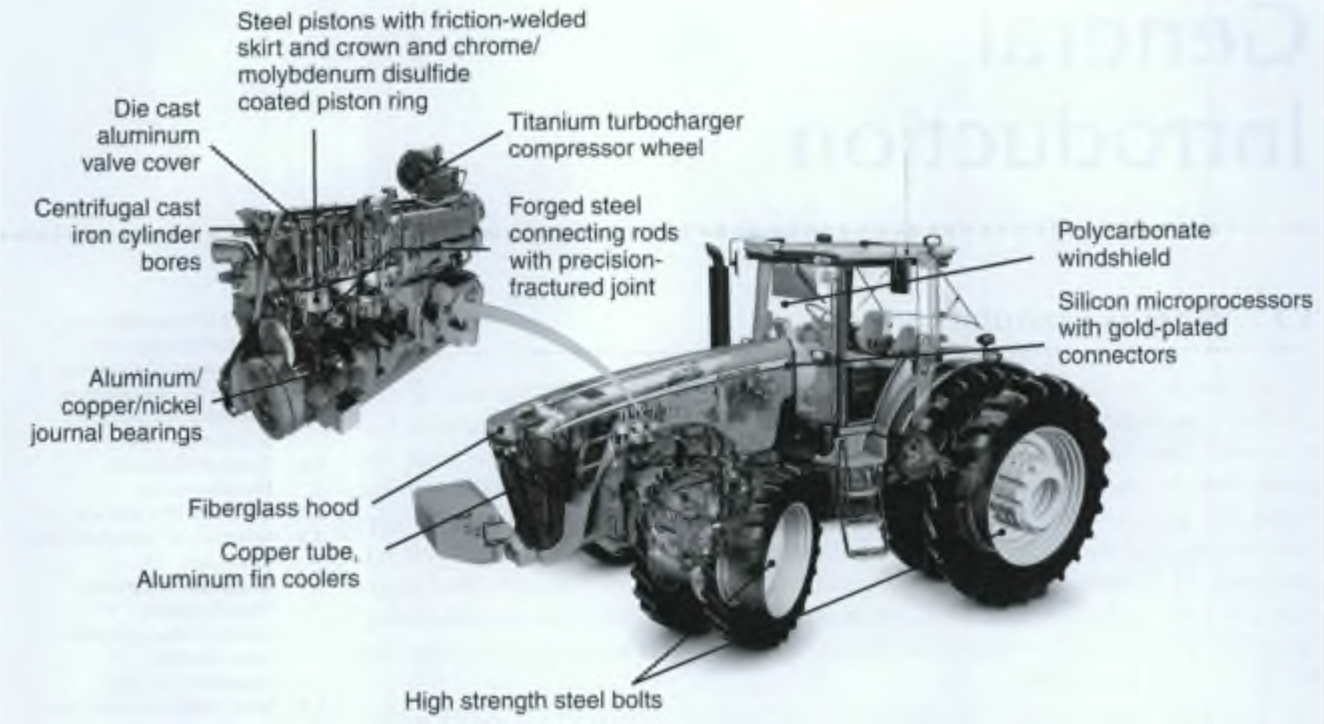


FIGURE I.1 Model 8430 John Deere tractor, with detailed illustration of its diesel engine, showing the variety of materials and processes incorporated. *Source:* Courtesy of John Deere Company.

tools for making incisions and carvings on the surfaces of stone, as in the hieroglyphs in ancient Egypt.

The manufacture of items for specific uses began with the production of various household artifacts, typically made of wood, stone, or metal. The materials first used in making utensils and ornamental objects included gold, copper, and iron, followed by silver, lead, tin, bronze, and brass. The processing methods first employed involved mostly *casting* and *hammering*, because they were relatively easy to perform. Over the centuries, these simple processes gradually began to be developed into more and more complex operations, at increasing rates of production and at higher levels of product quality. Note, for example, from Table I.2 that lathes for cutting screw threads already were available during the period from 1600 to 1700, but it was not until some three centuries later that automatic screw machines were developed.

Although ironmaking began in the Middle East in about 1100 B.C., a major milestone was the production of steel in Asia during the period 600–800 A.D. A wide variety of materials continually began to be developed. Today, countless metallic and nonmetallic materials with unique properties are available, including **engineered materials** and various other advanced materials. Among the materials now available are high-tech or industrial ceramics, reinforced plastics, composite materials, and nanomaterials that are now used in an extensive variety of products, ranging from prosthetic devices and computers to supersonic aircraft.

Until the **Industrial Revolution**, which began in England in the 1750s (also called the *First Industrial Revolution*), goods had been produced in batches, which required high reliance on manual labor in all phases of production. The **Second Industrial Revolution** is regarded by some as having begun in the mid-1900s, with the

TABLE I.2

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
Egypt: ~3100 B.C.–300 B.C.	~ 4000 B.C.	Gold, copper, meteoric iron	Earthenware, glazing, natural fibers	Hammering		Tools of stone, flint, wood, bone, ivory, composite tools
Greece: ~ 1100 B.C.–146 B.C.	3000	Copper casting, stone and metal molds, lost-wax process, silver, lead, tin, bronze		Stamping, jewelry	Soldering (CuAu, CuPb, PbSn)	Corundum (alumina, emery)
Roman Empire: ~ 500 B.C.–476 A.D.	2000	Bronze casting and drawing, gold leaf	Glass beads, potter's wheel, glass vessels	Wire by slitting sheet metal	Riveting, brazing	Hoe making, hammered axes, tools for ironmaking and carpentry
	1000	Wrought iron, brass				
Middle ages: ~ 476–1492	1 B.C.	Cast iron, cast steel	Glass pressing and blowing	Stamping of coins	Forge welding of iron and steel, gluing	Improved chisels, saws, files, woodworking lathes
	1 A.D.	Zinc, steel	Venetian glass	Armor, coining, forging, steel swords		Etching of armor
Renaissance: 1400–1600	1000	Blast furnace, type metals, casting of bells, pewter	Crystal glass	Wire drawing, gold-and silversmith work		Sandpaper, windmill driven saw
	1500	Cast-iron cannon, tinplate	Cast plate glass, flint glass	Waterpower for metalworking, rolling mill for coinage strips		Hand lathe for wood
	1600	Permanent-mold casting, brass from copper and metallic zinc	Porcelain	Rolling (lead, gold, silver), shape rolling (lead)		Boring, turning, screw-cutting lathe, drill press

(*continued*)

TABLE I.2 *(continued)*

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
	1700	Malleable cast iron, crucible steel (iron bars and rods)		Extrusion (lead pipe), deep drawing, rolling		
First Industrial Revolution: ~1780–1850	1800	Centrifugal casting, Bessemer process, electrolytic aluminum, nickel steels, babbitt, galvanized steel, powder metallurgy, open-hearth steel	Window glass from slit cylinder, light bulb, vulcanization, rubber processing, polyester, styrene, celluloid, rubber extrusion, molding	Steam hammer, steel rolling, seamless tube, steel-rail rolling, continuous rolling, electroplating		Shaping, milling, copying lathe for gunstocks, turret lathe, universal milling machine, vitrified grinding wheel
WWI	1900		Automatic bottle making, bakelite, borosilicate glass	Tube rolling, hot extrusion	Oxyacetylene; arc, electrical-resistance, and thermit welding	Geared lathe, automatic screw machine, hobbing, high-speed-steel tools, aluminum oxide and silicon carbide (synthetic)
WWII	1920	Die casting	Development of plastics, casting, molding, polyvinyl chloride, cellulose acetate, polyethylene, glass fibers	Tungsten wire from metal powder	Coated electrodes	Tungsten carbide, mass production, transfer machines
Second Industrial Revolution: 1947–	1940	Lost-wax process for engineering parts	Acrylics, synthetic rubber, epoxies, photosensitive glass	Extrusion (steel), swaging, powder metals for engineering parts	Submerged arc welding	Phosphate conversion coatings, total quality control
	1950	Ceramic mold, nodular iron, semiconductors, continuous casting	Acrylonitrile-butadiene-styrene, silicones, fluorocarbons, polyurethane, float glass, tempered glass, glass ceramics	Cold extrusion (steel), explosive forming, thermomechanical processing	Gas metal arc, gas tungsten arc, and electroslag welding; explosion welding	Electrical and chemical machining, automatic control

TABLE I.2

Historical Development of Materials, Tools, and Manufacturing Processes

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
Space age	1960–1970	Squeeze casting, single-crystal turbine blades	Acetals, polycarbonate, cold forming of plastics, reinforced plastics, filament winding	Hydroforming, hydrostatic extrusion, electroforming	Plasma-arc and electron-beam welding, adhesive bonding	Titanium carbide, synthetic diamond, numerical control, integrated circuit chip
	1970–1990	Compacted graphite, vacuum casting, organically bonded sand, automation of molding and pouring, rapid solidification, metal-matrix composites, semisolid metalworking, amorphous metals, shape-memory alloys (smart materials), computer simulation	Adhesives, composite materials, semiconductors, optical fibers, structural ceramics, ceramic-matrix composites, biodegradable plastics, electrically conducting polymers	Precision forging, isothermal forging, superplastic forming, dies made by computer-aided design and manufacturing, net-shape forging and forming, computer simulation	Laser beam, diffusion bonding (also combined with superplastic forming), surface-mount soldering	Cubic boron nitride, coated tools, diamond turning, ultraprecision machining, computer-integrated manufacturing, industrial robots, machining and turning centers, flexible-manufacturing systems, sensor technology, automated inspection, expert systems, artificial intelligence, computer simulation and optimization
Information age	1990–2010	Rheocasting, computer-aided design of molds and dies, rapid tooling, TRIP and TWIP steels	Nanophase materials, metal foams, advanced coatings, high-temperature superconductors. machinable ceramics, diamondlike carbon, carbon nanotubes, graphene	Rapid prototyping, rapid tooling, environmentally friendly metalworking fluids, digital manufacturing	Friction stir welding, lead-free solders, laser butt-welded (tailored) sheet-metal blanks, electrically conducting adhesives, linear friction welding	Micro- and nano fabrication, LIGA (a German acronym for a process involving lithography, electroplating, and molding), dry etching, linear motor drives, artificial neural networks, six sigma, three-dimensional computer chips, blue-arc machining, soft lithography

development of solid-state electronic devices and computers (Table I.2). **Mechanization** began in England and other countries of Europe, basically with the development of textile machinery and machine tools for cutting metal. This technology soon moved to the United States, where it continued to be further developed.

A major advance in manufacturing began in the early 1800s, with the design, production, and use of **interchangeable parts**, conceived by the American manufacturer and inventor E. Whitney (1765–1825). Prior to the introduction of interchangeable parts, much hand fitting was necessary, because no two parts could be made exactly alike. By contrast, it is now taken for granted that a broken bolt can easily be replaced with an identical one produced decades after the original. Further developments soon followed, resulting in countless consumer and industrial products that we now cannot imagine being without.

Beginning in the early 1940s, several milestones were reached in all aspects of manufacturing, as can be observed by a detailed review of Table I.2. Note particularly the progress that has been made during the 20th century, compared with that achieved during the 40-century period from 4000 B.C. to 1 B.C.

For example, in the Roman Empire (around 500 B.C. to 476 A.D.), factories were available for the mass production of glassware; however, the methods used were generally very slow, and much manpower was required in handling the parts and operating the machinery. Today, production methods have advanced to such an extent that (a) aluminum beverage cans are made at rates higher than 500 per minute, with each can costing about four cents to make, (b) holes in sheet metal are punched at rates of 800 holes per minute, and (c) light bulbs are made at rates of more than 2000 bulbs per minute.

The period approximately from the 1940s to the 1990s was characterized by **mass production** and expanding **global** markets. Initially, the United States had a dominant position, as it was the only developed nation with an intact infrastructure following World War II; however, this advantage dissipated by the 1960s. The **quality** revolution began to change manufacturing in the 1960s and 1970s, and programmable computers started becoming widely applied in the 1980s.

The era of **digital manufacturing** can be considered to have begun around 1990. As a fundamental change in manufacturing operations, powerful computers and software have now been fully integrated across the design and manufacturing enterprise. Communications advances, some Internet-based, have led to further improvements in organization and capabilities. The effects are most striking when considering the origin and proliferation of rapid prototyping. Prior to 1990, a prototype of a part could be produced only through intensive effort and costly manufacturing approaches, requiring significant operator skill. Today, a part can first be drafted in a CAD program, and then produced in a matter of minutes or hours (depending on size and part complexity) without the need for tools or skilled labor. Over time, prototyping systems have become more economical and faster, and use improved raw materials. The term *digital manufacturing* has been applied to reflect the notion that the manufacture of components can take place completely through such computer-driven CAD and production machinery.

I.2 Product Design and Concurrent Engineering

Product design involves the creative and systematic prescription of the shape and characteristics of an artifact to achieve specified objectives, while simultaneously satisfying several constraints. Design is a critical activity, because it has been estimated that as much as 80% of the cost of product development and manufacture is determined by the decisions made in the *initial* stages of design. The product design process has been studied extensively; it is briefly introduced here because of the strong interactions among manufacturing and design activities.

Innovative approaches are essential in successful product design, as are clearly specified functions and a clear statement of the performance expected of the product. The market for the product, which may be new or a modified version of an existing product, and its anticipated use or uses also must be defined at this stage. This aspect also involves the assistance of market analysts and sales personnel who will bring valuable and timely input to the manufacturer, especially regarding market needs and trends.

The Design Process. Traditionally, design and manufacturing activities have taken place *sequentially*, as shown in Fig. I.2a. This methodology may, at first, appear to be straightforward and logical; in practice, however, it is wasteful of resources. Consider the case of a manufacturing engineer who, for example, determines that, for a variety of reasons, it would be more desirable to (a) use a different material, such as a polymer or a ceramic instead of a metal, (b) use the same material but in a different condition, such as a softer instead of a harder material or a material with a smoother surface finish, or (c) modify the design of a component in order to make it easier, faster, and less costly to manufacture. Note that these decisions must take place at the sixth box from the top in Fig. I.2a.

Each of the modifications just described will necessitate a repeat of the design analysis stage (the third box from the top in Fig. I.2a) and the subsequent stages. This approach is to ensure that the product will still meet all specified requirements and will function satisfactorily. A later change from, say, a forged, cast, or machined component will, likewise, necessitate a repeat analysis. Such iterations obviously waste both time and the resources of a company.

Concurrent Engineering. Driven primarily by the consumer electronics industry, a continuing trend has been to bring products to the marketplace as rapidly as possible, so as to gain a higher percentage share of the market and thus higher profits. An important methodology aimed at achieving this end is *concurrent engineering*, which involves the product-development approach shown in Fig. I.2b.

Although this concept, also called **simultaneous engineering**, still has the same general product-flow sequence as in the traditional approach shown in Fig. I.2a, it now contains several deliberate modifications. From the earliest stages of product design and engineering, all relevant disciplines are now *simultaneously* considered. As a result, any iterations that may have to be made will require a smaller effort, thus resulting in much less wasted time than occurs in the traditional approach to design. It should be apparent that a critical feature of this approach is the recognition of the importance of *communication* among and within all relevant disciplines.

Concurrent engineering can be implemented in companies large or small; this is particularly significant because 98% of all U.S. manufacturing companies, for example, have fewer than 500 employees. Such companies are generally referred to as *small businesses*. As an example of the benefits of concurrent engineering, one automotive company reduced the number of components in one of its engines by 30%, decreased the engine weight by 25%, and reduced its manufacturing time by 50%.

Life Cycle. In concurrent engineering, the design and manufacture of products are integrated with a view toward optimizing all elements involved in the *life cycle* of the

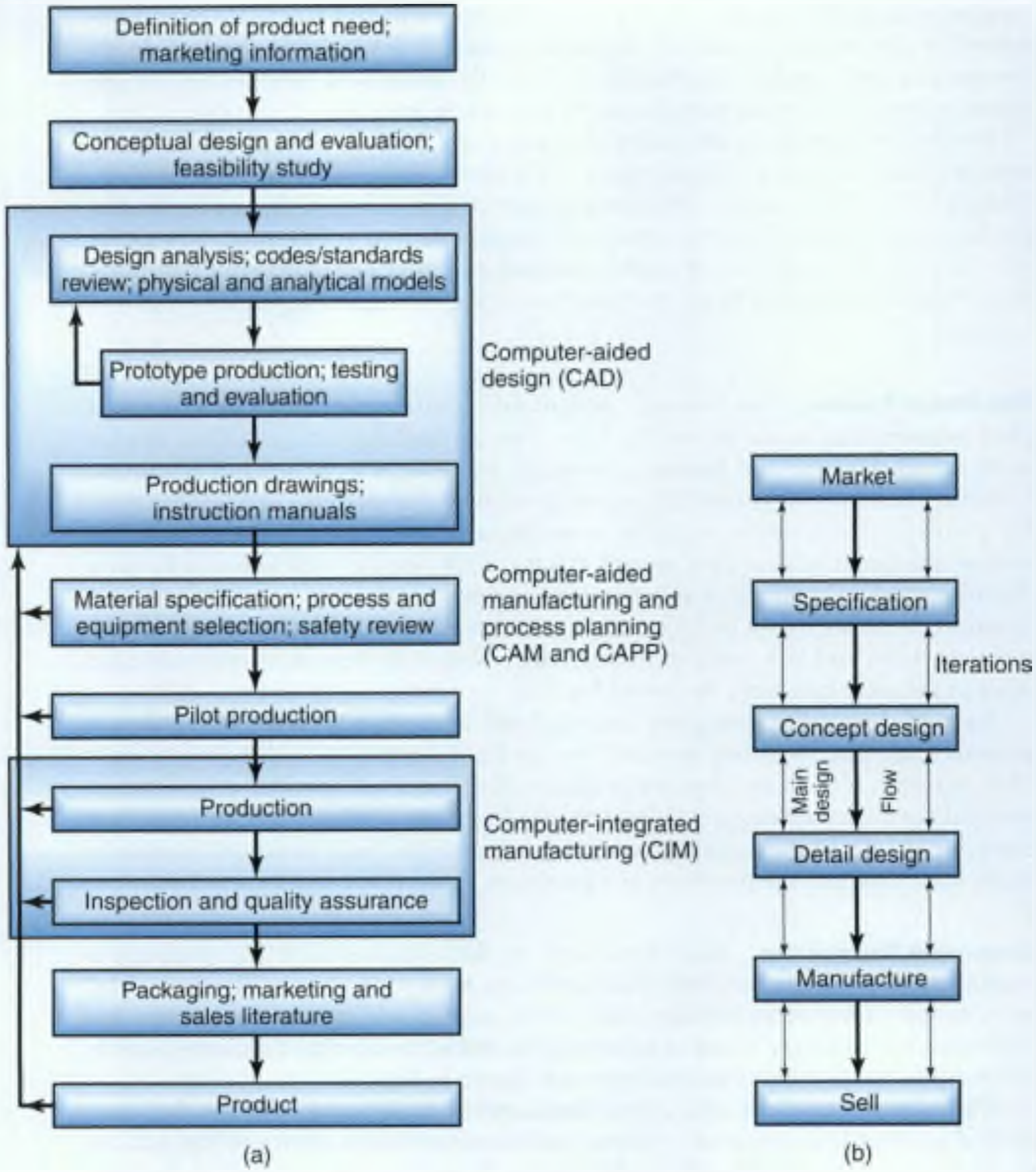


FIGURE I.2 (a) Chart showing various steps involved in *traditional* design and manufacture of a product. Depending on the complexity of the product and the type of materials used, the time span between the original concept and the marketing of the product may range from a few months to several years. (b) Chart showing general product flow in *concurrent engineering*, from market analysis to marketing the product. *Source:* After S. Pugh.

product (see Section I.4). The life cycle of a new product generally consists of four stages:

1. Product start-up
2. Rapid growth of the product in the marketplace
3. Product maturity
4. Decline

Consequently, **life-cycle engineering** requires that the *entire life* of a product be considered, beginning with the design stage and on through production, distribution, product use, and, finally, recycling or disposal of the product.

Role of Computers in Product Design. Typically, product design first requires the preparation of *analytical* and *physical models* of the product, for the purposes of visualization and engineering analysis. Although the need for such models depends on product complexity, constructing and studying these models are now highly simplified through the use of **computer-aided design** (CAD) and **computer-aided engineering** (CAE) techniques.

CAD systems are capable of rapid and thorough analyses of designs, whether it is a simple shelf bracket or a gear in large and complex structures. The Boeing 777 passenger airplane, for example, was designed completely by computers, in a process known as **paperless design**, with 2000 workstations linked to eight design servers. Unlike previous mock-ups of aircraft, no prototypes or mock-ups were built and the 777 was constructed and assembled *directly* from the CAD/CAM software that had been developed.

Through computer-aided engineering, the performance of structures subjected, for example, to static or fluctuating loads or to temperature gradients also can be simulated, analyzed, and tested, rapidly and accurately. The information developed is stored and can be retrieved, displayed, printed, and transferred anytime and anywhere within a company's organization. Design modifications can be made and optimized (as is often the practice in engineering, especially in the production of large structures such as aircraft) directly, easily, and at any time.

Computer-aided manufacturing involves all phases of manufacturing, by utilizing and processing the large amount of information on materials and processes gathered and stored in the organization's database. Computers greatly assist in organizing the information developed and performing such tasks as (a) programming for numerical-control machines and for robots for material-handling and assembly operations, (b) designing tools, dies, molds, fixtures, and work-holding devices, and (c) maintaining quality control throughout the total operation.

On the basis of the models developed and analyzed in detail, product designers then finalize the geometric features of each of the product's components, including specifying their dimensional tolerances and surface-finish characteristics. Because all components, regardless of their size, eventually have to be *assembled* into the final product, dimensional tolerances are a major consideration in manufacturing. Indeed, dimensional tolerances are equally important for small products as well as for car bodies or aircraft. The models developed also allow the specification of the mechanical and physical properties required, which in turn affect the selection of materials.

Prototypes. A *prototype* is a physical model of an individual component or product. The prototypes are carefully reviewed for possible modifications to the original design, materials, or production methods. An important and continuously evolving technology is **rapid prototyping.** Using CAD/CAM and various specialized technologies, designers can now make prototypes rapidly and at low cost, from metallic or nonmetallic materials such as plastics and ceramics.

Rapid prototyping can significantly reduce costs and the associated product-development times. Rapid-prototyping techniques are now advanced to such a level that they also can be used for low-volume (in batches typically of fewer than 100 parts) economical production of a variety of actual and functional parts, later to be assembled into products.

Virtual Prototyping. *Virtual prototyping* is a software-based method that uses advanced graphics and virtual-reality environments to allow designers to view and examine a part in detail. This technology, also known as **simulation-based design,** uses CAD packages to render a part such that, in a 3-D interactive virtual environment, designers can observe and evaluate the part as it is being developed. Virtual prototyping has been gaining importance, especially because of the availability of low-cost computers and simulation and analysis tools.

I.3 Design for Manufacture, Assembly, Disassembly, and Service

Design for manufacture (DFM) is a *comprehensive* approach to integrating the design process with production methods, materials, process planning, assembly, testing, and quality assurance. DFM requires a fundamental understanding of (a) the characteristics and capabilities of materials, manufacturing processes, machinery, equipment, and tooling and (b) variability in machine performance, dimensional accuracy and surface finish of the workpiece, processing time, and the effect of processing methods employed on product quality. Establishing *quantitative* relationships is essential in order to be able to analyze and optimize a design for ease of manufacturing and assembly at the lowest cost.

The concepts of **design for assembly** (DFA), **design for manufacture and assembly** (DFMA), and **design for disassembly** (DFD) are all important considerations in manufacturing. Methodologies and computer software are available for design for assembly, utilizing 3-D conceptual designs and solid models. Subassembly, assembly, and disassembly times and costs can now be minimized, while product integrity and performance are maintained. Experience has indicated that a product which is easy to assemble is, usually, also easy to disassemble.

Assembly is an important phase of manufacturing, requiring considerations of the ease, speed, and cost of putting together the numerous individual components of a product (Fig. I.3). Depending on the type of product, assembly costs in manufacturing can be substantial, typically ranging from 10 to 60% of the total product cost. *Disassembly* of a product is an equally important consideration, for such activities as maintenance, servicing, and recycling of individual components.

There are several methods of assembly of components, including the use of a wide variety of fasteners, adhesives, or joining techniques such as welding, brazing, or soldering. As is the case in all types of manufacturing, each of these assembly operations has its own specific characteristics, times, advantages and limitations, associated costs, and special design considerations. Individual parts may be assembled by hand or by a variety of automatic equipment and industrial robots. The choice depends on several factors, such as product complexity, the number of components to be assembled, the care and protection required to prevent damage to the individual parts, and the relative cost of labor compared with the cost of machinery required for automated assembly.

Design for Service. In addition to design for assembly and for disassembly, *design for service* is an important aspect of product design. Products often have to be disassembled to varying degrees in order to service them and, if necessary, repair them. The design should take into account the concept that, for ease of access, components that are most likely to be in need of servicing be placed, as much as possible, at the outer layers of the product. This methodology can be appreciated by anyone who has had the experience of servicing machinery.

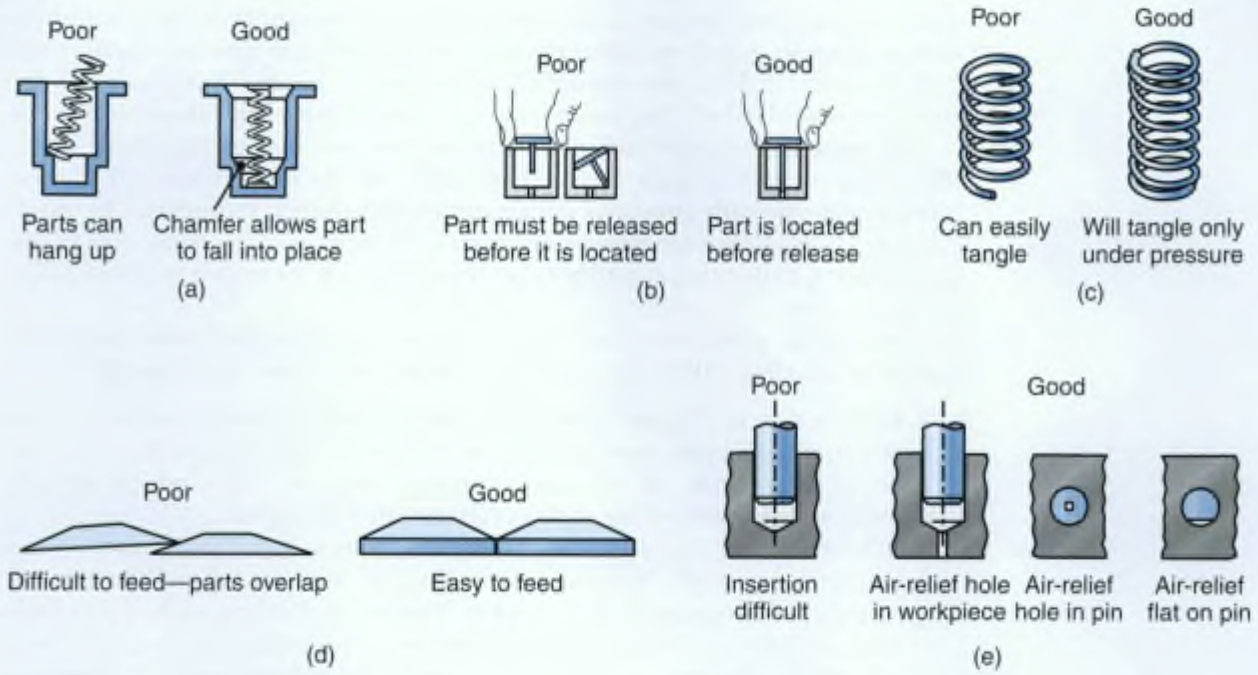


FIGURE I.3 Redesign of parts to facilitate assembly. *Source:* After G. Boothroyd and P. Dewhurst.

I.4 Green Design and Manufacturing

In the United States alone, 9 million passenger cars, 300 million tires, 670 million compact fluorescent lamps, and more than 5 billion kg of plastic products are discarded each year. Every 3 months, industries and consumers discard enough aluminum to rebuild the U.S. commercial air fleet. Note that, as indicated below, the term *discarding* suggests that the product has reached the end of its useful life; it does not necessarily mean that it has to be dumped into landfills.

The particular manufacturing process and the operation of machinery can each have a significant environmental impact. Manufacturing operations generally produce some waste, such as:

1. Chips from machining and trimmed materials from sheet forming, casting, and molding operations
2. Slag from foundries and welding operations
3. Additives in sand used in sand-casting operations
4. Hazardous waste and toxic materials used in various products
5. Lubricants and coolants in metalworking and machining operations
6. Liquids from processes such as heat treating and plating
7. Solvents from cleaning operations
8. Smoke and pollutants from furnaces and gases from burning fossil fuels

The adverse effects of these activities, their damage to our environment and to the Earth's ecosystem, and, ultimately, their effect on the quality of human life are now widely recognized and appreciated. Major concerns involve global warming, greenhouse gases (carbon dioxide, methane, and nitrous oxide), acid rain, ozone depletion, hazardous wastes, water and air pollution, and contaminant seepage into water sources. One measure of the adverse impact of human activities is called the **carbon footprint**, which quantifies the amount of greenhouse gases produced in our daily activities. In 2011, the amount of carbon dioxide released worldwide into the air was estimated to be 2.4 million pounds per second; China being the most polluter.

The term **green design and manufacturing** has become common in all industrial activities, with a major emphasis on **design for the environment** (DFE). Also called **environmentally conscious design and manufacturing**, this approach considers all possible adverse environmental impacts of materials, processes, operations, and products, so that they can all be taken into account at the earliest stages of design and production.

These goals, which now have become global, also have led to the concept of **design for recycling** (DFR). Recycling may involve one of two basic activities:

- **Biological cycle:** Organic materials degrade naturally, and in the simplest version of a biological cycle, they lead to new soil that can sustain life; thus, product design involves the use of (usually) organic materials. The products function well for their intended life and can then be safely discarded.
- **Industrial cycle:** The materials in the product are recycled and reused continuously; for example, aluminum beverage cans are recycled and the metal is reused. To demonstrate the economic benefits of this approach, it has been estimated that producing aluminum from scrap, instead of from bauxite ore, reduces production costs by as much as 66% and reduces energy consumption and pollution by more than 90%.

One of the basic principles of design for recycling is the use of materials and product-design features that facilitate biological or industrial recycling. In the U.S. automotive industry, for example, about 75% of automotive parts (mostly metal) are now recycled, and there are continuing plans to recycle the rest as well, including plastics, glass, rubber, and foam. About 80% of the discarded automobile tires are reused in various ways.

Cradle-to-cradle Production. Also called C2C, *cradle-to-cradle* production considers the impact of each stage of a product's life cycle, from the time natural resources are mined and processed into raw materials, through each stage of manufacturing products, their use and, finally, recycling. *Cradle-to-grave* production, also called *womb-to-tomb* production, has a similar approach, but it does not necessarily consider or take on the responsibility of recycling.

Cradle-to-cradle production especially emphasizes:

1. Sustainable and efficient manufacturing activities, using clean technologies
2. Waste-free production
3. Using recyclable and nonhazardous materials
4. Reducing energy consumption
5. Using renewable energy, such as wind and solar
6. Maintaining ecosystems by minimizing the environmental impact of all manufacturing activities
7. Using materials and energy sources that are available locally, so as to reduce energy use associated with their transport which, by and large, has an inherently high carbon footprint
8. Continuously exploring the reuse and recycling of materials, thus perpetually trying to recirculate materials; also included is investigating the composting of materials, whenever appropriate or necessary, instead of dumping them into landfills

Guidelines for Green Design and Manufacturing. In reviewing the various activities described thus far, it can be noted that there are overarching relationships among the basic concepts of DFMA, DFD, DFE, and DFR. These relationships can be summarized as guidelines, now rapidly accepted worldwide:

1. Reduce waste of materials, by refining product design, reducing the amount of materials used in products, and selecting manufacturing processes that minimize scrap (such as forming instead of machining).
2. Reduce the use of hazardous materials in products and processes.
3. Investigate manufacturing technologies that produce environmentally friendly and safe products and by-products.
4. Make improvements in methods of recycling, waste treatment, and reuse of materials.
5. Minimize energy use and, whenever possible, encourage the use of renewable sources of energy; selection of materials can have a major impact on the latent energy in products.
6. Encourage recycling by using materials that are a part of either industrial or biological cycling, but not both in the same product assembly. Ensure proper handling and disposal of all waste of materials that are used in products, but are not appropriate for industrial or biological cycling.

I.5 Selection of Materials

An increasingly wide variety of materials are now available, each type having its own specific properties and manufacturing characteristics, advantages and limitations, and costs. The selection of materials for products (consumer or industrial) and their components is typically made in consultation with materials engineers, although design engineers may also be sufficiently experienced and qualified to do so.

The general types of materials used, either individually or in combination with other materials, are:

- **Ferrous metals:** Carbon, alloy, stainless, and tool and die steels (Chapter 5)
- **Nonferrous metals:** Aluminum, magnesium, copper, nickel, titanium, superalloys, refractory metals, beryllium, zirconium, low-melting-point alloys, and precious metals (Chapter 6)
- **Plastics (polymers):** Thermoplastics, thermosets, and elastomers (Chapter 7)
- **Ceramics, glasses, glass ceramics, graphite, diamond,** and **diamondlike materials** (Chapter 8)
- **Composite materials:** Reinforced plastics and metal-matrix and ceramic-matrix composites (Chapter 9)
- **Nanomaterials** (Section 8.8)
- **Shape-memory alloys** (*smart materials*), **amorphous alloys, semiconductors,** and **superconductors** (Chapters 6, 18 and 28)

As new developments continue, the selection of an appropriate material for a particular application from a very large variety of options has become even more challenging. Furthermore, there are continuously shifting trends in the substitution of materials, driven not only by technological considerations but also by economics.

Properties of Materials. *Mechanical properties* of interest in manufacturing generally include strength, ductility, hardness, toughness, elasticity, fatigue, and creep resistance (Chapter 2). *Physical properties* are density, specific heat, thermal expansion and conductivity, melting point, and electrical and magnetic properties (Chapter 3). Optimum designs often require a consideration of a combination of mechanical and physical properties. A typical example is the *strength-to-weight* and *stiffness-to-weight* ratios of materials for minimizing the weight of structural members; weight minimization is particularly important for aerospace and automotive applications, in order to improve performance and fuel economy.

Chemical properties include oxidation, corrosion, degradation, toxicity, and flammability; these properties play a significant role under both hostile (such as corrosive) and normal environments. *Manufacturing properties* indicate whether a particular material can be cast, formed, machined, joined, and heat treated with relative ease. As Table I.3 illustrates, no one material has the same manufacturing characteristics. Another consideration is *appearance*, which includes such characteristics as surface texture, color, and feel, all of which can play a significant role in a product's acceptance by the public.

Availability. As emphasized throughout this book, the economic aspect of material selection is as important as technological considerations (Chapter 40); thus, the availability of materials is a major concern in manufacturing. Furthermore, if materials are not available in the desired shapes, dimensions, surface texture, and quantities, then materials substitution or additional processing of a particular material may well be required, all of which can contribute significantly to product cost.

Reliability of supply is important in order to meet production schedules; in automotive industries, for example, materials must arrive at a plant at appropriate time intervals. (See also *just-in-time*, Section I.7.) Reliability of supply is also important, because most countries import numerous raw materials. The United States, for example, imports most of the cobalt, titanium, chromium, aluminum, nickel, natural rubber, and diamond that it needs. Consequently, a country's self-reliance on resources, especially energy, is an often-expressed political goal, but challenging to achieve. *Geopolitics* (defined briefly as the study of the influence of a nation's physical geography on its foreign policy) must thus be a consideration, particularly during periods of global instability or hostility.

Service Life. Everyone has directly experienced a shortened service life of a product, which often can be traced to one or more of the following: (a) improper selection of materials, (b) improper selection of production methods, (c) insufficient control of processing variables, (d) defective raw materials or parts, or manufacturing-induced

TABLE I.3

General Manufacturing Characteristics of Various Materials

Alloy	Castability	Weldability	Machinability
Aluminum	Excellent	Fair	Excellent–good
Copper	Good–fair	Fair	Good–fair
Gray cast iron	Excellent	Difficult	Good
White cast iron	Good	Very poor	Very poor
Nickel	Fair	Fair	Fair
Steels	Fair	Excellent	Fair
Zinc	Excellent	Difficult	Excellent

The ratings shown depend greatly on the particular material, its alloys, and its processing history.

defects, (e) poor maintenance of machinery or equipment, and (f) improper use of the product.

Generally, a product is considered to have failed when it

- Stops functioning, due to the failure of one or more of its components, such as a broken shaft, gear, bolt, or turbine blade, or a burned-out electric motor
- Does not function properly or perform within required specifications, due, for example, to worn gears or bearings
- Becomes unreliable or unsafe for further use, as in the erratic behavior of a switch, poor connections in a printed-circuit board, or delamination of a composite material

Material Substitution in Products. For a variety of reasons, numerous substitutions are made in materials, as evidenced by a routine inspection and comparison of common products, such as home appliances, sports equipment, or automobiles. As a measure of the challenges faced in material substitution, consider the following examples: (a) metal versus wooden handle for a hammer, (b) aluminum versus cast-iron lawn chair, (c) copper versus aluminum electrical wire, (d) plastic versus steel car bumper, and (e) alloy steel versus titanium submarine hull.

The following two case studies describe some details of the major factors involved in material substitution in common products.

CASE STUDY I.1 Baseball Bats

Baseball bats for the major and minor leagues are generally made of wood from the northern white ash tree, a material that has high dimensional stability, high elastic modulus and strength-to-weight ratio, and high shock resistance. Wooden bats can break, however, and may cause serious injury. (This is especially true of the relatively new trend of using maple wood in baseball bats.) Wooden bats are made on semiautomatic lathes (Section 23.3), followed by finishing operations for appearance and labeling. The straight uniform grain required for such bats has become increasingly difficult to find, particularly when the best wood comes from ash trees that are at least 45 years old.

For the amateur market and for school and college players, aluminum bats (top portion of Fig. I.4) have been made since the 1970s as a cost-saving alternative to wood. The bats are made by various metalworking operations, described throughout Part III. Although, at first, their performance was not as good as that of wooden bats, the technology has advanced to a great extent. Metal bats are now mostly made from high-strength aluminum tubing, but can incorporate titanium. The bats are designed to have the same center of percussion (known as the

FIGURE I.4 Cross-sections of baseball bats made of aluminum (top two) and composite material (bottom two).

(continued)

sweet spot, as in tennis racquets) as wooden bats, and are usually filled with polyurethane or cork for improved sound damping and for controlling the balance of the bat.

Metal bats possess such desirable performance characteristics as lower weight than wooden bats, optimum weight distribution along the bat's length, and superior impact dynamics. Also, as documented by scientific studies, there is a general consensus that metal bats outperform wooden bats. Further developments in bat materials include composite materials (Chapter 9), consisting of high-strength graphite or glass fibers embedded in an epoxy resin matrix. The inner woven sleeve (lower portion of Fig. I.4) is made of Kevlar fibers (an aramid), which add strength to the bat and dampen its vibrations; these bats perform and sound much like wooden bats.

Source: Mizuno USA, Inc.

CASE STUDY I.2 U.S. Pennies

Billions of pennies are produced and put into circulation each year by the U.S. Mint. The materials used have undergone significant changes throughout its history, largely because of periodic material shortages and the resulting fluctuating cost of appropriate materials. The following table shows the chronological development of material substitutions in pennies:

1793–1837	100% copper
1837–1857	95% copper, 5% tin and zinc
1857–1863	88% copper, 12% nickel
1864–1962	95% copper, 5% tin and zinc
1943 (WWII years)	Steel, plated with zinc
1962–1982	95% copper, 5% zinc
1982–present	97.5% zinc, plated with copper

I.6 Selection of Manufacturing Processes

There is often more than one method that can be employed to produce a component for a product from a given material. The following broad categories of manufacturing methods are all applicable to metallic as well as nonmetallic materials:

1. Casting (Fig. I.5a): Expendable mold and permanent mold (Part II)
2. Forming and shaping (Figs. I.5b–d): Rolling, forging, extrusion, drawing, sheet forming, powder metallurgy, and molding (Part III)
3. Machining (Fig. I.5e): Turning, boring, drilling, milling, planing, shaping, broaching; grinding; ultrasonic machining; chemical, electrical, and electrochemical machining; and high-energy-beam machining (Part IV); this broad category also includes micromachining for producing ultraprecision parts (Part V)
4. Joining (Fig. I.5f): Welding, brazing, soldering, diffusion bonding, adhesive bonding, and mechanical joining (Part VI)
5. Finishing: Honing, lapping, polishing, burnishing, deburring, surface treating, coating, and plating (Chapters 26 and 34)
6. Microfabrication and nanofabrication: Technologies that are capable of producing parts with dimensions at the micro (one-millionth of a meter) and nano (one-billionth of a meter) levels; fabrication of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), typically involving processes such as lithography, surface and bulk micromachining, etching, LIGA, and various other specialized processes (Chapters 28 and 29)

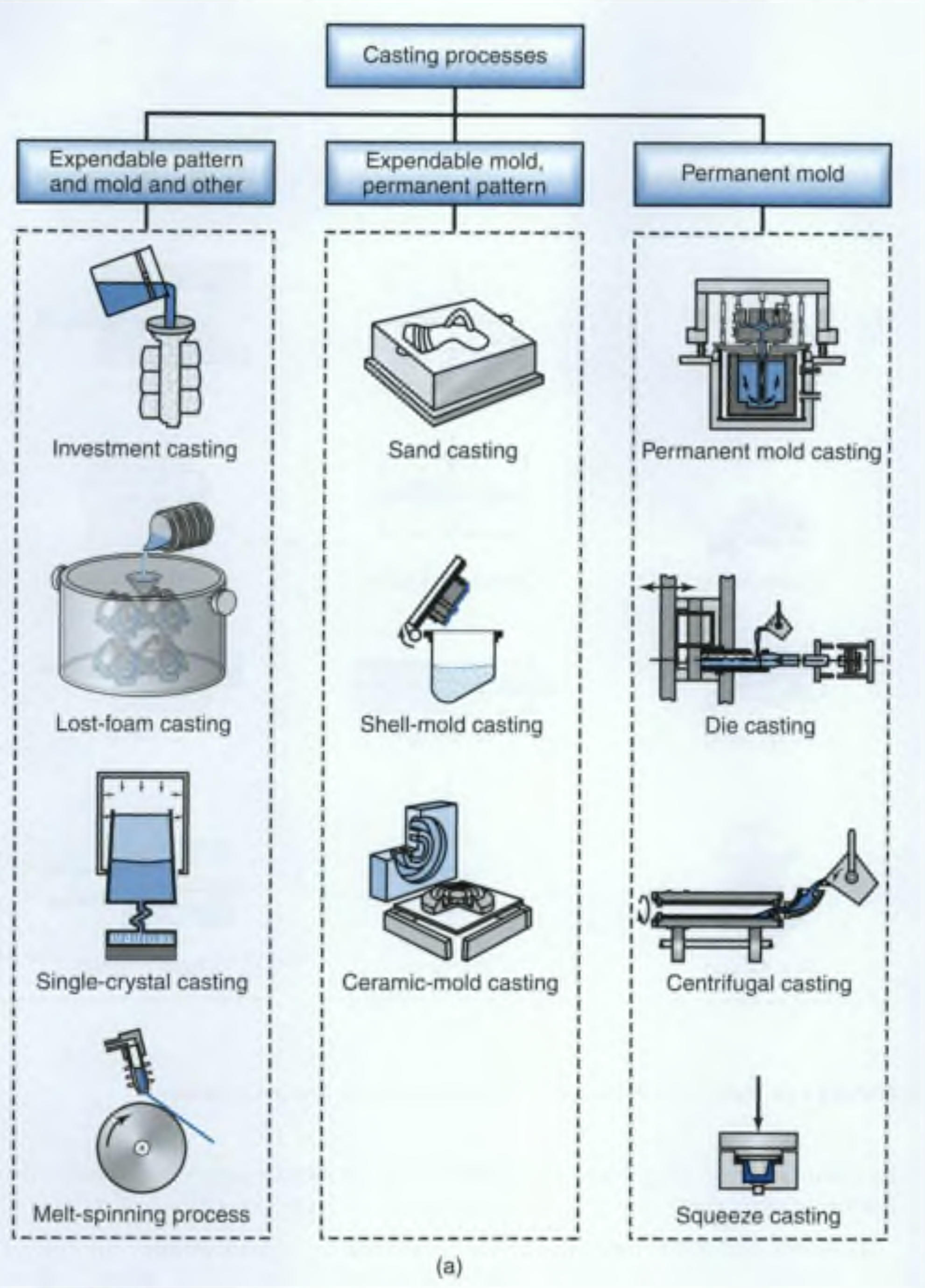


FIGURE I.5a Schematic illustrations of various casting processes.

Process Selection. The selection of a particular manufacturing process or, more often, sequence of processes, depends on the geometric features of the parts to be produced, including the dimensional tolerances and surface texture required, and on numerous factors pertaining to the particular workpiece material and

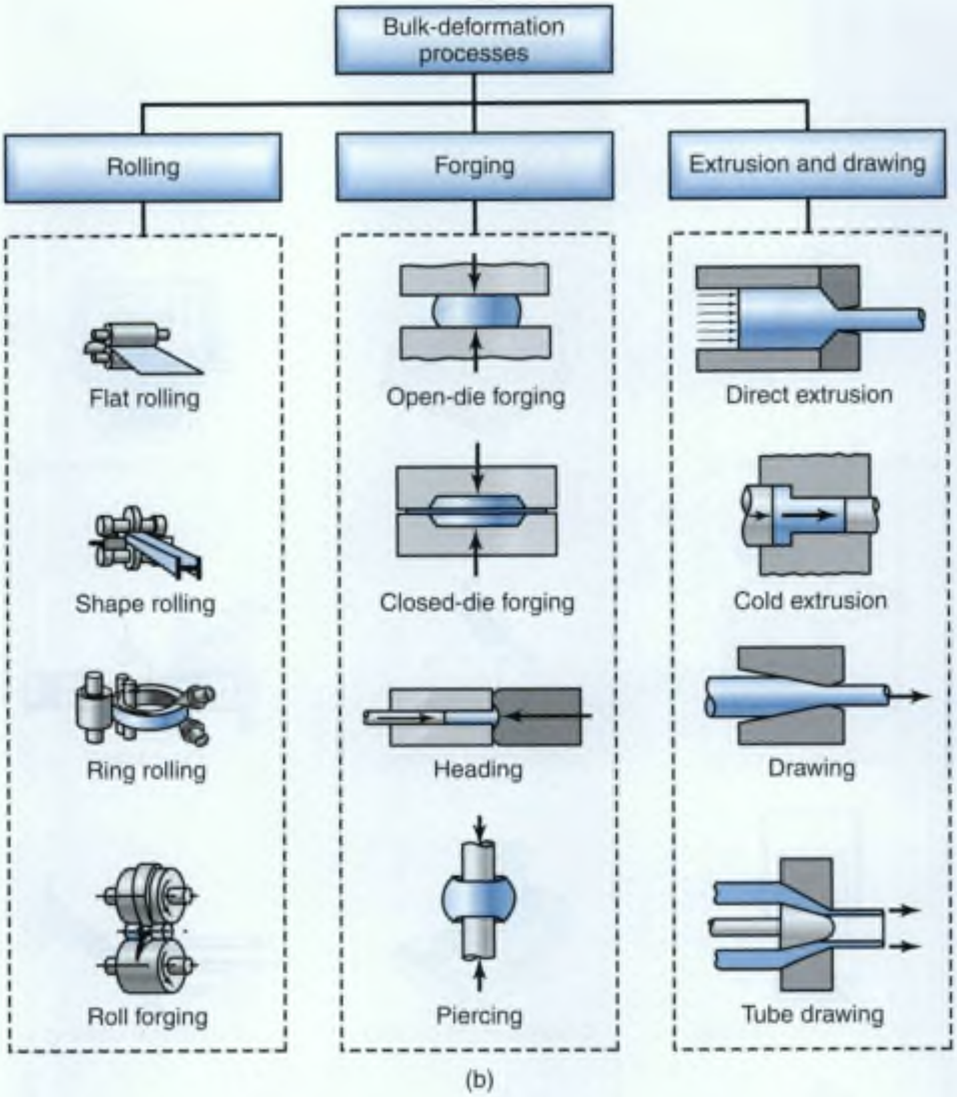


FIGURE I.5b Schematic illustrations of various bulk-deformation processes.

its manufacturing properties. To emphasize the challenges involved, consider the following two cases:

1. Brittle and hard materials cannot be shaped or formed without the risk of fracture, unless they are performed at elevated temperatures, whereas these materials can be cast, machined, or ground with relative ease.
2. Metals that have been preshaped at room temperature become less formable during subsequent processing, which, in practice, is often necessary to finish the part; this is because the metals have become stronger, harder, and less ductile than they were prior to processing them further.

There is a constant demand for new approaches to production challenges and, especially, for manufacturing cost reduction; for example, sheet-metal parts traditionally have been cut and fabricated using common mechanical tools, such as punches and dies. Although still widely used, some of these operations have been replaced by

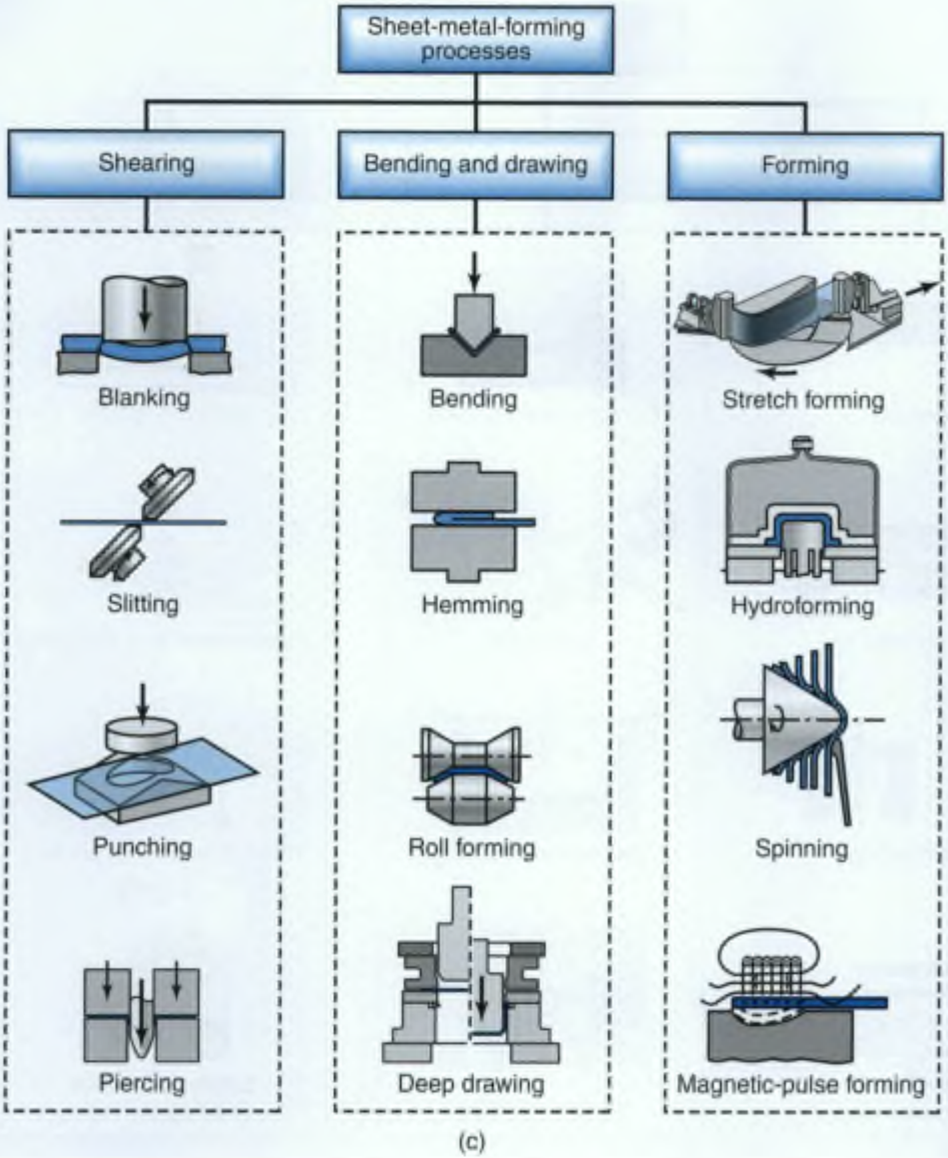


FIGURE I.5c Schematic illustrations of various sheet-metal forming processes.

laser cutting, as shown in Fig. I.6. This method eliminates the need for hard tools, which typically have only fixed shapes, and can be expensive and time consuming to make.

The laser path in this cutting operation is computer controlled, thereby increasing the operation's flexibility and its capability of producing an infinite variety of shapes accurately, repeatably, and economically. Because of the high heat involved in using lasers, however, the surfaces produced after cutting have very different characteristics (such as surface texture and discoloration) than those produced by traditional methods. This difference can have significant adverse effects, not only on appearance but especially on its subsequent processing and in the service life of the product. Moreover, the inherent flexibility of the laser cutting process is countered by the fact that it is slower than traditional punching operations.

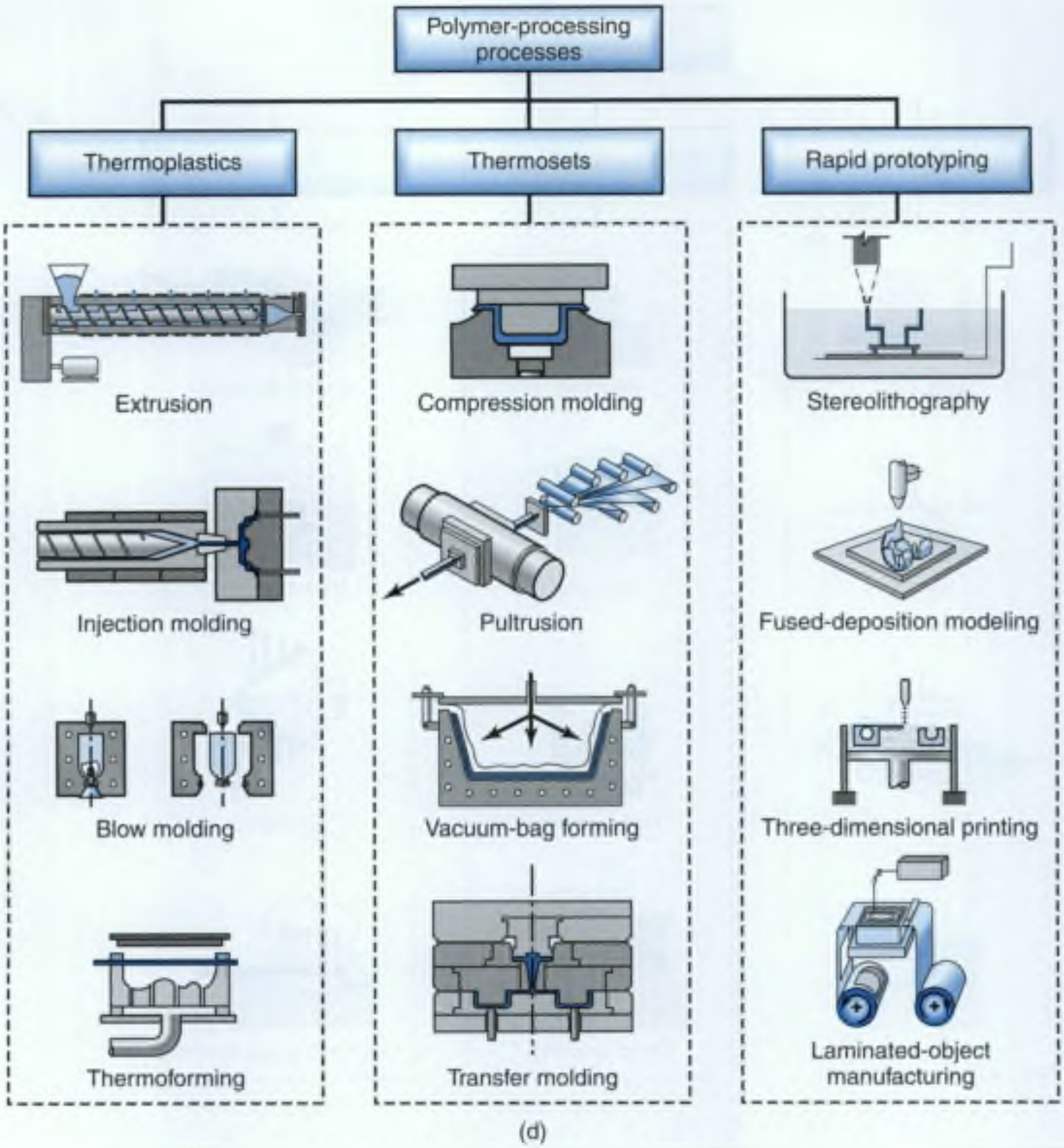


FIGURE I.5d Schematic illustrations of various polymer-processing methods.

Several factors can have a major role in process selection, including part size, shape complexity, and dimensional accuracy and surface finish required. For example:

- Flat parts and thin cross-sections can be difficult to cast.
- Complex parts generally cannot be shaped easily and economically by such metalworking techniques as forging, whereas, depending on part size and level of complexity, the parts may be precision cast, fabricated and assembled from individual pieces, or produced by powder metallurgy techniques.
- Dimensional tolerances and surface finish in hot-working operations are not as fine as those obtained in operations performed at room temperature (cold

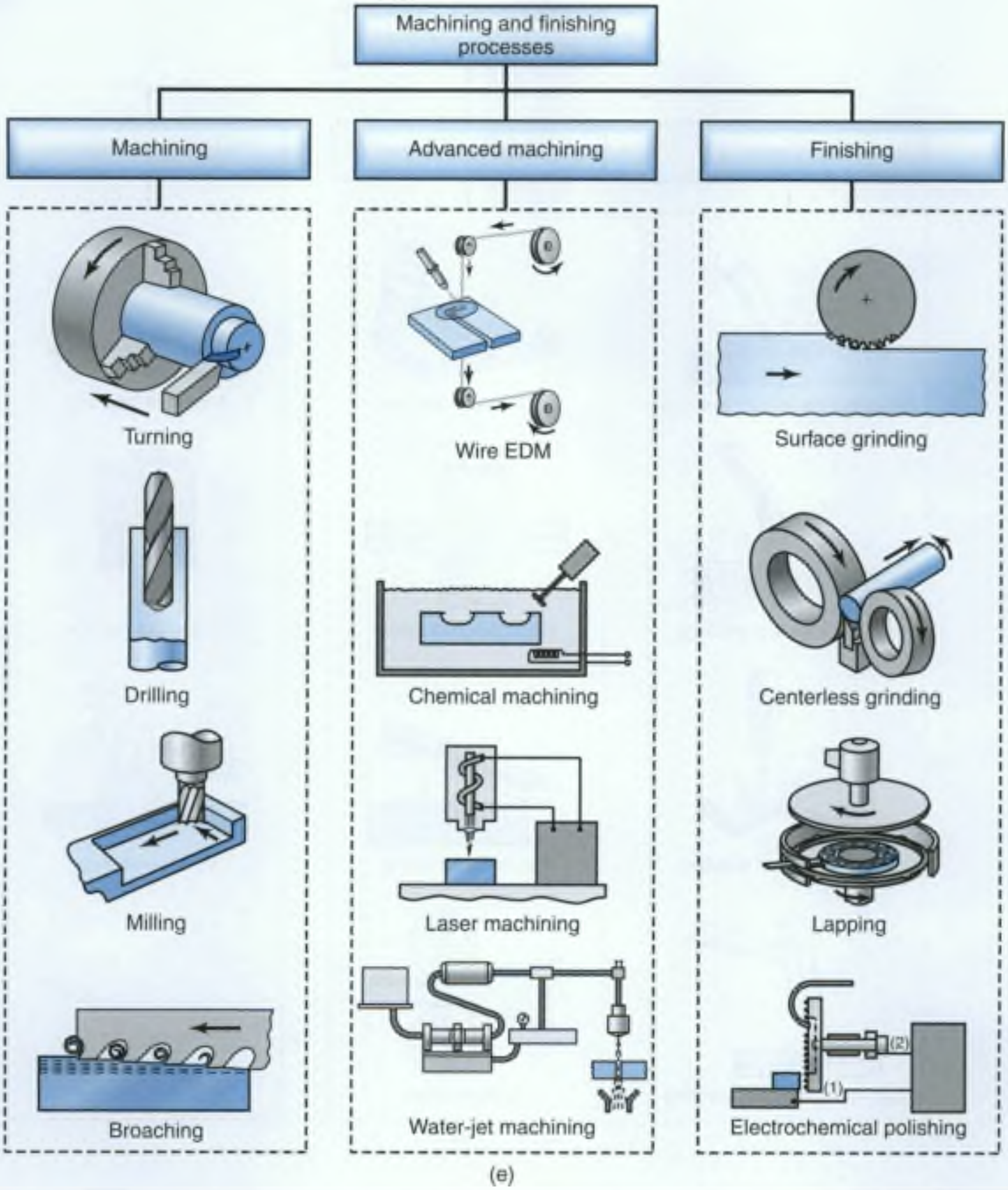


FIGURE I.5e Schematic illustrations of various machining and finishing processes.

working), because of the dimensional changes, distortion, warping, and surface oxidation due to the elevated temperatures employed.

The size of manufactured products, and the machinery and equipment involved in processing them, vary widely, ranging from microscopic gears and mechanisms of micrometer size, as illustrated in Fig. I.7, to (a) the main landing gear for the Boeing

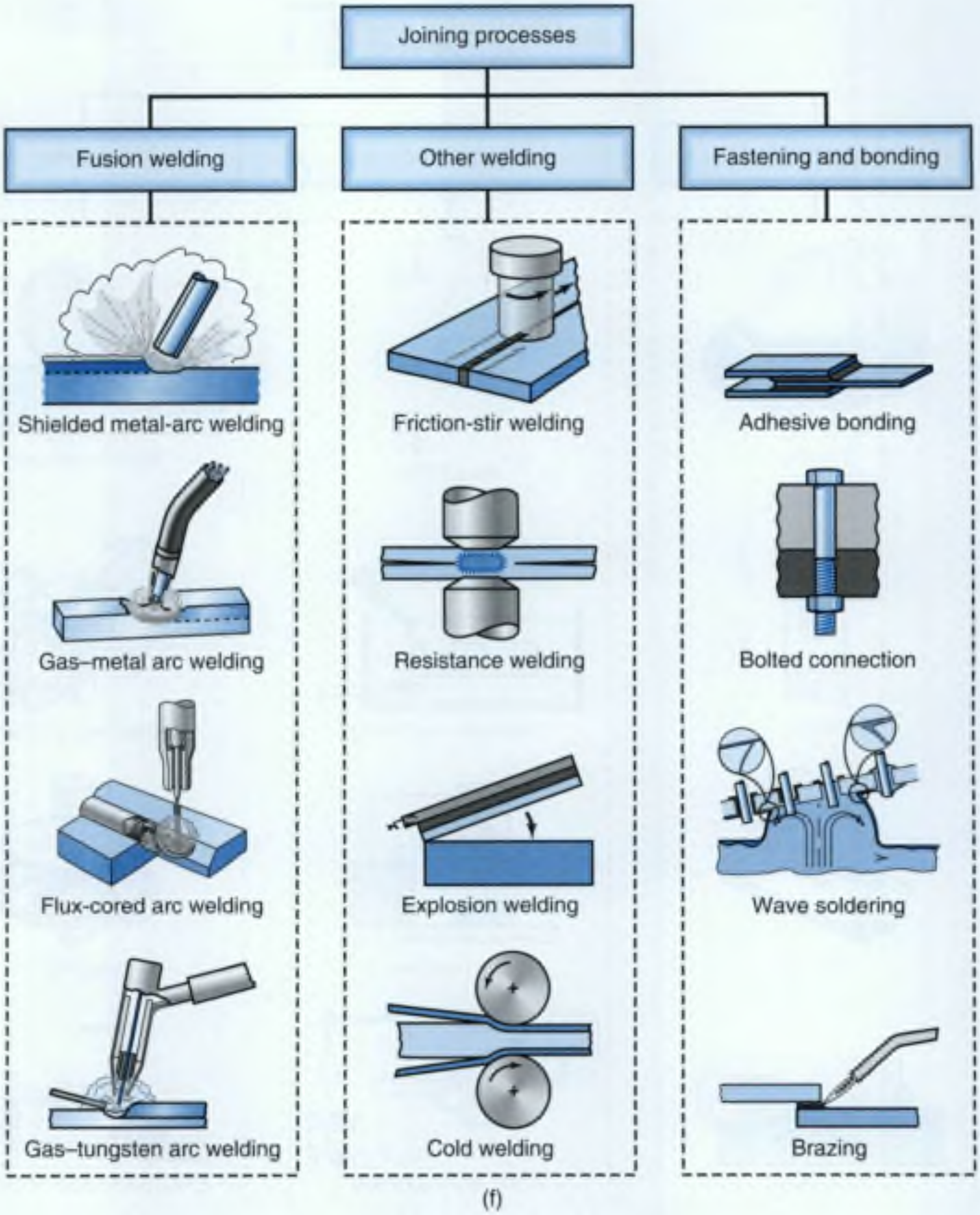


FIGURE I.5f Schematic illustrations of various joining processes.

777 aircraft, which is 4.3 m tall and includes three axles and six wheels; (b) the runner for the turbine for a hydroelectric power plant, which is 4.6 m in diameter and weighs 50,000 kg; and (c) a large steam turbine rotor, weighing 300,000 kg.

Process Substitution. It is common practice in industry that, for a variety of reasons and after a review of all appropriate and applicable processes, a particular production method (that may have been employed in the past) may well have to be substituted with another. Consider, for example, the following products that can be produced by any of the sets of the following processes: (a) cast versus forged crankshaft, (b) stamped sheet-metal versus forged or cast automobile wheels, (c) cast versus stamped sheet-metal frying pan, (d) injection molded versus extruded or cast polymer bracket, and (e) welded versus riveted sheet-metal safety hood for a machine.

Criteria for their selection include factors such as cost, the maintenance required, whether the product is for industrial or consumer use, the parameters to which the product will be subjected (such as external forces, impact, temperatures, and chemicals), environmental concerns that have to be addressed, and the product's appeal to the customer.

Net-shape and Near-net-shape Manufacturing. *Net-shape* and *near-net-shape manufacturing* together constitute an important methodology, by which a part is made in only one operation and at or close to the final desired dimensions, tolerances, and surface finish. The difference between net shape and near net shape is a matter of degree of how close the product is to its final dimensional and surface finish characteristics.

The necessity for, and benefits of, net-shape manufacturing can be appreciated from the fact that, in the majority of cases, more than one additional manufacturing operation or step is often necessary to produce the part. For example, a cast or forged crankshaft generally will not have the necessary dimensional surface finish characteristics, and will typically require additional processing, such as machining or grinding. These additional operations can contribute significantly to the cost of a product.

Typical examples of net-shape manufacturing include precision casting (Chapter 11), forging (Chapter 14), forming sheet

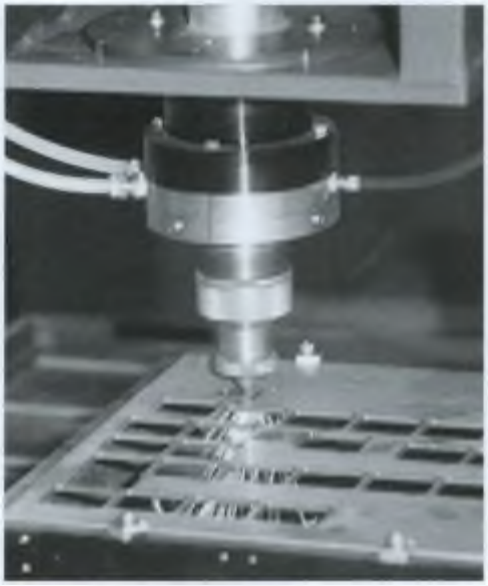
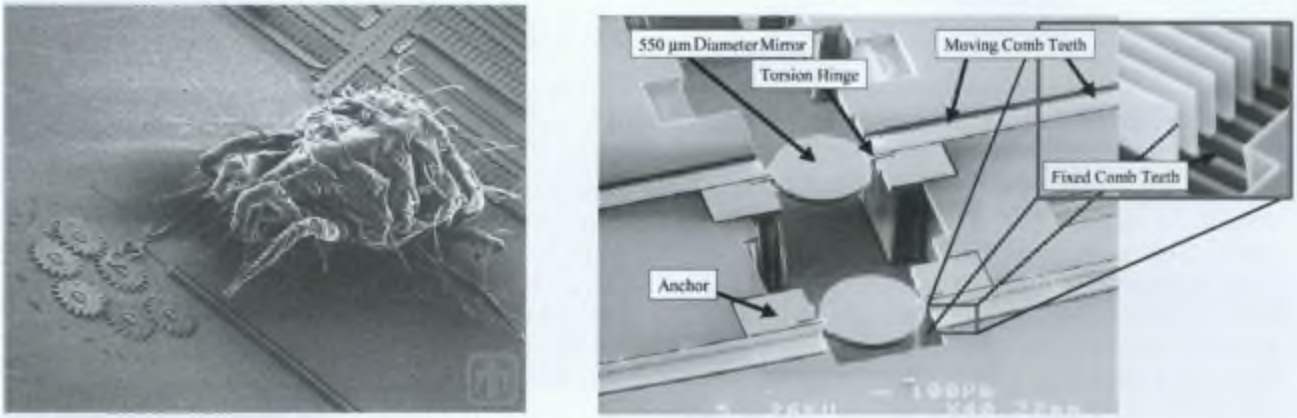


FIGURE I.6 Cutting sheet metal with a laser beam. *Source:* Courtesy of Rofin-Sinar, Inc., and Society of Manufacturing Engineers.



(a) (b)

FIGURE I.7 (a) Microscopic gears with dust mite. *Source:* Courtesy of Sandia National Laboratory. Printed with permission; (b) a movable micromirror component of a light sensor; note the scale at the bottom of the figure. *Source:* Courtesy of R. Mueller, University of California at Berkeley.

metal (Chapter 16), powder metallurgy and injection molding of metal powders (Chapter 17), and injection molding of plastics (Chapter 19).

Ultraprecision Manufacturing. Dimensional accuracies for some modern equipment and instrumentation have now reached the magnitude of the atomic lattice (below 1 nm). Several techniques, including the use of highly sophisticated technologies (see *micromechanical and microelectromechanical device fabrication*, Chapter 29), are rapidly being developed to attain such extreme accuracy. Also, mirrorlike surfaces on metals can now be produced by machining, using a very sharp diamond, with a nose radius of 250 μm, as the cutting tool. The equipment is highly specialized, with very high stiffness (to minimize deflections, as well as vibration and chatter, during machining). It is operated in a room where the ambient temperature is controlled to within 1°C, in order to avoid thermal distortions of the machine.

Types of Production. The number of parts to be produced (such as the annual quantity) and the production rate (the number of pieces made per unit time) are important economic considerations in determining the appropriate processes and the types of machinery required. Note, for example, that light bulbs, beverage cans, fuel-injection nozzles, and hubcaps are produced in numbers and at rates that are much higher than those for jet engines.

A brief outline of the general types of production, in increasing order of annual quantities produced, are:

1. **Job shops:** Small lot sizes, typically less than 100, using general-purpose machines, such as lathes, milling machines, drill presses, and grinders, many now typically equipped with computer controls.
2. **Small-batch production:** Quantities from about 10 to 100, using machines similar to those in job shops.
3. **Batch production:** Lot sizes typically between 100 and 5000, using more advanced machinery with computer control.
4. **Mass production:** Lot sizes generally over 100,000, using special-purpose machinery, known as dedicated machines, and various automated equipment in a plant for transferring materials and parts in progress.

CASE STUDY I.3 Saltshaker and Pepper Mill

The saltshaker and pepper mill set shown in Fig. I.8 consists of metallic as well as nonmetallic components. The main parts (the body) of the set are made by injection molding of a thermoplastic (Chapter 19), such as an acrylic, which has both transparency and other desirable characteristics for this application and is easy to mold. The round metal top of the saltshaker is made of sheet metal, has punched holes (Chapter 16), and is electroplated for improved appearance (Section 34.9).

The knob on the top of the pepper mill is made by machining (Chapter 23) and is threaded on the inside to allow it to be screwed and unscrewed. The square rod connecting the top portion of the pepper mill to the two pieces shown at the bottom of the figure is made by a rolling operation (Chapter 13). The two grinder components shown at the bottom of the figure are made of stainless steel. A design for manufacturing analysis indicated that casting or machining the two components would be too costly; consequently, it was determined that an appropriate and economical method would be the powder metallurgy technique (Chapter 17).

FIGURE I.8 A saltshaker and pepper mill set. The two metal pieces (at the bottom) for the pepper mill are made by powder metallurgy techniques. *Source:* Metal Powder Industries Federation.

I.7 Computer-integrated Manufacturing

Computer-integrated manufacturing (CIM), as the name suggests, integrates the software and hardware needed for computer graphics, computer-aided modeling, and computer-aided design and manufacturing activities, from initial product concept through its production and distribution in the marketplace. This comprehensive and integrated approach began in the 1970s and has been particularly effective because of its capability of making possible the following tasks:

- Responsiveness to rapid changes in product design modifications and to varying market demands
- Better use of materials, machinery, and personnel
- Reduction in inventory
- Better control of production and management of the total manufacturing operation

The following is a brief outline of the various elements in CIM, all described in detail in Chapters 38 and 39:

1. **Computer numerical control** (CNC). First implemented in the early 1950s, this is a method of controlling the movements of machine components by the direct insertion of coded instructions in the form of numerical data.
2. **Adaptive control** (AC). The processing parameters in an operation are automatically adjusted to optimize the production rate and product quality and to minimize manufacturing costs. For example, in machining, the forces, temperature, surface finish, and the dimensions of the part can be constantly monitored. If they move outside a specified range, the system automatically adjusts the appropriate variables until the parameters are within the specified range.
3. **Industrial robots.** Introduced in the early 1960s, industrial robots (Fig. I.9) have rapidly been replacing humans, especially in operations that are repetitive, dangerous, and boring. As a result, variability in product quality is decreased and productivity improved. Robots are particularly effective in material movement

FIGURE I.9 Automated spot welding of automobile bodies in a mass-production line.

and assembly operations; *intelligent* robots have been developed with sensory-perception capabilities and movements that simulate those of humans.

4. **Automated materials handling.** Computers have made possible highly efficient handling of materials and components in various stages of completion (work in progress), as in moving a part from one machine to another, and then to points of inspection, to inventory, and finally, to shipment.
5. **Automated assembly systems.** These systems have been developed to replace assembly by humans, although they still have to perform some operations. Depending on the type of product, assembly costs can be high; consequently, products must be designed such that they can be assembled more easily and faster by automated machinery.
6. **Computer-aided process planning** (CAPP). By optimizing process planning, this system is capable of improving productivity, product quality, and consistency, and thus reducing costs. Functions such as cost estimating and monitoring work standards (time required to perform a certain operation) are also incorporated into the system.
7. **Group technology** (GT). The concept behind group technology is that numerous parts can be grouped and produced by classifying them into families according to similarities in (a) design and (b) the manufacturing processes employed to produce them. In this way, part designs and process plans can be standardized and new parts, based on similar parts made previously, can be produced efficiently and economically.
8. **Just-in-time production** (JIT). The principle behind JIT is that (a) supplies of raw materials and parts are delivered to the manufacturer just in time to be used, (b) parts and components are produced just in time to be made into subassemblies, and (c) products are assembled and finished just in time to be delivered to the customer. As a result, inventory carrying costs are low, defects in components are detected right away, productivity is increased, and high-quality products are made and at low cost.
9. **Cellular manufacturing** (CM). This system utilizes workstations that consist of a number of *manufacturing cells*, each containing various production machinery,

all controlled by a central robot, with each machine performing a specific operation on the part, including inspection.

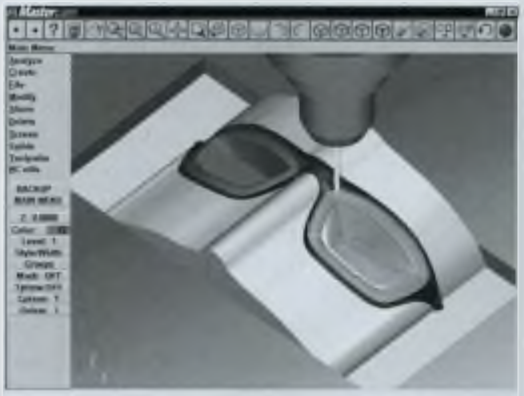
10. **Flexible manufacturing systems** (FMS). These systems integrate manufacturing cells into a large production facility, with all of the cells interfaced with a central computer. Although very costly, flexible manufacturing systems are capable of producing parts efficiently (although in relatively small quantities, because hard automation is still most efficient for mass production) and of quickly changing manufacturing sequences required for making different parts. Flexibility enables these systems to meet rapid changes in market demand for all types of products.
11. **Expert systems** (ES). Consisting basically of complex computer programs, these systems have the capability of performing various tasks and solving difficult real-life problems (much as human experts would), including expediting the traditional iterative process.
12. **Artificial intelligence** (AI). Computer-controlled systems are capable of learning from experience and of making decisions that optimize operations and minimize costs, ultimately replacing human intelligence.
13. **Artificial neural networks** (ANN). These networks are designed to simulate the thought processes of the human brain, with such capabilities as modeling and simulating production facilities, monitoring and controlling manufacturing operations, diagnosing problems in machine performance, and conducting financial planning and managing a company's manufacturing strategy.

CASE STUDY I.4 Mold for Making Sunglass Frames

The metal mold used for injection molding of plastic sunglass frames is made on a computer numerical-control milling machine, using a cutter (called a ball-nosed end mill) as illustrated in Fig. I.10. First, a model of the sunglass is made using a computer-aided design software package, from which a model of the mold is automatically generated. The geometric information is sent to the milling machine, and the machining steps are planned.

Next, an offset is added to each surface to account for the nose radius of the end mill during machining, thus determining the cutter path (the path followed by the center of rotation of the machine spindle). The numerical-control programming software executes this machining program on the milling machine, producing the die cavity with appropriate dimensions and tolerances. Electrical-discharge machining (Section 27.5) can also be used to make this mold; however, it was determined that the operation was about twice as expensive as machining the mold by computer numerical control, and it also produced molds that had lower dimensional accuracy.

Source: Based on Mastercam/CNC Software, Inc.



(a)

FIGURE I.10 Machining a mold cavity for making sunglasses. (a) Computer model of the sunglasses as designed and viewed on the monitor. *Source:* Courtesy of Mastercam/CNC Software, Inc.

(continued)

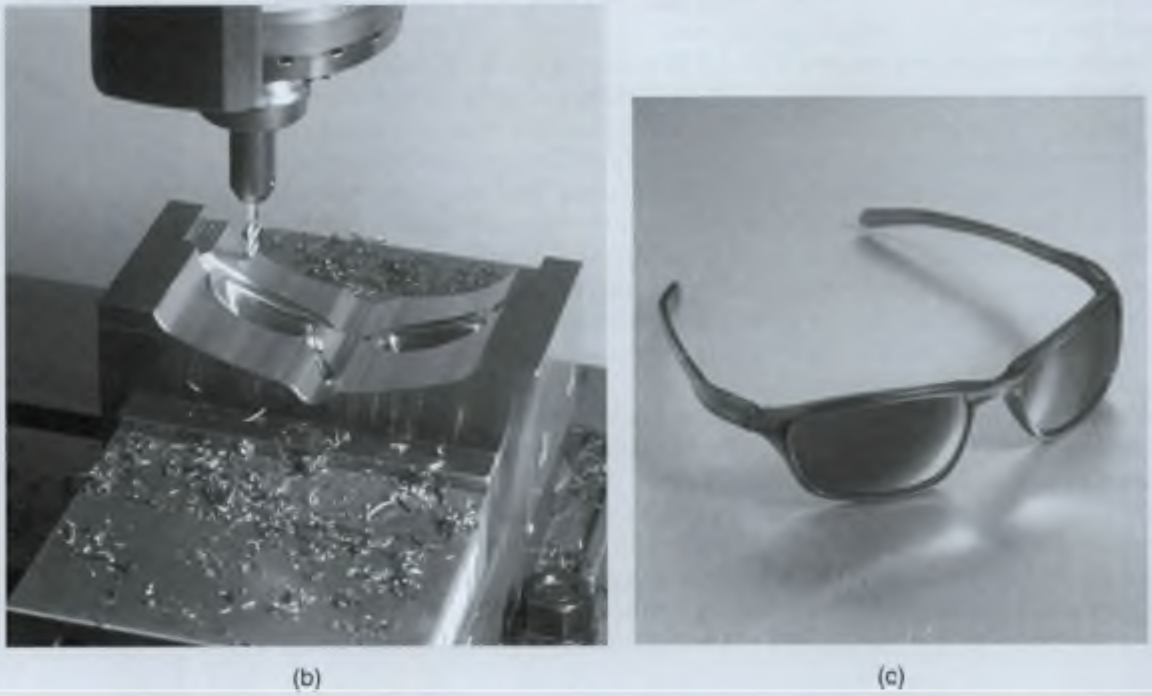


FIGURE I.10 (*continued*) (b) Machining of the die cavity, using a computer numerical-control milling machine. (c) Final product produced from the mold. *Source:* Courtesy of Mastercam/CNC Software, Inc.

I.8 Quality Assurance and Total Quality Management

Product quality is one of the most critical considerations in manufacturing, because it directly influences customer satisfaction, thus playing a crucial role in determining a product's success in the marketplace (Chapter 36). The traditional approach of inspecting products after they are made has largely been replaced by the recognition that *quality must be built into the product*, from its initial design through all subsequent stages of manufacture and assembly.

Because products are typically made through several manufacturing steps and operations, each step can involve its own significant variations in performance; this variation can occur even within a relatively short time. A production machine, for example, may perform differently when it is first turned on than after it warms up during its use, or when the ambient temperature in the plant fluctuates. Consequently, *continuous control of processes* (known as *online monitoring*) is a critical factor in maintaining product quality, the objective being to *control processes, not products.*

Quality assurance and *total quality management* (TQM) are widely recognized as being the responsibility of everyone involved in the design and manufacture of products and their components. *Product integrity* is a term generally used to define the degree to which a product

- Functions reliably during its life expectancy (Table I.4)
- Is suitable for its intended purposes
- Can be maintained with relative ease

Producing and marketing defective products can be very costly to the manufacturer, with costs varying by orders of magnitude, as shown in Table I.5.

Pioneers in quality control, particularly W.E. Deming (1900–1993), J.M. Juran (1904–2008), and G. Taguchi (1924–2012), all emphasized the importance of management's commitment to (a) product quality, (b) pride of workmanship at all levels of production, and (c) the necessity of using **statistical process control** (SPC) and **control charts** (Chapter 36). They also pointed out the importance of online monitoring and rapidly identifying the *sources of quality problems* in production, before even another defective part is produced. The major goal of control is to *prevent* defective parts from ever being made, rather than to inspect, detect, and reject defective parts after they have been made.

As an example of strict quality control, computer chips are now produced with such high quality that only a few out of a million chips may be defective. The level of defects is identified in terms of **standard deviation**, denoted by the symbol σ (the Greek letter *sigma*). Three sigma would result in 2700 defective parts per million, which is much too high in modern manufacturing. In fact, it has been estimated that at this level, no modern computer would function reliably. At **six sigma**, defective parts are reduced to only 3.4 per million parts made; this level has been reached through major improvements in manufacturing *process capabilities* in order to *reduce variability* in product quality.

Important developments in quality assurance include the implementation of **experimental design**, a technique in which the factors involved in a manufacturing operation and their interactions are studied simultaneously. For example, the variables affecting dimensional accuracy or surface finish in a machining operation can be identified readily, thus making it possible for appropriate preventive on-time adjustments to be taken.

TABLE I.4

Average Life Expectancy of Various Products

Type of product	Life expectancy (years)
U.S. dollar bill	1.5
Personal computer	2
Car battery	4
Hair dryer	5
Automobile	8
Dishwasher	10
Kitchen disposal unit	10
Vacuum cleaner	10
Water heater (gas)	12
Clothes dryer (gas)	13
Clothes washer	13
Air-conditioning unit (central)	15
Manufacturing cell	15
Refrigerator	17
Furnace (gas)	18
Machinery	30
Nuclear reactor	40

Note: Significant variations can be expected, depending on the quality of the product and how well it has been maintained.

Quality Standards. Global manufacturing and competitiveness have led to an obvious need for international conformity and consensus in establishing quality control methods. This need resulted in the establishment of the ISO 9000 standards series on quality management and quality assurance standards, as well as of the QS 9000 standards (Section 36.6), introduced in 1994. A company's registration for these standards, which is a *quality process certification* and not a product certification, means that the company conforms to consistent practices as specified by its own quality system. ISO 9000 and QS 9000 have permanently influenced the manner in which companies conduct business in world trade, and they are now the world standard for quality.

TABLE I.5

Relative Cost of Repair at Various Stages of Product Development and Sale

Stage	Relative cost of repair
When the part is being made	1
Subassembly of the product	10
Assembly of the product	100
Product at the dealership	1000
Product at the customer	10,000

Human-factors Engineering. This topic deals with human–machine interactions, and thus is an important aspect of manufacturing operations in a plant, as well as of products in their expected use. The human-factors approach is essential in the design and manufacture of safe products; it emphasizes **ergonomics**, defined as the study of how a workplace and the machinery and equipment in it can best be designed and arranged for comfort, safety, efficiency, and productivity.

Some examples of the need for proper ergonomic considerations are: (a) a mechanism that is difficult to operate manually, causing injury to the worker, (b) a poorly designed keyboard that causes pain to the user's hands and arms during its normal use (known as *repetitive stress syndrome*), and (c) a control panel on a machine that is difficult to reach or use safely and comfortably.

Product Liability. Designing and manufacturing safe products is an essential aspect of a manufacturer's responsibilities. All those involved with product design, manufacture, and marketing must fully recognize the consequences of a product's failure, including failure due to foreseeable misuse of the product.

A product's malfunction or failure can cause bodily injury or even death, as well as financial loss to an individual, a bystander, or an organization. This important topic is referred to as *product liability*. The laws governing it generally vary from state to state and from country to country. Among the numerous examples of products that could involve liability are:

- A grinding wheel shatters and causes injury to a worker
- A cable supporting a platform snaps, allowing the platform to drop and cause bodily harm or death
- Automotive brakes suddenly become inoperative because of the failure of a particular component of the brake system
- Production machinery lacks appropriate safety guards
- Electric and pneumatic tools lack appropriate warnings and instructions for their safe use

I.9 Lean Production and Agile Manufacturing

Lean production (Section 39.6) is a methodology that involves a thorough assessment of each activity of a company, with the basic purpose of minimizing waste at all levels and calling for the elimination of unnecessary operations that do not provide any added value to the product being made. This approach, also called *lean manufacturing*, identifies all of a manufacturer's activities and optimizes the processes used in order to *maximize added value*. Lean production focuses on (a) the efficiency and effectiveness of each and every manufacturing step, (b) the efficiency of the machinery and equipment used, and (c) the activities of the personnel involved in each operation. This methodology also includes a comprehensive analysis of the costs incurred in each activity and those for productive and for nonproductive labor.

The lean production strategy requires a fundamental change in corporate culture, as well as having an understanding of the importance of *cooperation and teamwork* among the company's workforce and management. Lean production does not necessarily require cutting back on a company's physical or human resources; rather, it aims at *continually* improving efficiency and profitability by removing all waste in the company's operations and dealing with any problems as soon as they arise.

Agile Manufacturing. The principle behind *agile manufacturing* is ensuring *agility*, hence *flexibility*, in the manufacturing enterprise, so that it can respond rapidly and effectively to changes in product demand and the needs of the customer. Flexibility can be achieved through people, equipment, computer hardware and software, and advanced communications systems. As an example of this approach, it has been demonstrated that the automotive industry can configure and build a car in three days and that, eventually, the traditional assembly line will be replaced by a system in which a nearly custom-made car will be produced by combining several individual modules.

The methodologies of both lean and agile production require that a manufacturer **benchmark** its operations. Benchmarking involves assessing the competitive position of other manufacturers with respect to one's own position (including product quality, production time, and manufacturing costs) and setting realistic goals for the future. Benchmarking thus becomes a *reference point* from which various measurements can be made and to which they can be compared.

I.10 Manufacturing Costs and Global Competition

Always critically important, the economics of manufacturing has become even more so with (a) ever-increasing global competition and (b) the demand for high-quality products, generally referred to as *world-class manufacturing*, and at low prices. Typically, the *manufacturing cost* of a product represents about 40% of its *selling price*, which often is the overriding consideration in a product's marketability and general customer satisfaction. An approximate, but typical, breakdown of costs in modern manufacturing is given in Table I.6; the percentages indicated can, however, vary significantly depending on product type.

TABLE I.6

Typical Cost Breakdown in Manufacturing

Design	5%
Materials	50%
Manufacturing	
Direct labor	15%
Indirect labor	30%

The *total cost* of manufacturing a product generally consists of the following components:

1. **Materials.** Raw-material costs depend on the material itself and on supply and demand for the material. Low cost may not be the deciding factor if the cost of processing a particular material is higher than that for a more expensive material. For example, a low-cost piece of metal may require more time to machine, or form, than one of higher cost, thus increasing production costs.
2. **Tooling.** Tooling costs include those for cutting tools, dies, molds, work-holding devices, and fixtures. Some cutting tools cost as little as \$2 and as much as about \$100 for materials such as cubic boron nitride and diamond. Depending on their size and the materials involved in making them, molds and dies can cost from only a few hundred dollars to over \$2 million for a set of dies for stamping sheet metal to make automobile fenders.
3. **Fixed.** Fixed costs include costs for energy, rent for facilities, insurance, and real-estate taxes.
4. **Capital.** Production machinery, equipment, buildings, and land are typical capital costs. Machinery costs can range from a few hundred to millions of dollars. Although the cost of computer-controlled machinery can be very high, such an expenditure may well be warranted if it reduces labor costs.
5. **Labor.** Labor costs consist of direct and indirect costs. Direct labor, also called productive labor, concerns the labor that is directly involved in manufacturing products. Indirect labor, also called nonproductive labor or overhead, pertains to servicing of the total manufacturing operation.

Direct-labor costs may be only 10 to 15% of the total cost (Table I.6), but it can be as much as 60% for labor-intensive products. Reductions in the direct-labor share of manufacturing costs can be achieved by such means as extensive automation, computer control of all aspects of manufacturing, implementation of modern technologies, and increased efficiency of operations.

As expected and shown in Table I.7, there continues to be a worldwide disparity in labor costs, by an order of magnitude. It is not surprising that today numerous consumer products are manufactured or assembled in Pacific Rim countries, especially China. Likewise, software and information technologies are often much less costly to develop in countries such as India and China than in the United States or

TABLE I.7

Approximate Relative Hourly Compensation for Workers in Manufacturing in 2010 (United States = 100)

Norway	166	Italy	96
Switzerland	153	Japan	92
Belgium	146	Spain	76
Denmark	131	New Zealand	59
Germany	126	Israel	58
Sweden	126	Singapore	55
Finland	122	Korea (South)	48
Austria	118	Argentina, Slovakia	36
Netherlands, Australia	118	Portugal	34
France	117	Czech Republic	33
Ireland	104	Poland	23
United States	100	Mexico	18
Canada	97	China, India, Philippines	6

Note: Compensation can vary significantly with benefits. Data for China and India are estimates, they use different statistical measures of compensation, and are provided here for comparison purposes only.
Source: U.S. Department of Labor.

Europe. As living standards continue to rise, however, labor costs, too, are beginning to rise significantly in these countries.

Outsourcing. *Outsourcing* is defined as the purchase by a company of parts and/or labor from an outside source, either from another company or another country, in order to reduce design and manufacturing costs. In theory, this approach allows companies to concentrate on their core competencies, and be able to optimize their critical technologies. Outsourcing, however, has several drawbacks, including its social impact and political implications of any ensuing lowered employment, especially in the European Union countries and the United States. In recent years, the costs of shipping and transport have increased and have become more uncertain, and also manufacturers often prefer to be located near their customers and/or suppliers. As a result, a **reshoring** trend has begun, which involves relocating manufacturing activities to a few critical locations, usually near the customers.

I.11 Trends in Manufacturing

Several trends regarding various aspects of modern manufacturing are:

1. Product variety and complexity continue to increase.
2. Product life cycles are becoming shorter.
3. Markets continue to become multinational and global competition is increasing rapidly.
4. Customers are consistently demanding high-quality, reliable, and low-cost products.
5. Developments continue in the quality of materials and their selection for improved recyclability.
6. Weight savings continue with the use of materials with higher strength-to-weight and stiffness-to-weight ratios, particularly in the automotive, aerospace, and sporting industries.

7. Improvements are being made in predictive models of the effects of material-processing parameters on product integrity, applied during a product's design stage.
8. Developments in ultraprecision manufacturing, micromanufacturing, and nanomanufacturing, approaching the level of atomic dimensions.
9. Computer simulation, modeling, and control strategies are being applied to all areas of manufacturing.
10. Rapid-prototyping technologies are increasingly being applied to the production of tooling and direct digital manufacturing.
11. Advances in optimization of manufacturing processes and production systems are making them more agile.
12. Lean production and information technology are being implemented as powerful tools to help meet global challenges.
13. Manufacturing activities are viewed not as individual, separate tasks, but as making up a large system, with all its parts interrelated.
14. It has become common to build quality into the product at each stage of its production.
15. The most economical and environmentally friendly (green) manufacturing methods are being increasingly pursued; energy management is increasingly important.
16. Continued efforts are aimed at achieving higher levels of productivity and eliminating or minimizing waste with optimum use of an organization's resources.

Fundamentals of Materials: Behavior and Manufacturing Properties

PART I

Part I of this text begins by describing the behavior and properties of materials, their manufacturing characteristics, and their applications, as well as their advantages and limitations that influence their selection in the design and manufacture of products.

In order to emphasize the importance of the topics to be described, consider a typical automobile as an example of a common product that utilizes a wide variety of materials (Fig. I.1). These materials were selected not only because they possess the desired properties and characteristics for the intended functions of specific parts, but also they were the ones that could be manufactured at the lowest cost.

For example, steel was chosen for parts of the body because it is strong, easy to shape, and inexpensive. Plastics were used in many components because of characteristics such as light weight, resistance to corrosion, availability in a wide variety of colors, and ease of manufacturing into complex shapes and at low cost. Glass was chosen for all the windows because it is transparent, hard (hence scratch resistant), easy to shape, and easy to clean. Numerous similar observations can be made about each component of an automobile, ranging from very small screws to wheels. In recent years, fuel efficiency and the need for improved performance have driven the

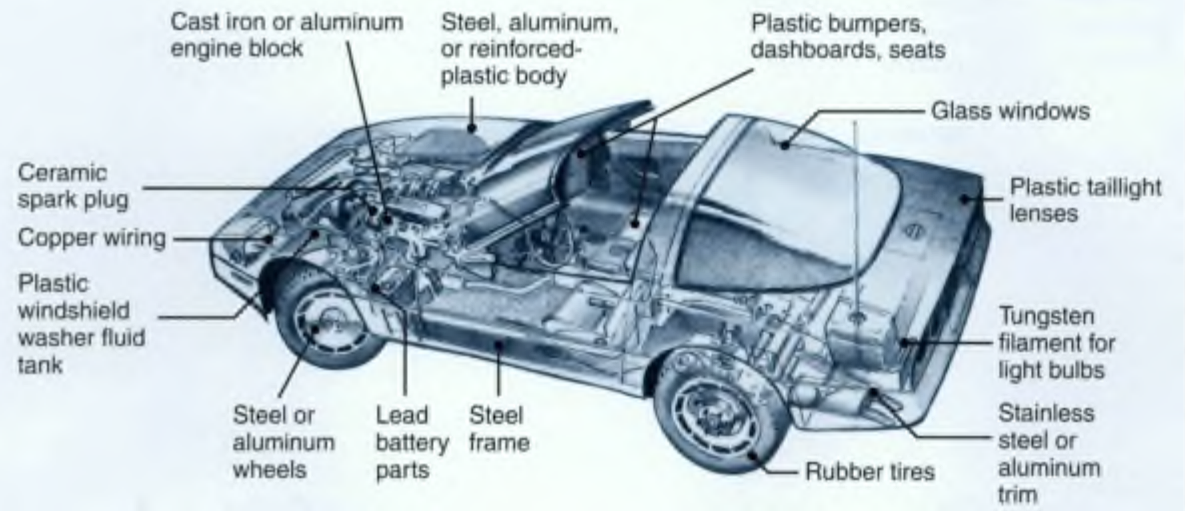


FIGURE I.1 An outline of the topics described in Part I.

QR Code I.1 Demonstration of a tension test. (*Source:* Courtesy of Instron®)

substitution of such materials as aluminum, magnesium, and plastics for steel, and the use of composite materials for structural (load-bearing) components.

As stated in the General Introduction, the selection of materials for individual components in a product requires a thorough understanding and assessment of their properties, functions, and manufacturing costs. A typical automobile is an assemblage of some 15,000 individual parts; consequently, by saving just one cent on the cost per part, such as by selecting a different material or manufacturing process, the cost of an automobile would be reduced by $150. This task thus becomes very challenging, especially with the ever-increasing variety of materials and manufacturing processes that are now available, as outlined in Fig. I.2.

A general outline of the topics described in Part I of this text is given in Fig. I.3. The fundamental knowledge presented on the behavior, properties, and characteristics of materials will help understand their significance and relevance to all the manufacturing processes described in Parts II through V.

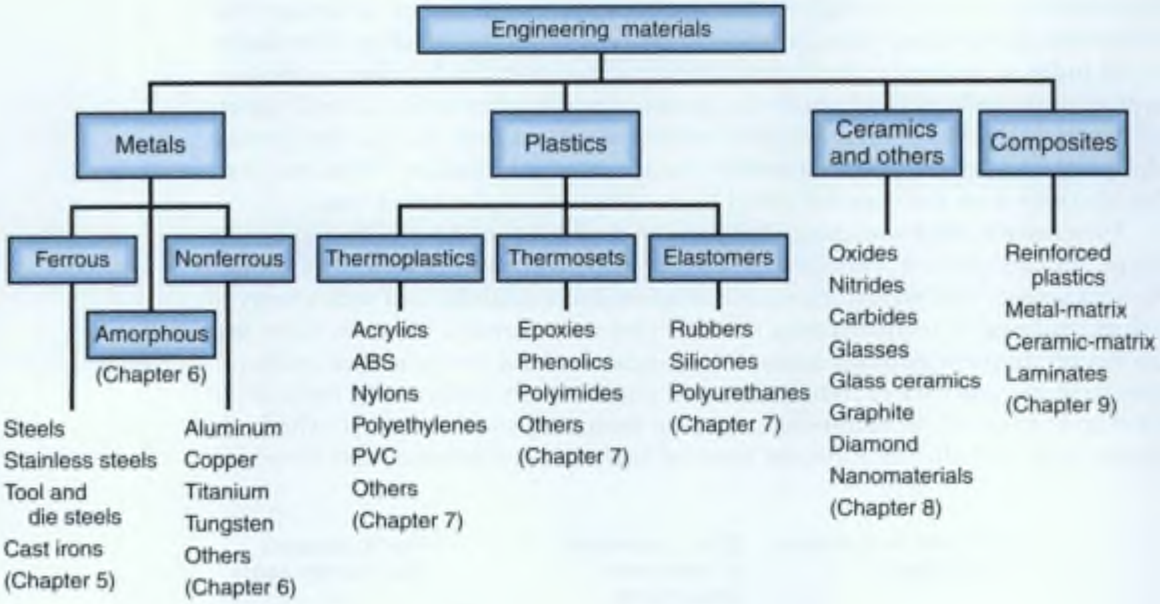


FIGURE I.2 An outline of the engineering materials described in Part I.

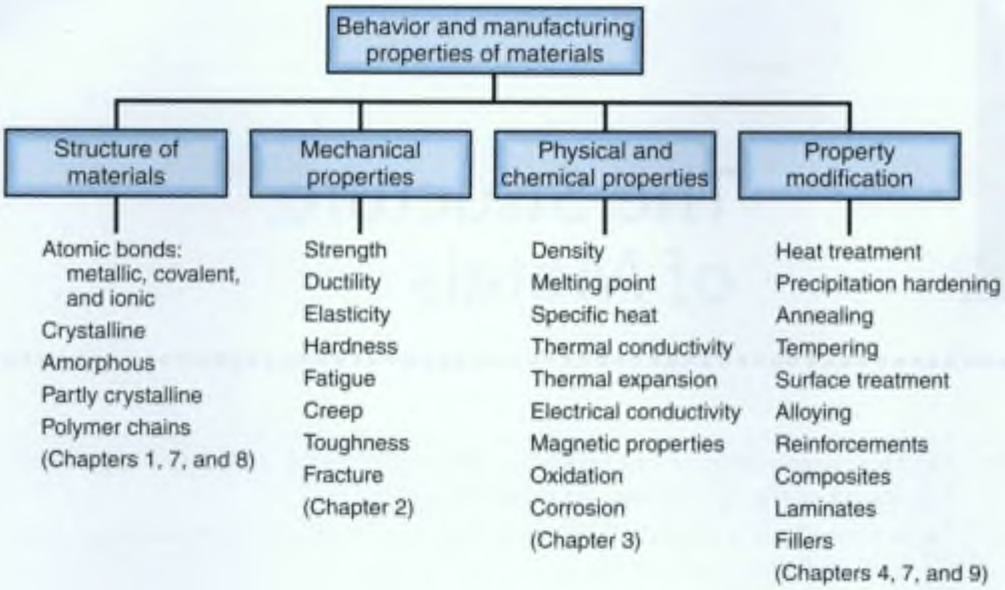


FIGURE I.3 An outline of the behavior and the manufacturing properties of materials described in Part I.

CHAPTER

1

The Structure of Metals

- This chapter describes the crystalline structure of metals and explains how they determine their properties and behavior.
- It begins with a review of the types of atomic bonds and their characteristics: ionic, covalent, and metallic.
- Metal structures and the arrangement of atoms within the structure are then examined, and the types of imperfections in the crystal structure and their effects are presented.
- The effects of grains and grain boundaries are examined, followed by a discussion of strain hardening and anisotropy of metals.

1.1 Introduction

Why are some metals hard and others soft? Why are some brittle, while others are ductile and can be shaped easily without fracture? Why is it that some metals can withstand high temperatures, while others cannot? Why a piece of sheet metal may behave differently when stretched in one direction versus another?

These questions can be answered by studying the **atomic structure** of metals—that is, the arrangement of the atoms within metals. This knowledge then serves as a guide to controlling and predicting the behavior and performance of metals in various manufacturing processes. Understanding the structure of metals also allows us to predict and evaluate their **properties** (such as strength and stiffness), thus help us to make appropriate selections for specific applications. For example, single-crystal turbine blades (Fig. 1.1) for use in jet engines have properties that are better than those for conventional blades. In addition to atomic structure, several other factors also influence the properties and behavior of metals. They include the composition of the particular metal, impurities and vacancies in their atomic structure, grain size, grain boundaries, environment, size and surface condition of the metal, and the methods by which they are made into products.

The topics described in this chapter and their sequence are outlined in Fig. 1.2. The structure and general properties of materials other than metals are described in Chapter 7 (polymers), Chapter 8 (ceramics and glasses), and Chapter 9 (composite materials). The structure of metal alloys, the control of their structure, and heat-treatment processes are described in Chapter 4.

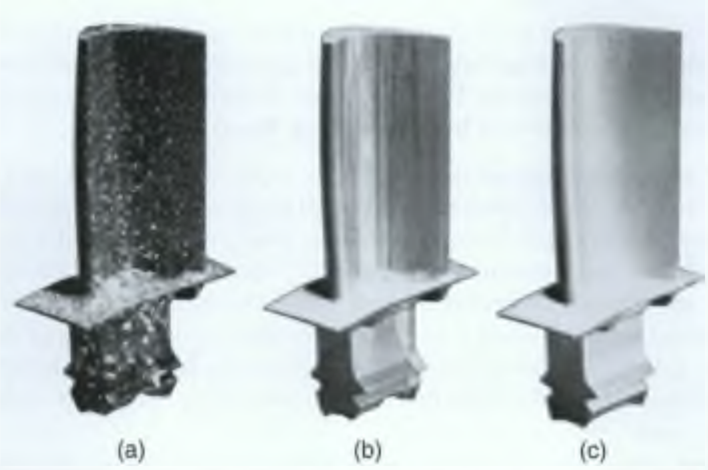


FIGURE 1.1 Turbine blades for jet engines, manufactured by three different methods: (a) conventionally cast, (b) directionally solidified, with columnar grains as can be seen from the vertical streaks, and (c) single crystal. Although more expensive, single-crystal blades have properties at high temperatures that are superior to those of other blades. *Source:* Courtesy of United Technologies Pratt and Whitney.

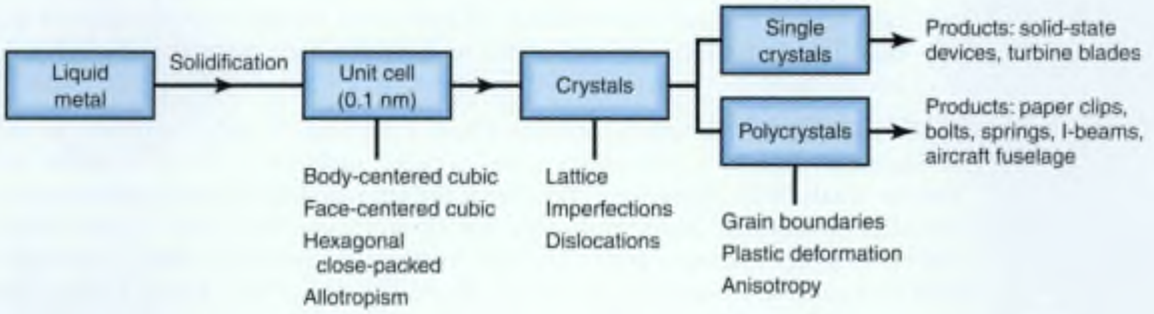


FIGURE 1.2 An outline of the topics described in this chapter.

1.2 Types of Atomic Bonds

All matter is made up of **atoms** consisting of a nucleus of *protons* and *neutrons* and surrounding clouds or orbits of electrons. The number of protons in the nucleus determines whether a particular atom will be metallic, nonmetallic, or semimetallic. An atom with a balanced charge has the same number of electrons as protons; when there are too many or too few electrons, the atom is called an **ion**. An excess of electrons results in a negatively charged atom, referred to as an **anion**, while too few electrons results in a positively charged atom, called a **cation**. The number of electrons in the outermost orbit of an atom determines the chemical affinity of that atom for other atoms.

Atoms can transfer or share electrons; in doing so, multiple atoms combine to form **molecules**. Molecules are held together by attractive forces called **bonds**, which act through electron interaction. The basic types of atomic attraction associated with electron transfer, called **primary bonds** or **strong bonds**, are:

- **Ionic bonds**. When one or more electrons from an outer orbit are transferred from one material to another, a strong attractive force develops between the two ions. An example is that of sodium (Na) and chlorine (Cl) in common table salt; the salt consists of Na^+ and Cl^- ions (hence the term *ionic bond*), which are strongly attracted to each other. Also, the attraction is between all adjacent ions, allowing crystalline structures to be formed, as discussed in Section 1.3. Molecules with ionic bonds generally have low ductility and low thermal and electrical conductivity. Ionic bonding is the predominant bond in ceramic materials.
- **Covalent bonds**. In a covalent bond, the electrons in outer orbits are shared by atoms to form molecules. The number of electrons shared is reflected by terms such as "single bond," "double bond," etc. Polymers consist of large molecules that are covalently bonded together. Solids formed by covalent bonding typically have low electrical conductivity and can have high hardness; diamond, a form of covalently bonded carbon, is an example.
- **Metallic bonds**. Metals have relatively few electrons in their outer orbits, and thus they cannot complete the outer shell when self-mated. Instead, metals and alloys form *metallic bonds*, whereby the available electrons are shared by all atoms in contact. The resulting electron cloud provides attractive forces to hold the atoms together and results in generally high thermal and electrical conductivity.

In addition to the strong attractive forces associated with electrons, weak or **secondary bonds** or attractions occur between molecules. Also referred to as **van der Waals** forces, these forces arise from the attraction of opposite charges without electron transfer. Water molecules, for example, consist of one oxygen atom and two smaller hydrogen atoms, located around 104° from each other. Although each molecule has a balanced, or neutral, charge, there are more hydrogen atoms on one side of the molecule (i.e., it is a *dipole*), so that the molecule develops a weak attraction to nearby oxygen atoms on that side.

1.3 The Crystal Structure of Metals

When metals solidify from a molten state (Chapter 10), the atoms arrange themselves into various orderly configurations, called **crystals**; this atomic arrangement is called **crystal structure** or **crystalline structure**. The smallest group of atoms showing the characteristic **lattice structure** of a particular metal is known as a **unit cell**.

The following are the three basic atomic arrangements in metals:

1. **Body-centered cubic** (**bcc**); alpha iron, chromium, molybdenum, tantalum, tungsten, and vanadium.
2. **Face-centered cubic** (**fcc**); gamma iron, aluminum, copper, nickel, lead, silver, gold, and platinum.
3. **Hexagonal close-packed** (**hcp**); beryllium, cadmium, cobalt, magnesium, alpha titanium, zinc, and zirconium.

These structures are represented by the illustrations given in Figs. 1.3–1.5, in which each sphere represents an atom. The distance between the atoms in these

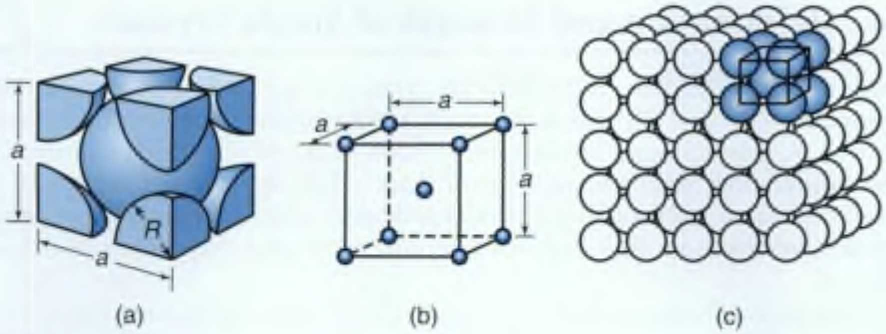


FIGURE 1.3 The body-centered cubic (bcc) crystal structure: (a) hard-ball model, (b) unit cell, and (c) single crystal with many unit cells.

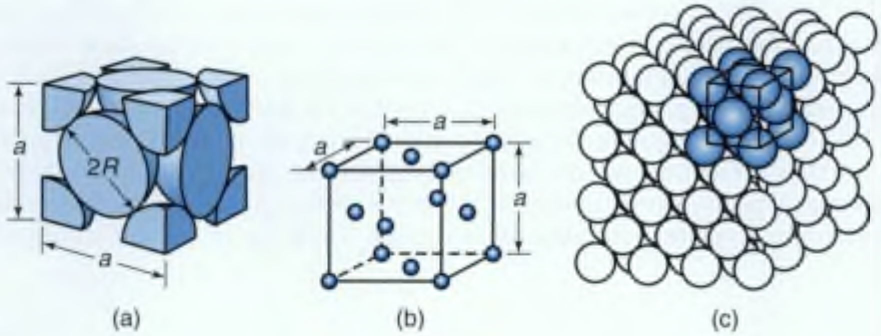


FIGURE 1.4 The face-centered cubic (fcc) crystal structure: (a) hard-ball model, (b) unit cell, and (c) single crystal with many unit cells.

crystal structures is on the order of 0.1 nm. The models shown are known as **hard-ball** or **hard-sphere** models, and can be likened to tennis balls arranged in various configurations in a box.

In the three structures illustrated, the hcp crystals have the most densely packed configurations, followed by fcc and then bcc. In the hcp structure, the top and bottom planes are called **basal planes**. All three arrangements can be modified by adding atoms of some other metal or metals, known as **alloying**, often to improve various properties of the metal.

The appearance of more than one type of crystal structure in metals is known as **allotropism** or **polymorphism** (meaning "many shapes"). Because the properties and behavior of a particular metal depend greatly on its crystal structure, allotropism is an important factor in the heat treatment of metals, as well as in metalworking and welding operations, described in Parts III and VI, respectively. Single crystals of metals are now produced as ingots in sizes on the order of 1 m long and up to 300 mm in diameter, with applications such as turbine blades and semiconductors (see Sections 11.5 and 28.3). Most metals used in manufacturing are, however, polycrystalline, as described in Section 1.5.

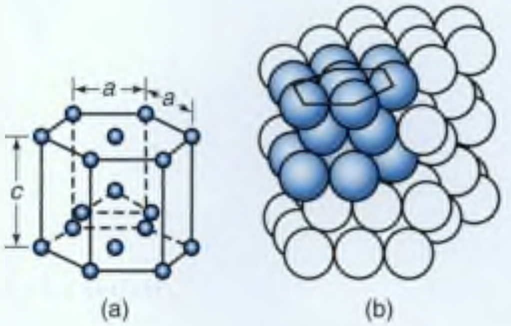


FIGURE 1.5 The hexagonal close-packed (hcp) crystal structure: (a) unit cell and (b) single crystal with many unit cells.

1.4 Deformation and Strength of Single Crystals

When a single crystal is subjected to an external force, it first undergoes **elastic deformation** (Chapter 2); that is, it returns to its original shape when the force is removed. A simple analogy to this type of behavior is a helical spring that stretches when loaded and returns to its original shape when the load is removed. If the force is increased sufficiently, the crystal undergoes **plastic deformation** or **permanent deformation**; that is, it does not return to its original shape when the force is removed.

There are two basic mechanisms by which plastic deformation takes place in crystal structures. One mechanism involves a plane of atoms slipping over an adjacent plane (called the **slip plane**) under a **shear stress** (Fig. 1.6a); note that this behavior is much like sliding of a set of playing cards against each other. *Shear stress* is defined as the ratio of the applied shearing force to the cross-sectional area being sheared.

Just as it takes a certain force to slide playing cards against each other, a single crystal requires a certain magnitude of shear stress (called **critical shear stress**) to undergo permanent deformation. Thus, there must be a shear stress of sufficient magnitude to cause plastic deformation; otherwise the deformation remains elastic.

The shear stress required to cause slip in single crystals is directly proportional to the ratio b/a in Fig. 1.6a, where a is the spacing of the atomic planes and b is inversely proportional to the atomic density in the atomic plane. As the ratio b/a decreases, the shear stress required to cause slip decreases. Thus, slip in a single crystal takes

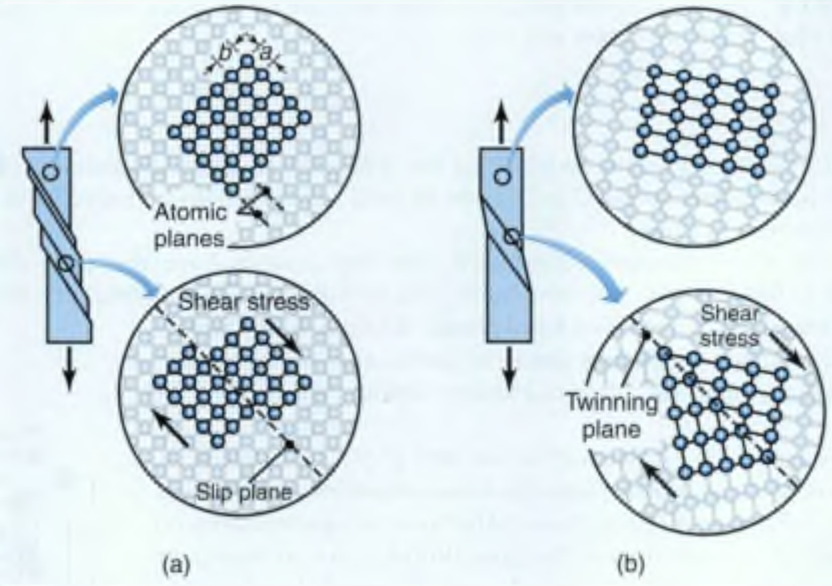


FIGURE 1.6 Permanent deformation of a single crystal under a tensile load; the highlighted grid of atoms emphasizes the movement that occurs within the lattice. (a) Deformation by slip. The b/a ratio influences the magnitude of the shear stress required to cause slip. (b) Deformation by twinning, involving the generation of a "twin" around a line of symmetry subjected to shear. Note that the tensile load results in a shear stress in the plane illustrated.

place along planes of *maximum atomic density*; in other words, slip takes place in closely packed planes and in closely packed directions.

Because the b/a ratio varies for different directions within the crystal, a single crystal exhibits different properties when tested in different directions, a property called **anisotropy**. An example is the behavior of plywood, which is much stronger in the planar direction than along its thickness direction.

The second, and less common, mechanism of plastic deformation in crystals is **twinning**, in which a portion of the crystal forms a mirror image of itself across the *plane of twinning* (Fig. 1.6b). Twins form abruptly and are the cause of the creaking sound (called "tin cry") that occurs when a rod of tin or zinc is bent at room temperature. Twinning usually occurs in hcp metals.

Slip Systems. The combination of a slip plane and slip direction is known as a *slip system*. In general, metals with five or more slip systems are ductile.

1. In **body-centered cubic** crystals, there are 48 possible slip systems; therefore, the probability is high that an externally applied shear stress will operate on one of these systems and cause slip. Because of the relatively high b/a ratio in this type of crystal, however, the required shear stress is high. Metals with bcc structures (such as titanium, molybdenum, and tungsten) generally have good strength and moderate ductility, but can have high ductility at elevated temperatures.
2. In **face-centered cubic** crystals, there are 12 slip systems. The probability of slip is moderate, and the shear stress required is low because of the relatively low b/a ratio. These metals (such as aluminum, gold, copper, and silver) generally have moderate strength and good ductility.
3. The **hexagonal close-packed** crystal has three slip systems, and therefore has a low probability of slip; however, more slip systems become active at elevated temperatures. Metals with hcp structures (such as beryllium, magnesium, and zinc) are generally brittle at room temperature.

Note in Fig. 1.6a that the portions of the single crystal that have slipped have rotated from their original angular position toward the direction of the tensile force; note also that slip has taken place only along certain planes. It can be observed using electron microscopy that what appears to be a single slip plane is actually a **slip band**, consisting of a number of slip planes (Fig. 1.7).

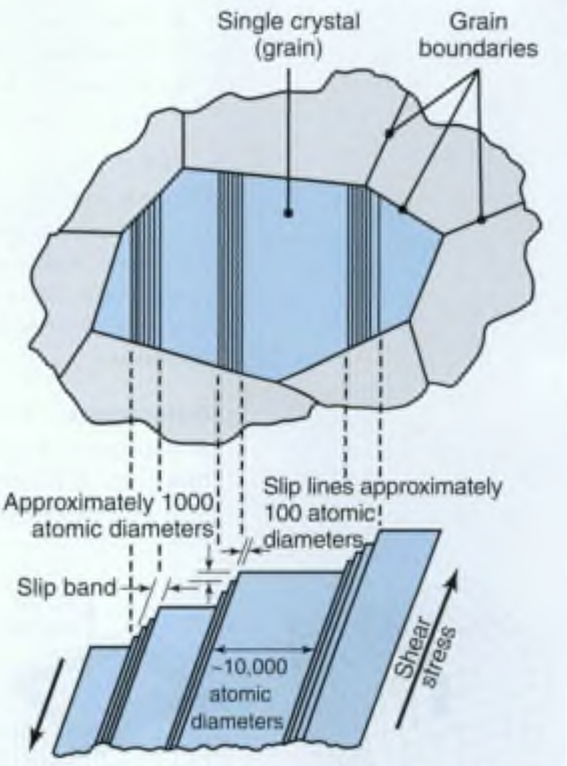


FIGURE 1.7 Schematic illustration of slip lines and slip bands in a single crystal (grain) subjected to a shear stress. A slip band consists of a number of slip planes. The crystal at the center of the upper illustration is an individual grain surrounded by several other grains.

1.4.1 Imperfections in the Crystal Structure of Metals

The actual strength of metals is approximately one to two orders of magnitude lower than the strength levels obtained from theoretical calculations. This discrepancy is explained in terms of **defects** and **imperfections** in the crystal structure. Unlike in idealized models described earlier, actual metal

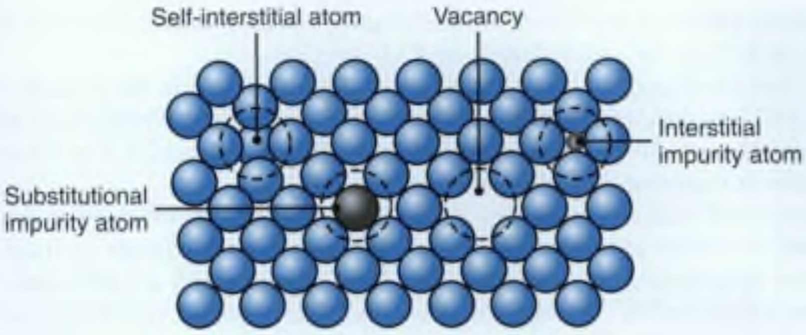


FIGURE 1.8 Schematic illustration of types of defects in a single-crystal lattice: self-interstitial, vacancy, interstitial, and substitutional.

crystals contain a large number of defects and imperfections, which generally are categorized as:

1. *Point defects*, such as a **vacancy** (missing atom), an **interstitial atom** (extra atom in the lattice), or an **impurity** (foreign atom that has replaced the atom of the pure metal) (Fig. 1.8).
2. *Linear,* or *one-dimensional, defects*, called **dislocations** (Fig. 1.9).
3. *Planar*, or *two-dimensional, imperfections*, such as **grain boundaries** and **phase boundaries** (Section 1.5).
4. *Volume*, or *bulk, imperfections*, such as **voids, inclusions** (nonmetallic elements such as oxides, sulfides, and silicates), other **phases**, or **cracks.**

Mechanical and electrical properties of metals, such as yield stress, fracture strength, and electrical conductivity, are adversely affected by the presence of defects; these properties are known as **structure sensitive.** By contrast, physical and chemical properties, such as melting point, specific heat, coefficient of thermal expansion, and elastic constants, such as modulus of elasticity and modulus of rigidity (Sections 2.2.1 and 2.4), are not sensitive to these defects; these properties are known as **structure insensitive.**

Dislocations. First observed in the 1930s, *dislocations* are defects in the orderly arrangement of a metal's atomic structure. Because a slip plane containing a dislocation (Fig. 1.10) requires much lower shear stress to allow slip than does a plane in a perfect lattice, dislocations are the most significant defects that explain the discrepancy between the actual and theoretical strengths of metals.

There are two types of dislocations: **edge** and **screw** (Fig. 1.9). An analogy to the movement of an edge dislocation is the progress of an earthworm, which moves forward by means of a hump that starts at the tail and moves toward the head. Another analogy is moving a large carpet on a floor by first forming a hump at one end and moving the hump gradually to the other end. (Recall that the force required to move a carpet in this way is much lower than that required to slide the whole carpet along the floor.) Screw dislocations are so named because the atomic planes form a spiral ramp, like the threads on a screw or bolt.

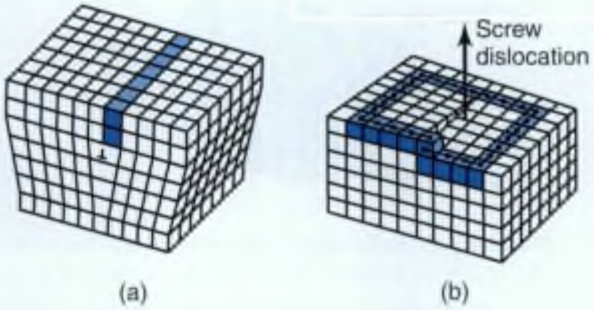


FIGURE 1.9 Types of dislocations in a single crystal: (a) edge dislocation and (b) screw dislocation.

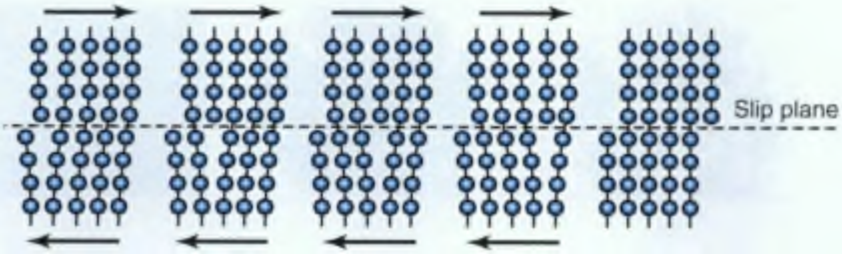


FIGURE 1.10 Movement of an edge dislocation across the crystal lattice under a shear stress. Dislocations help explain why the actual strength of metals is much lower than that predicted by theory.

1.4.2 Work Hardening (Strain Hardening)

Although the presence of a dislocation lowers the shear stress required to cause slip, dislocations can be

1. Entangled and interfere with each other
2. Impeded by barriers, such as grain boundaries, impurities, and inclusions in the material

The higher shear stress required to overcome entanglements and impediments results in an increase in the overall strength and hardness of the metal, and is known as **work hardening** or **strain hardening**. The greater the deformation, the greater is the number of entanglements and hence the higher the increase in the metal's strength. Work hardening is a mechanism used extensively for strengthening of metals in metalworking processes at low to moderate temperatures. Typical examples are producing sheet metal for automobile bodies and aircraft fuselages by cold rolling (Chapter 13), producing the head of a bolt by forging (Chapter 14), and strengthening wire by reducing its cross-section by drawing it through a die (Chapter 15).

1.5 Grains and Grain Boundaries

When a mass of molten metal begins to solidify, crystals form independently of each other at various locations within the liquid mass, and thus have random and unrelated orientations (Fig. 1.11). Each of these crystals eventually grows into a crystalline structure, or *grain*; each grain consists of either a single crystal (for pure metals) or a polycrystalline aggregate (for alloys).

The number and size of the grains developed in a unit volume of the metal depends on the *rate* at which **nucleation** (the initial stage of crystal formation) takes place. The *median size* of the grains developed depends on (a) the number of different sites at which individual crystals begin to form (note that there are seven in Fig. 1.11a) and (b) the rate at which these crystals grow. If the nucleation rate is high, the number of grains in a unit volume of metal will be large, and thus grain size will be small. Conversely, if the crystal growth rate is high (as compared with their nucleation rate), there will be fewer grains per unit volume, and thus grain size will be larger. Generally, rapid cooling produces smaller grains, whereas slow cooling produces larger grains.

Note in Fig. 1.11d that the growing grains eventually interfere with and impinge upon one another; the interfaces that separate the individual grains are called **grain boundaries**. Note also that the crystallographic orientation changes abruptly from one grain to the next across the grain boundaries. Recall, from Section 1.4, that the

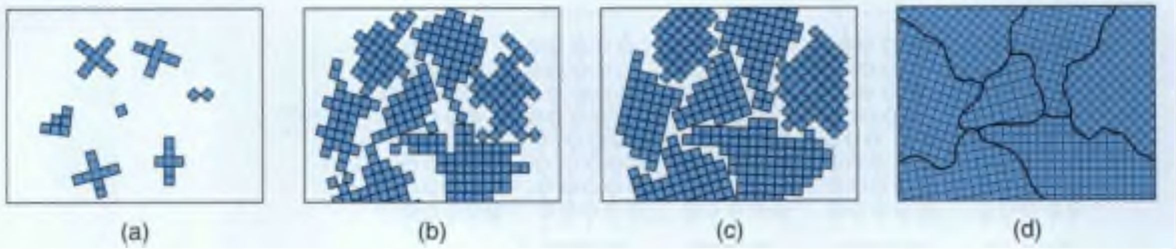


FIGURE 1.11 Schematic illustration of the stages during the solidification of molten metal; each small square represents a unit cell. (a) Nucleation of crystals at random sites in the molten metal; note that the crystallographic orientation of each site is different. (b) and (c) Growth of crystals as solidification continues. (d) Solidified metal, showing individual grains and grain boundaries; note the different angles at which neighboring grains meet each other.

behavior of a single crystal or a single grain is anisotropic. Thus, because its many grains have random crystallographic orientations, the behavior of a polycrystalline metal is essentially **isotropic**; that is, its properties do not vary with direction.

1.5.1 Grain Size

Grain size has a major influence on the mechanical properties of metals. At room temperature, for example, a large grain size is generally associated with low strength, low hardness, and low ductility. Grains can be so large as to be visible with the naked eye; zinc grains on the surface of galvanized sheet steels are an example. Large grains also cause a rough surface appearance after the material has been plastically deformed, particularly in the stretching of sheet metals (see **orange peel**, Section 1.7).

The yield strength, Y, of the metal is the most sensitive property and is related to grain size by the empirical formula (known as the *Hall–Petch equation*)

$$Y = Y_i + kd^{-1/2}, \tag{1.1}$$

where Y_i is the yield stress for a large grained material, k is a constant, and d is the mean grain diameter. Equation (1.1) is valid below the recrystallization temperature of the material.

Grain size is usually measured by counting the number of grains in a given area, or by counting the number of grains that intersect a prescribed length of a line randomly drawn on an enlarged photograph of the grains (taken under a microscope on a polished and etched specimen). Grain size may also be determined by comparing such a photograph against a standard chart.

The ASTM (American Society for Testing and Materials) grain size number, n, is related to the number of grains, N, per square inch at a magnification of 100 × (equal to 0.0645 mm^2 of actual area) by the formula

$$N = 2^{n-1}. \tag{1.2}$$

Because grains are typically extremely small, many grains can occupy a very small volume of metal (Table 1.1). Grain sizes between 5 and 8 are generally considered fine grained. A grain size of 7 is typically acceptable for sheet metals for making car bodies, appliances, and kitchen utensils (Chapter 16).

TABLE 1.1

Grain sizes

ASTM No.	Grains/mm^2	Grains/mm^3
−3	1	0.7
−2	2	2
−1	4	5.6
0	8	16
1	16	45
2	32	128
3	64	360
4	128	1020
5	256	2900
6	512	8200
7	1024	23,000
8	2048	65,000
9	4096	185,000
10	8200	520,000
11	16,400	1,500,000

EXAMPLE 1.1 Number of Grains in a Paper Clip

Given: A paper clip is made of wire that is 120 mm long and 0.75 mm in diameter, with an ASTM grain size of 9.

Find: Calculate the number of grains in the paper clip.

Solution: A metal with an ASTM grain size of 9 has 185,000 grains per mm^3 (see Table 1.1). The volume of the paper clip is

$$V = \frac{\pi}{4}d^2l = \frac{\pi}{4}(0.75)^2(120) = 53.0\ \text{mm}^3.$$

The total number of grains is calculated by multiplying the volume by the grains per mm^3, or

$$\begin{aligned}\text{No. grains} &= (53.0\ \text{mm}^3)(185{,}000\ \text{grains/mm}^3)\\ &= 9.81\ \text{million}.\end{aligned}$$

1.5.2 Influence of Grain Boundaries

Grain boundaries have an important influence on the strength and ductility of metals; they interfere with dislocation movement and thus also influence strain hardening. The magnitude of these effects depends on temperature, deformation rate, and the type and amount of impurities present along grain boundaries.

Because the atoms along the grain boundaries are more disordered and hence packed less efficiently, grain boundaries are more reactive than the grains themselves. As a result, the boundaries have lower energy than the atoms in the orderly lattice within the grains; thus, they can be more easily removed or chemically bonded to another atom. As a result, for example, the surface of a metal piece becomes rougher when etched or is subjected to corrosive environments (see also *end grains in forging*, in Section 4.11).

At elevated temperatures, and in metals whose properties depend on the rate at which they are deformed, plastic deformation also takes place by means of grain-boundary sliding. The **creep** mechanism (deformation under stress over time, usually at elevated temperatures) involves *grain-boundary sliding* (Section 2.8).

Grain-boundary embrittlement. When exposed to certain low-melting-point metals, a normally ductile and strong metal can crack when subjected to very low external stresses. Examples of such behavior are (a) aluminum wetted with a mercury–zinc amalgam or with liquid gallium and (b) copper at elevated temperature wetted with lead or bismuth; these elements weaken the grain boundaries of the metal by **embrittlement**. The term **liquid-metal embrittlement** is used to describe such phenomena, because the embrittling element is in a liquid state. However, embrittlement can also occur at temperatures well below the melting point of the embrittling element, a phenomenon known as **solid-metal embrittlement**.

Another embrittlement phenomenon, called **hot shortness,** is caused by local melting of a constituent or of an impurity along the grain boundary at a temperature below the melting point of the metal itself. When subjected to plastic deformation at elevated temperatures (*hot working*), a piece of metal crumbles along its grain boundaries; examples are (a) antimony in copper, (b) leaded steels (Section 21.7.1), and (c) leaded brass. To avoid hot shortness, the metal is usually worked at a lower temperature to prevent softening and melting along the grain boundaries. **Temper embrittlement** in alloy steels is another form of embrittlement, caused by segregation (movement) of impurities to the grain boundaries (Section 4.11).

1.6 Plastic Deformation of Polycrystalline Metals

When a polycrystalline metal with uniform *equiaxed grains* (grains having equal dimensions in all directions) is subjected to plastic deformation at room temperature (called *cold working*), the grains become deformed and elongated, as shown schematically in Fig. 1.12. Deformation may be carried out by, for example, compressing the metal piece, as is done in a forging operation to make a turbine disk (Chapter 14) or by subjecting it to tension, as is done in stretch forming of sheet metal (Section 16.6). The deformation within each grain takes place by the mechanisms described in Section 1.4 for a single crystal.

During plastic deformation, the grain boundaries remain intact and mass continuity is maintained. The deformed metal exhibits higher strength, because of the entanglement of dislocations with grain boundaries and with each other. The increase in strength depends on the degree of deformation (*strain*) to which the metal is subjected; the higher the deformation, the stronger the metal becomes. The strength is higher for metals with smaller grains, because they have a larger grain-boundary surface area per unit volume of metal and hence more entanglement of dislocations.

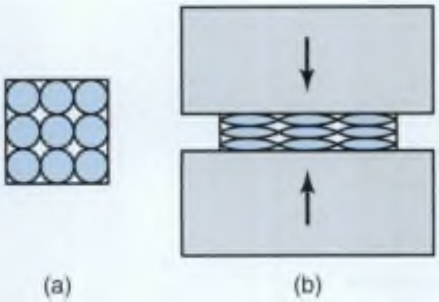


FIGURE 1.12 Plastic deformation of idealized (equiaxed) grains in a specimen subjected to compression (such as occurs in the forging or rolling of metals): (a) before deformation and (b) after deformation. Note the alignment of grain boundaries along a horizontal direction, an effect known as *preferred orientation*.

Anisotropy (Texture). Note in Fig. 1.12b that, as a result of plastic deformation, the grains have elongated in one direction and contracted in the other. Consequently, this piece of metal has become *anisotropic*, and thus its properties in the vertical direction are different from those in the horizontal direction. The degree of anisotropy depends on the temperature at which deformation takes place and on how uniformly the metal is deformed. Note from the crack direction in Fig. 1.13, for example, that the ductility of the cold-rolled sheet in the transverse direction is lower than in its rolling direction (see also Section 16.5).

Anisotropy influences both mechanical and physical properties of metals, described in Chapter 3. For example, sheet steel for electrical transformers is rolled in such a manner that the resulting deformation imparts anisotropic magnetic properties to the sheet. This operation

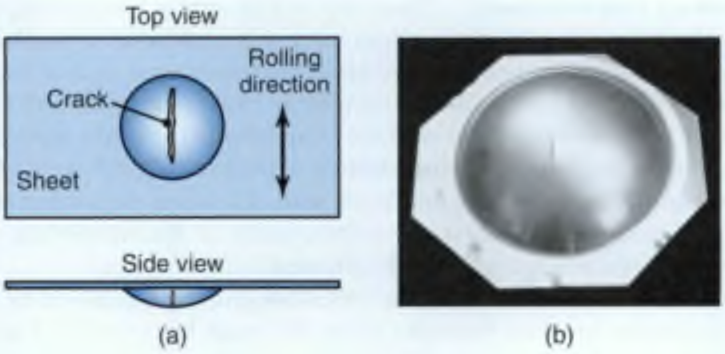


FIGURE 1.13 (a) Schematic illustration of a crack in sheet metal that has been subjected to bulging (caused, for example, by pushing a steel ball against the sheet). Note the orientation of the crack with respect to the rolling direction of the sheet; this sheet is anisotropic. (b) Aluminum sheet with a crack (vertical dark line at the center) developed in a bulge test; the rolling direction of the sheet was vertical. *Source:* Courtesy of J.S. Kallend, Illinois Institute of Technology.

reduces magnetic-hysteresis losses and thus improves the efficiency of transformers. (See also *amorphous alloys*, Section 6.14.) There are two general types of anisotropy in metals: preferred orientation and mechanical fibering.

Preferred Orientation. Also called **crystallographic anisotropy**, *preferred orientation* can be best described by referring to Fig. 1.6a. When a single-crystal metal piece is subjected to tension, the sliding blocks rotate toward the direction of the tensile force; as a result, slip planes and slip bands tend to align themselves with the general direction of deformation. Similarly, for a polycrystalline metal, with grains in random orientations, all slip directions tend to align themselves with the direction of the tensile force. By contrast, slip planes under compression tend to align themselves in a direction perpendicular to the direction of the compressive force.

Mechanical Fibering. This is a type of anisotropy that results from the alignment of inclusions (*stringers*), impurities, and voids in the metal during deformation. Note that if the spherical grains in Fig. 1.12a were coated with impurities, these impurities would align themselves in a generally horizontal direction after deformation. Because impurities weaken the grain boundaries, this piece of metal will now be weaker and less ductile when tested in the vertical direction. As an analogy, consider plywood, which is strong in tension along its planar direction, but splits easily when pulled in tension in its thickness direction.

1.7 Recovery, Recrystallization, and Grain Growth

Recall that plastic deformation at room temperature causes (a) distortion of the grains and grain boundaries, leading to anisotropic behavior; (b) a general increase in strength; and (c) a decrease in ductility. These effects can be reversed, and the properties of the metal can be brought back to their original levels, by heating the metal to a specific temperature range for a given period of time—a process called **annealing** (described in detail in Section 4.11). Three events take place consecutively during the annealing process:

1. **Recovery.** During *recovery*, which occurs at a certain temperature range below the **recrystallization temperature** of the metal (described next), the stresses in the highly deformed regions of the metal are relieved. Subgrain boundaries begin to form (called **polygonization**), with no significant change in mechanical properties such as hardness and strength (Fig. 1.14).
2. **Recrystallization.** This is the process in which, within a certain temperature range, new equiaxed and strain-free grains are formed, replacing the older grains. The temperature required for recrystallization ranges approximately between 0.3 and $0.5T_m$, where T_m is the melting point of the metal on the absolute scale.

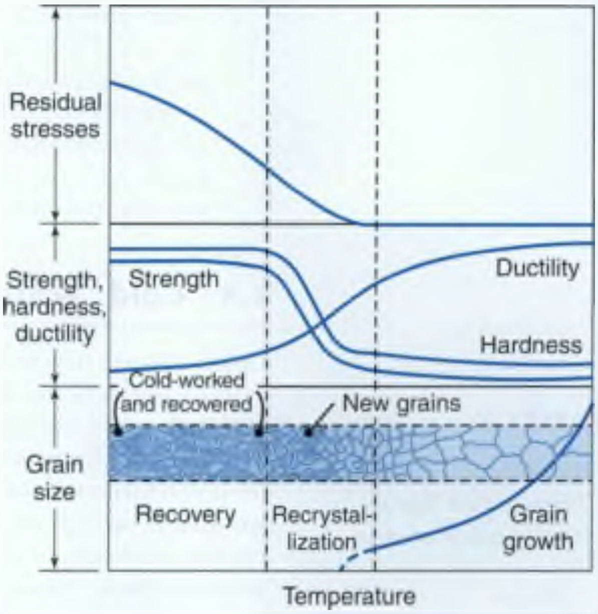


FIGURE 1.14 Schematic illustration of the effects of recovery, recrystallization, and grain growth on mechanical properties and on the shape and size of grains; note the formation of small new grains during recrystallization. *Source:* After G. Sachs.

Generally, the recrystallization temperature is defined as the temperature at which complete recrystallization occurs within approximately one hour. Recrystallization decreases the density of dislocations, lowers the strength, and raises the ductility of the metal (Fig. 1.14). Lead, tin, cadmium, and zinc recrystallize at about room temperature; consequently, they do not normally work harden.

The recrystallization temperature depends on the degree of prior cold work (work hardening): the more the cold work, the lower the temperature required for recrystallization. The reason is that, as the amount of cold work increases, the number of dislocations and hence the amount of energy stored in dislocations (**stored energy**) also increase. This energy supplies some of the work required for recrystallization. Recrystallization is also a function of time, because it involves **diffusion**—the movement and exchange of atoms across grain boundaries.

The effects of temperature, time, and plastic deformation by cold working on recrystallization are:

a. For a constant amount of deformation by cold working, the time required for recrystallization decreases with increasing temperature.
b. The more the prior cold work, the lower the temperature required for recrystallization.
c. The higher the amount of deformation, the smaller the grain size becomes during recrystallization; this effect is a commonly used method of converting a coarse-grained structure to one having a finer grain, and thus one with improved properties.
d. Some anisotropy due to preferred orientation usually persists after recrystallization; to restore isotropy, a temperature higher than that required for recrystallization may be necessary.

3. **Grain growth.** If the temperature is raised further, the grains begin to grow (see lower part of Fig. 1.14) and their size may eventually exceed the original grain size; called *grain growth*, this phenomenon adversely affects mechanical properties (Fig. 1.14). Large grains also produce a rough surface appearance on sheet metals, called **orange peel**, when they are stretched to form a part, or on the surfaces of a piece of metal when subjected to bulk deformation, such as compression in forging.

1.8 Cold, Warm, and Hot Working

Cold working refers to plastic deformation that is usually carried out at room temperature; when deformation occurs above the recrystallization temperature, it is called **hot working**. "Cold" and "hot" are relative terms, as can be seen from the fact that deforming lead at room temperature is a hot-working process, because the recrystallization temperature of lead is about room temperature. As the name implies, **warm working** is carried out at intermediate temperatures; thus, warm working is a compromise between cold and hot working. The important technological differences in products that are processed by cold, warm, and hot working are described in Part III.

The temperature ranges for these three categories of plastic deformation are given in Table 1.2 in terms of a ratio, T/T_m, where T is the working temperature and T_m is the melting point of the metal, both on the absolute scale. Although it is a dimensionless quantity, this ratio is known as the **homologous temperature**.

TABLE 1.2

Homologous Temperature Ranges for Various Processes

Process	T/T_m
Cold working	<0.3
Warm working	0.3–0.5
Hot working	>0.6

SUMMARY

- There are three basic crystal structures in metals: body-centered cubic (bcc), face-centered cubic (fcc), and hexagonal close-packed (hcp). Grains made of these crystals typically contain various defects and imperfections, such as dislocations, vacancies, impurities, inclusions, and grain boundaries. Polycrystalline metals consist of many crystals, or grains, in random orientations.
- Plastic deformation in metals takes place by a slip mechanism. Although the theoretical shear stress required to cause slip is very high, actual stresses are much lower because of the presence of dislocations (edge or screw type). Dislocations become entangled with one another or are impeded by barriers such as grain boundaries, impurities, and inclusions. As a result, the shear stress required to cause further slip is increased; consequently, the overall strength and hardness of the metal is also increased (through work hardening or strain hardening).
- Grain size has a significant effect on the strength of metals: the smaller the size, the stronger is the metal, and the larger the size, the more ductile is the metal; however, excessively large grains are generally associated with brittle behavior.
- Grain boundaries have a major influence on the behavior of metals. Boundaries can undergo embrittlement, severely reducing ductility at elevated temperatures (hot shortness); they are also responsible for the creep phenomenon, which is due to grain boundary sliding.
- Metals may be plastically deformed at room, warm, or high temperatures; their behavior and workability depend largely on whether deformation takes place below or above the recrystallization temperature of the metal. Deformation at room temperature (cold working) results in higher strength, but reduced ductility; generally, it also causes anisotropy (preferred orientation or mechanical fibering), whereby the properties are different in different directions.
- The effects of cold working can be reversed by annealing the metal; that is, heating it within a certain temperature range for a given period of time, thereby allowing the successive processes of recovery, recrystallization, and grain growth to take place.

KEY TERMS

Allotropism
Anisotropy
Basal plane
Body-centered cubic
Cold working
Covalent bond
Creep
Crystals
Dislocations
Elastic deformation
Embrittlement
Face-centered cubic
Grains
Grain boundaries
Grain growth
Grain size
Hall–Petch equation
Hexagonal close-packed
Homologous temperature
Hot shortness
Hot working
Imperfections
Ionic bond
Lattice structure
Mechanical fibering
Metallic bond
Nucleation
Orange peel
Plastic deformation
Polycrystalline
Polygonization
Polymorphism
Preferred orientation
Primary bond
Recovery
Recrystallization
Secondary bond
Shear stress
Slip band
Slip plane
Slip system
Strain hardening
Structure insensitive
Structure sensitive
Texture
Twinning
Unit cell
Vacancy
van der Waals force
Warm working
Work hardening

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REVIEW QUESTIONS

1.1 What is the difference between an atom and a molecule? A molecule and a crystal?

1.2 Describe ionic, covalent, and metallic bonds.

1.3 Explain the difference between a unit cell and a single crystal.

1.4 In tables on crystal structures, iron is listed as having both a bcc and an fcc structure. Why?

1.5 Define anisotropy. What is its significance?

1.6 What effects does recrystallization have on the properties of metals?

1.7 What is strain hardening, and what effects does it have on the properties of metals?

1.8 Explain what is meant by structure-sensitive and structure-insensitive properties of metals.

1.9 Make a list of each of the major types of imperfection in the crystal structure of metals, and describe them.

1.10 What influence does grain size have on the mechanical properties of metals?

1.11 What is the relationship between the nucleation rate and the number of grains per unit volume of a metal?

1.12 What is a slip system, and what is its significance?

1.13 Explain the difference between recovery and recrystallization.

1.14 What is hot shortness, and what is its significance?

1.15 Explain the advantages and limitations of cold, warm, and hot working, respectively.

1.16 Describe what the orange peel effect is. Explain why we may have to be concerned with the orange-peel effect on metal surfaces.

1.17 Some metals, such as lead, do not become stronger when worked at room temperature. Explain the reason.

1.18 Describe the difference between preferred orientation and mechanical fibering.

1.19 Differentiate between stress relaxation and stress relieving.

1.20 What is twinning? How does it differ from slip?

QUALITATIVE PROBLEMS

1.21 Explain your understanding of why the study of the crystal structure of metals is important.

1.22 What is the significance of the fact that some metals undergo allotropism?

1.23 Is it possible for two pieces of the same metal to have different recrystallization temperatures? Is it possible for recrystallization to take place in some regions of a part before it does in other regions of the same part? Explain.

1.24 Describe your understanding of why different crystal structures exhibit different strengths and ductilities.

1.25 A cold-worked piece of metal has been recrystallized. When tested, it is found to be anisotropic. Explain the probable reason.

1.26 What materials and structures can you think of (other than metals) that exhibit anisotropic behavior?

1.27 Two parts have been made of the same material, but one was formed by cold working and the other by hot working. Explain the differences you might observe between the two.

1.28 Do you think it might be important to know whether a raw material to be used in a manufacturing process has anisotropic properties? What about anisotropy in the finished product? Explain.

1.29 Explain why the strength of a polycrystalline metal at room temperature decreases as its grain size increases.

1.30 Describe the technique you would use to reduce the orange-peel effect on the surface of workpieces.

1.31 What is the significance of the fact that such metals as lead and tin have a recrystallization temperature that is about room temperature?

1.32 It was stated in this chapter that twinning usually occurs in hcp materials, but Fig. 1.6b shows twinning in a rectangular array of atoms. Can you explain the discrepancy?

1.33 It has been noted that the more a metal has been cold worked, the less it strain hardens. Explain why.

1.34 Is it possible to cold work a metal at temperatures above the boiling point of water? Explain.

1.35 Comment on your observations regarding Fig. 1.14.

1.36 Is it possible for a metal to be completely isotropic? Explain.

QUANTITATIVE PROBLEMS

1.37 How many atoms are there in a single repeating cell of an fcc crystal structure? How many in a repeating cell of an hcp structure?

1.38 The atomic weight of copper is 63.55, meaning that 6.023×10^{23} atoms weigh 63.55 g. The density of copper is 8970 kg/m^3, and pure copper forms fcc crystals. Estimate the diameter of a copper atom.

1.39 Plot the data given in Table 1.1 in terms of grains/mm^2 versus grains/mm^3, and discuss your observations.

1.40 A strip of metal is reduced from 30 mm in thickness to 20 mm by cold working; a similar strip is reduced from 40 to 30 mm. Which of these cold-worked strips will recrystallize at a lower temperature? Why?

1.41 The ball of a ballpoint pen is 1 mm in diameter and has an ASTM grain size of 10. How many grains are there in the ball?

Video Solution 1.1 Calculating the Number of Grains in a Ball Bearing

1.42 How many grains are there on the surface of the head of a pin? Assume that the head of a pin is spherical with a 1-mm diameter and has an ASTM grain size of 12.

1.43 The unit cells shown in Figs. 1.3–1.5 can be represented by tennis balls arranged in various configurations in a box. In such an arrangement, the *atomic packing factor* (APF) is defined as the ratio of the sum of the volumes of the atoms to the volume of the unit cell. Show that the APF is 0.68 for the bcc structure and 0.74 for the fcc structure.

Video Solution 1.2 Atomic Packing Factor for Hexagonal Close-packed Materials

1.44 Show that the lattice constant a in Fig. 1.4a is related to the atomic radius by the formula $a = 2\sqrt{2}R$, where R is the radius of the atom as depicted by the tennis-ball model.

1.45 Show that, for the fcc unit cell, the radius r of the largest hole is given by $r = 0.414R$. Determine the size of the largest hole for the iron atoms in the fcc structure.

1.46 A technician determines that the grain size of a certain etched specimen is 8. Upon further checking, it is found that the magnification used was 125×, instead of the 100× that is required by the ASTM standards. Determine the correct grain size.

1.47 If the diameter of the aluminum atom is 0.28 nm, how many atoms are there in a grain of ASTM grain size 8?

1.48 The following data are obtained in tension tests of brass:

Grain size (μm)	Yield stress (MPa)
15	150
20	140
50	105
75	90
100	75

Does the material follow the Hall–Petch equation? If so, what is the value of k?

1.49 Assume that you are asked to submit a quantitative problem for a quiz. Prepare such a question, supplying the answer.

1.50 The atomic radius of iron is 0.125 nm, while that of a carbon atom is 0.070 nm. Can a carbon atom fit inside a steel bcc structure without distorting the neighboring atoms?

1.51 Estimate the atomic radius for the following materials and data: (a) Aluminum (atomic weight = 26.98 g/mol, density = 2700 kg/m^3); (b) tungsten (atomic weight = 183.85 g/mol, density = 19,300 kg/m^3); and (c) magnesium (atomic weight = 24.31 g/mol, density = 1740 kg/m^3).

1.52 A simple cubic structure consists of atoms located at the cube corners that are in contact with each other along the cube edges. Make a sketch of a simple cubic structure, and calculate its atomic packing factor.

1.53 Same as Prob. 1.39, but ASTM no. versus grains/mm^3.

SYNTHESIS, DESIGN, AND PROJECTS

1.54 By stretching a thin strip of polished metal, as in a tension-testing machine, demonstrate and comment on what happens to its reflectivity as the strip is being stretched.

1.55 Draw some analogies to mechanical fibering—for example, layers of thin dough sprinkled with flour or melted butter between each layer.

1.56 Draw some analogies to the phenomenon of hot shortness.

1.57 Obtain a number of small balls made of plastic, wood, marble, or metal, and arrange them with your hands or glue them together to represent the crystal structures shown in Figs. 1.3–1.5. Comment on your observations.

1.58 Take a deck of playing cards, place a rubber band around it, and then slip the cards against each other to represent Figs. 1.6a and 1.7. If you repeat the same experiment with more and more rubber bands around the same deck, what are you accomplishing as far as the behavior of the deck is concerned?

1.59 Give examples in which anisotropy is scale dependent. For example, a wire rope can contain annealed wires that are isotropic on a microscopic scale, but the rope as a whole is anisotropic.

1.60 The movement of an edge dislocation was described in Section 1.4.1, by means of an analogy involving a hump in a carpet on the floor and how the whole carpet can eventually be moved by moving the hump forward. Recall that the entanglement of dislocations was described in terms of two humps at different angles. Use a piece of cloth placed on a flat table to demonstrate these phenomena.

Mechanical Behavior, Testing, and Manufacturing Properties of Materials

CHAPTER 2

- This chapter examines the effects of external forces on the behavior of materials, and the test methods employed in determining their mechanical properties.
- The tension test, described first, is commonly used for quantifying several material parameters, including elastic modulus, yield stress, ultimate strength, ductility, and toughness.
- Compression tests, described next, are useful because they more closely simulate some metalworking processes; nonetheless, they have the unavoidable drawback of contributing friction to the test results.
- Bending tests are particularly useful for brittle materials; three- and four-point tests are in common use.
- Hardness and the variety of hardness tests and their range of applicability are then described.
- Fatigue involves the failure of material due to cyclic or repeating loads, whereas creep is deformation due to the application of a constant load over an extended period; these concepts are also discussed.
- The chapter ends with descriptions of the types of and factors involved in failure and fracture of materials.

2.1 Introduction

In manufacturing operations, parts and components of products are formed into a wide variety of shapes by applying external forces to the workpiece, typically by means of various tools and dies. Common examples of such operations are forging of turbine disks, extruding various components for aluminum ladders, drawing wire for making nails, and rolling metal to make sheets for car bodies, appliances, and office equipment. Forming operations may be carried out at room temperature or elevated temperatures and at a low or a high rate of deformation. Many of these operations are also used in forming and shaping nonmetallic materials such as plastics, ceramics, and composite materials, as described throughout this text.

As indicated in Table 1.2, a wide variety of metallic and nonmetallic materials is now available, with an equally wide range of properties and characteristics, as shown qualitatively in Table 2.1. This chapter covers those aspects of mechanical properties and behavior of metals that are relevant to the design and manufacturing of products, and includes commonly used test methods employed in assessing various properties.

TABLE 2.1

Relative Mechanical Properties of Various Materials at Room Temperature (in Decreasing Order). Metals Are in Their Alloy Form

Strength	Hardness	Toughness	Stiffness	Strength/Density
Glass fibers	Diamond	Ductile metals	Diamond	Reinforced plastics
Carbon fibers	Cubic boron nitride	Reinforced plastics	Carbides	Titanium
Kevlar fibers	Carbides	Thermoplastics	Tungsten	Steel
Carbides	Hardened steels	Wood	Steel	Aluminum
Molybdenum	Titanium	Thermosets	Copper	Magnesium
Steels	Cast irons	Ceramics	Titanium	Beryllium
Tantalum	Copper	Glass	Aluminum	Copper
Titanium	Thermosets		Ceramics	Tantalum
Copper	Magnesium		Reinforced plastics	
Reinforced thermosets	Thermoplastics		Wood	
Reinforced thermoplastics	Tin		Thermosets	
Thermoplastics	Lead		Thermoplastics	
Lead			Rubbers	

2.2 Tension

The **tension test** is the most commonly used method for determining the *mechanical properties* of materials, such as strength, ductility, toughness, elastic modulus, and strain-hardening capability. The test first requires the preparation of a **test specimen,** as shown in Fig. 2.1a; although most tension-test specimens are solid and round, they can also be flat or tubular. The specimen is prepared generally according to

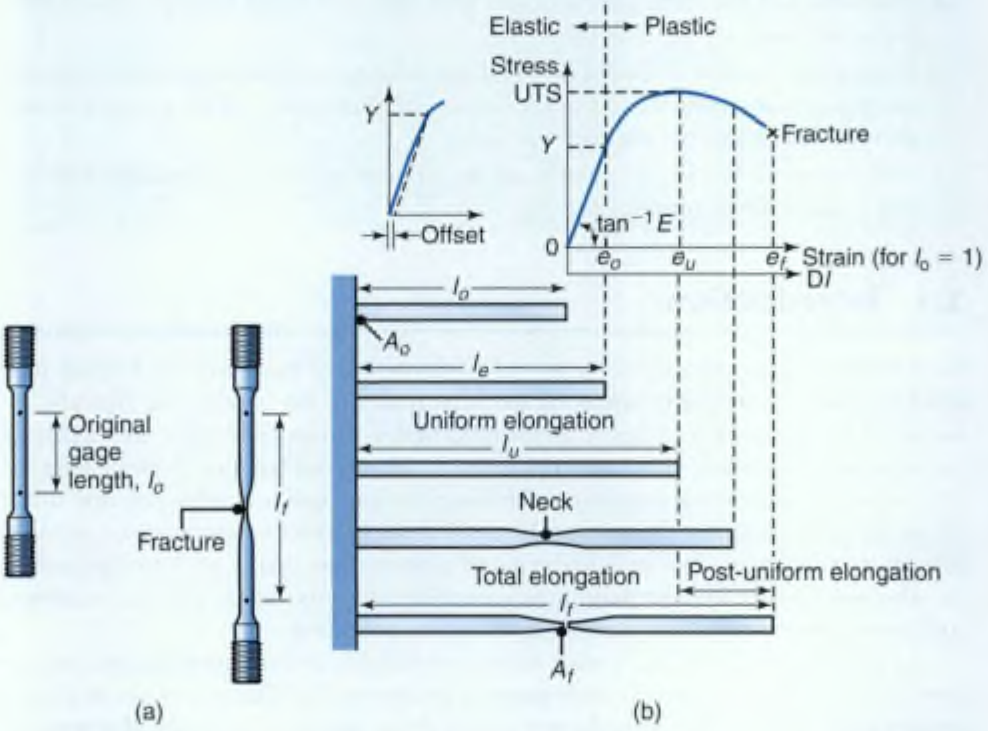


FIGURE 2.1 (a) A standard tensile-test specimen before and after pulling, showing original and final gage lengths. (b) Stages in specimen behavior in a tension test.

ASTM specifications, although various other specifications also are available from corresponding organizations around the world.

The specimen has an **original gage length,** l_o, generally 50 mm, and a crosssectional area, A_o, usually with a diameter of 12.5 mm. It is mounted in the jaws of a tensiontesting machine, equipped with various accessories and controls so that the specimen can be tested at different temperatures and rates of deformation.

2.2.1 Stress–strain Curves

A typical sequence in a tension test is shown in Fig. 2.1b. When the load is first applied, the specimen elongates in proportion to the load, called **linear elastic behavior** (Fig. 2.2). If the load is removed, the specimen returns to its original length and shape, in a manner similar to stretching a rubber band and releasing it.

The **engineering stress,** also called **nominal stress,** is defined as the ratio of the applied load, P, to the original cross-sectional area, A_o, of the specimen:

$$\sigma = \frac{P}{A_o}. \tag{2.1}$$

The **engineering strain** is defined as

$$e = \frac{l - l_o}{l_o}, \tag{2.2}$$

where l is the instantaneous length of the specimen.

As the load is increased, the specimen begins to undergo *nonlinear* elastic deformation, at a stress called the *proportional limit*. At that point, the stress and strain are no longer proportional, as they were in the linear elastic region; but when unloaded, the specimen still returns to its original shape. **Permanent (plastic) deformation** occurs when the **yield stress,** Y, of the material is reached. The yield stress and other properties of various metallic and nonmetallic materials are given in Table 2.2.

For soft and ductile materials, it may not be easy to determine the exact location on the stress–strain curve at which yielding occurs, because the slope of the curve

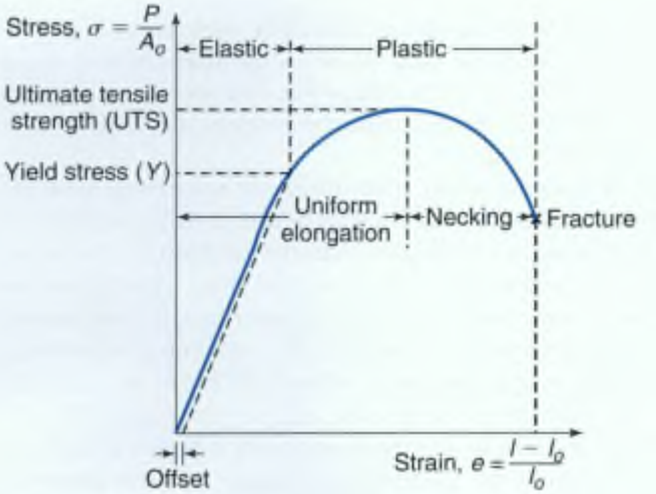


FIGURE 2.2 A typical stress–strain curve obtained from a tension test, showing various features.

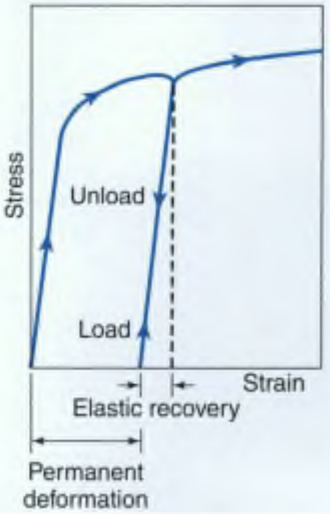


FIGURE 2.3 Schematic illustration of the loading and the unloading of a tensile-test specimen. Note that, during unloading, the curve follows a path parallel to the original elastic slope.

TABLE 2.2

Mechanical Properties of Various Materials at Room Temperature

Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50 mm (%)	Poisson's ratio, ν
Metals (wrought)					
Aluminum and its alloys	69–79	35–550	90–600	45–4	0.31–0.34
Copper and its alloys	105–150	76–110	140–1310	65–3	0.33–0.35
Lead and its alloys	14	14	20–55	50–9	0.43
Magnesium and its alloys	41–45	130–305	240–380	21–5	0.29–0.35
Molybdenum and its alloys	330–360	80–2070	90–2340	40–30	0.32
Nickel and its alloys	180–214	105–1200	345–1450	60–5	0.31
Steels	190–210	205–1725	415–1750	65–2	0.28–0.33
Titanium and its alloys	80–130	344–1380	415–1450	25–7	0.31–0.34
Tungsten and its alloys	350–400	550–690	620–760	0	0.27
Zinc and its alloys	50	25–180	240–550	65–5	0.27
Nonmetallic materials					
Ceramics	70–1000	—	140–2600	0	0.2
Diamond	820–1050	—	60,000	—	0.2
Glass and porcelain	70–80	—	140	0	0.24
Silicon carbide (SiC)	200–500	—	310–400	—	0.19
Silicon nitride (Si_2N_4)	280–310	—	160–580	—	0.26
Rubbers	0.01–0.1	—	—	—	0.5
Thermoplastics	1.4–3.4	—	7–80	1000–5	0.32–0.40
Thermoplastics, reinforced	2–50	—	20–120	10–1	0–0.5
Thermosets	3.5–17	—	35–170	0	0.34–0.5
Boron fibers	380	—	3500	0	0.27
Carbon fibers	275–415	—	2000–3000	0	0.21–0.28
Glass fibers	73–85	—	3500–4600	0	0.22–0.26
Kevlar fibers	62–117	—	2800	0	0.36
Spectra Fibers	73–100	—	2400–2800	3	0.46

Note: In the upper part of the table the lowest values for E, Y, and UTS and the highest values for elongation are for pure metals. Multiply gigapascals (GPa) by 145,000 to obtain pounds per square in. (psi), and megapascals (MPa) by 145 to obtain psi.

begins to decrease slowly above the proportional limit. For such materials, Y is usually defined by drawing a line with the same slope as the linear elastic curve but that is **offset** by a strain of 0.002, or 0.2% elongation. The yield stress is then defined as the stress where this offset line intersects the stress–strain curve; this simple procedure is shown on the left side in Fig. 2.2.

As the specimen begins to elongate under a continuously increasing load, its cross-sectional area decreases **permanently** and **uniformly** within its gage length. If the specimen is unloaded (from a stress level higher than the yield stress), the curve follows a straight line downward and parallel to the original slope of the curve, as shown in Fig. 2.3. As the load is increased further, the engineering stress eventually reaches a maximum and then begins to decrease (Fig. 2.2). The maximum engineering stress is called the **tensile strength** or **ultimate tensile strength (UTS)** of the material. Values for UTS for various materials are given in Table 2.2.

If the specimen is loaded beyond its ultimate tensile strength, it begins to **neck**, or *neck down*; the cross-sectional area of the specimen is no longer uniform along the gage length and is smaller in the necked region. As the test progresses, the engineering stress drops further and the specimen finally fractures at the necked region (Fig. 2.1a); the engineering stress at fracture is known as the **breaking** or **fracture stress.**

The ratio of stress to strain in the elastic region is the **modulus of elasticity**, E, or **Young's modulus** (after the British scientist T. Young, 1773–1829):

$$E = \frac{\sigma}{e}. \tag{2.3}$$

This linear relationship is known as **Hooke's law** (after the British physicist R. Hooke, 1635–1703).

Note in Eq. (2.3) that, because engineering strain is dimensionless, E has the same units as stress. The modulus of elasticity is the slope of the elastic portion of the curve and hence indicates the **stiffness** of the material. The higher the elastic modulus, the higher is the load required to stretch the specimen to the same extent, and thus the stiffer is the material. Compare, for example, the stiffness of metal wire with that of a rubber band or plastic sheet when they are stretched.

The elongation of the specimen under tension is accompanied by lateral contraction; this effect can easily be observed by stretching a rubber band. The absolute value of the ratio of the lateral strain to the longitudinal strain is known as **Poisson's ratio** (after the French mathematician S.D. Poisson, 1781–1840) and is denoted by the symbol ν.

2.2.2 Ductility

An important behavior observed during a tension test is **ductility**—the extent of plastic deformation that the material undergoes prior to fracture. There are two common measures of ductility. The first is the **total elongation** of the specimen, given by

$$\text{Elongation} = \frac{l_f - l_o}{l_o} \times 100, \tag{2.4}$$

where l_f and l_o are measured as shown in Fig. 2.1a. Note that the elongation is based on the original gage length of the specimen and that it is calculated as a percentage.

The second measure of ductility is the **reduction of area**, given by

$$\text{Reduction of area} = \frac{A_o - A_f}{A_o} \times 100, \tag{2.5}$$

where A_o and A_f are, respectively, the original and final (fracture) cross-sectional areas of the test specimen. Thus, the ductility of a piece of chalk is zero, because it does not stretch at all or reduce in cross-section; by contrast, a ductile specimen, such as a pure metal or thermoplastic, stretches and necks considerably before it fails.

2.2.3 True Stress and True Strain

Recall that engineering stress is based on the original cross-sectional area, A_o, of the specimen. However, the instantaneous cross-sectional area of the specimen becomes smaller as it elongates, just as the area of a rubber band does; thus, engineering stress does not represent the *actual* (or true) stress to which the specimen is subjected.

True stress is defined as the ratio of the load, P, to the actual (instantaneous, hence *true*) cross-sectional area, A, of the specimen:

$$\sigma = \frac{P}{A}. \tag{2.6}$$

For determining **true strain**, first consider the elongation of the specimen as consisting of increments of instantaneous change in length. Then, using calculus, it can be shown that the true strain (*natural* or *logarithmic strain*) is calculated as

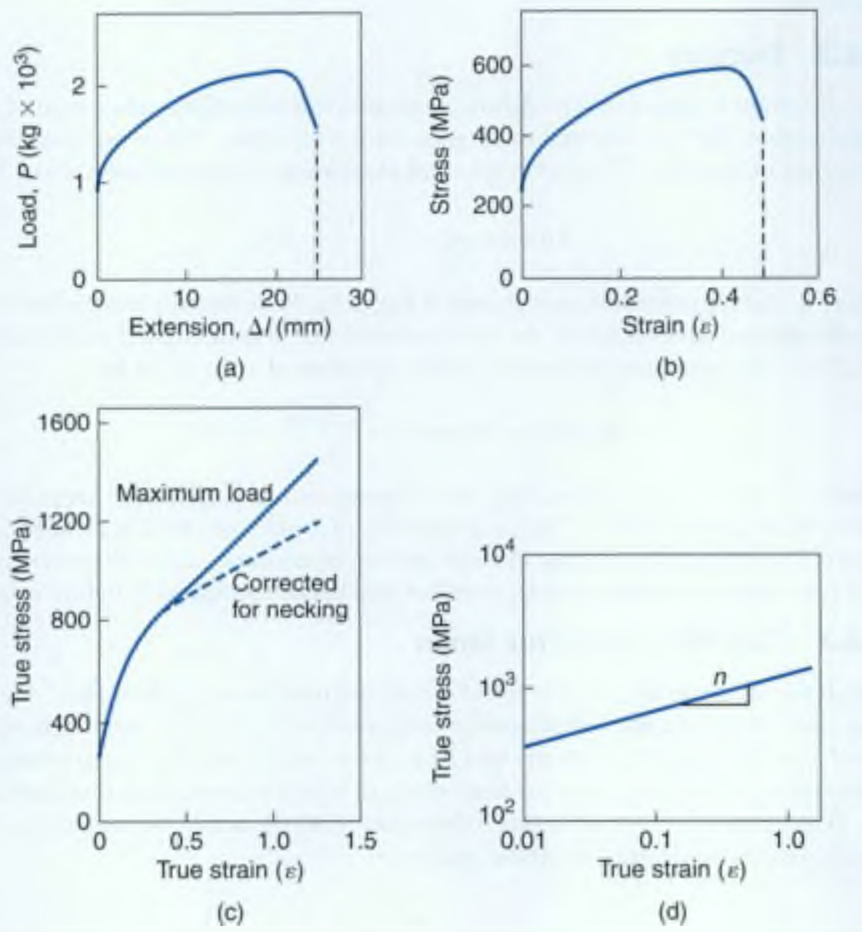
$$\epsilon = \ln\left(\frac{l}{l_o}\right). \tag{2.7}$$

Note from Eqs. (2.2) and (2.7) that, for small values of strain, the engineering and true strains are approximately equal; however, they diverge rapidly as the strain increases. For example, when $e = 0.1$, $\epsilon = 0.095$, and when $e = 1$, $\epsilon = 0.69$.

Unlike engineering strains, true strains are consistent with actual physical phenomena in the deformation of materials. For example, consider a hypothetical situation where a specimen 50 mm in height is compressed, between flat platens, to a final height of zero; in other words, the specimen is deformed infinitely. According to their definitions, the engineering strain that the specimen undergoes is $(0 - 50)/50 = -1$, but the true strain is $-\infty$; note that the answer will be the same regardless of the original height of the specimen. Clearly, then, true strain describes the extent of deformation correctly, since the deformation is indeed infinite.

2.2.4 Construction of Stress–strain Curves

The procedure for constructing an engineering stress–strain curve is to take the load–elongation curve (Fig. 2.4a, and also Fig. 2.2) and then to divide the load (vertical



(a) (b)

(c) (d)

FIGURE 2.4 (a) Load–elongation curve in tension testing of a stainless steel specimen. (b) Engineering stress–engineering strain curve, drawn from the data in Fig. 2.4a. (c) True stress–true strain curve, drawn from the data in Fig. 2.4b. Note that this curve has a positive slope, indicating that the material is becoming stronger as it is strained. (d) True stress–true strain curve plotted on log–log paper and based on the corrected curve in Fig. 2.4c. The correction is due to the triaxial state of stress that exists in the necked region of the specimen.

axis) by the original cross-sectional area, A_o, and the elongation (horizontal axis) by the original gage length, l_o. Because A_o and l_o are constants, the engineering stress–strain curve obtained (shown in Fig. 2.4b) has the same shape as the load–elongation curve shown in Fig. 2.4a. (In this example, $A_o = 36.1\,\text{mm}^2$ and $A_f = 10.3\text{mm}^2$.)

True stress–true strain curves are obtained similarly, by dividing the load by the instantaneous cross-sectional area, with the true strain calculated from Eq. (2.7); the result is shown in Fig. 2.4c. Note the *correction* to the curve, reflecting the fact that the specimen's necked region is subjected to three-dimensional tensile stresses, as described in more advanced texts. This stress state gives higher stress values than the actual true stress; hence, to compensate, the curve must be corrected downward.

The true stress–true strain curve in Fig. 2.4c can be represented by the equation

$$\sigma = K\epsilon^n, \qquad (2.8)$$

where K is the **strength coefficient** and n is the **strain-hardening** or **work-hardening exponent**. Typical values for K and n for several metals are given in Table 2.3.

When the curve shown in Fig. 2.4c is a log–log plot, it will be found that the curve is approximately a straight line (Fig. 2.4d); the slope of the curve is the exponent n. Thus, the higher the slope, the greater is the strain-hardening capacity of the material—that is, the stronger and harder it becomes as it is strained. True stress–true strain curves for a variety of metals are given in Fig. 2.5. When reviewed in detail, some differences between Table 2.3 and Fig. 2.5 will be noted. These discrepancies result from the fact that different sources of data and different specimens have been involved in obtaining them.

TABLE 2.3

Typical Values for *K* and *n* for Selected Metals

Material	K (MPa)	n
Aluminum		
1100-O	180	0.20
2024-T4	690	0.16
5052-O	202	0.13
6061-O	205	0.20
6061-T6	410	0.05
7075-O	400	0.17
Brass		
70-30, annealed	900	0.49
85-15, cold rolled	580	0.34
Cobalt-based alloy, heat treated	2070	0.50
Copper, annealed	315	0.54
Steel		
Low-C, annealed	530	0.26
1020, annealed	745	0.20
4135, annealed	1015	0.17
4135, cold rolled	1100	0.14
4340, annealed	640	0.15
304 stainless, annealed	1275	0.45
410 stainless, annealed	960	0.10
Titanium		
Ti-6Al-4V, annealed, 20°C	1400	0.015
Ti-6Al-4V, annealed, 200°C	1040	0.026
Ti-6Al-4V, annealed, 600°C	650	0.064
Ti-6Al-4V, annealed, 800°C	350	0.146

Note that the elastic regions in the curves have been deleted, because the slope in this region is very high. Consequently, the point of intersection of each curve with the vertical axis in this figure can be considered to be the yield stress, Y, of the material.

The area under the true stress–true strain curve at a particular strain is the energy per unit volume (**specific energy**) of the material deformed, and indicates the work required to plastically deform a unit volume of the material to that strain. The area under the true stress–true strain curve up to fracture is known as the material's **toughness**, that is, the amount of energy per unit volume that the material dissipates prior to fracture. Note that toughness involves both the height and width of the stress–strain curve of the material, whereas strength is related only to the *height* of the curve and ductility is related only to the *width* of the curve.

Video Solution 2.1 Toughness and Resilience of Power Law Materials

2.2.5 Strain at Necking in a Tension Test

As stated earlier, the onset of necking in a tension-test specimen corresponds to the ultimate tensile strength of the material. Note that the slope of the load–elongation curve at this point is zero, and it is there that the specimen begins to neck. The specimen cannot support the load being applied because the cross-sectional area of the neck is becoming smaller at a rate that is higher than the rate at which the material becomes stronger (strain hardens).

The true strain at the onset of necking is numerically equal to the strain-hardening exponent, n, of the material. Thus, the higher the value of n, the higher the strain

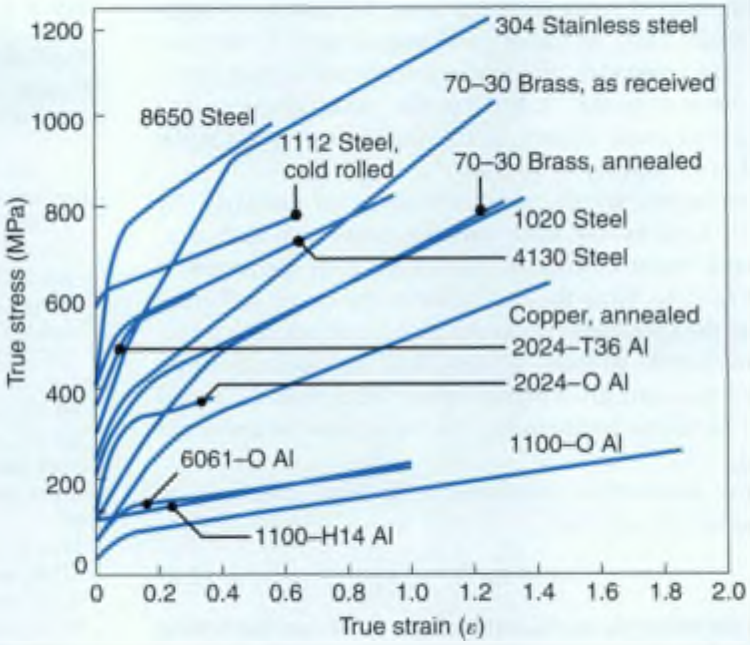


FIGURE 2.5 True stress–true strain curves in tension at room temperature for various metals; the curves start at a finite level of stress. The elastic regions have too steep a slope to be shown in this figure; thus, each curve starts at the yield stress, Y, of the material.

that a piece of material can experience before it begins to neck. This observation is important, particularly in regard to sheet-metal forming operations that involve stretching of the workpiece material (Chapter 16). It can be seen in Table 2.3 that annealed copper, brass, and stainless steel have high n values, meaning that they can be stretched uniformly to a greater extent than can the other metals listed in the table.

EXAMPLE 2.1 Calculation of Ultimate Tensile Strength

Given: This example shows that the UTS of a material can be calculated from its strength coefficient, K, and strain hardening exponent, n. Assume that a material has a true stress–true strain curve given by

$$\sigma = 690\epsilon^{0.5}\ \text{MPa}.$$

Find: Calculate the true ultimate tensile strength and the engineering UTS of this material.

Solution: Recall that the necking strain corresponds to the strain hardening exponent; the necking strain for this material is

$$\epsilon = n = 0.5,$$

therefore the *true* ultimate tensile strength is

$$\sigma = Kn^n = 690(0.5)^{0.5} = 488\ \text{MPa}.$$

The true area at the onset of necking is obtained from

$$\ln\left(\frac{A_o}{A_{\text{neck}}}\right) = n = 0.5.$$

Thus,

$$A_{\text{neck}} = A_o\epsilon^{-0.5},$$

and the maximum load, P, is

$$P = \sigma A_{\text{neck}} = \sigma A_o e^{-0.5},$$

where σ is the true UTS. Hence,

$$P = (488)(0.606)(A_o) = 2900A_o\ \text{MPa}.$$

Since $\text{UTS} = P/A_o$,

$$\text{UTS} = 296\ \text{MPa}.$$

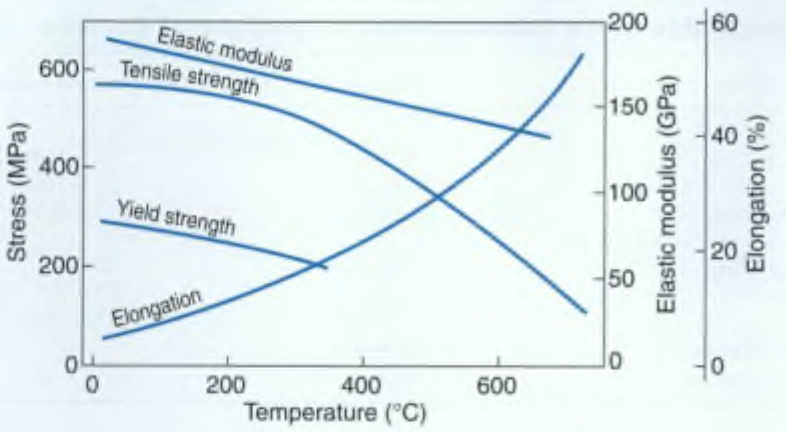


FIGURE 2.6 Effect of temperature on mechanical properties of a carbon steel; most materials display similar temperature sensitivity for elastic modulus, yield strength, ultimate strength, and ductility.

2.2.6 Temperature Effects

Increasing the temperature generally has the following effects on stress–strain curves (Fig. 2.6):

a. The ductility and toughness increase
b. The yield strength and modulus of elasticity decrease

Temperature also affects the strain-hardening exponent, n, of most metals, in that it increases with increasing temperature. The influence of temperature is, however, best described in conjunction with the rate of deformation because increasing strain rate tends to decrease n, as described below.

2.2.7 Effects of Rate of Deformation and Strain Rate

Just as a balloon can be inflated or a rubber band stretched at different rates, a piece of material in a manufacturing process can be shaped at different speeds. Some machines, such as hydraulic presses, form materials at low speeds, while others, such as mechanical presses, shape materials at high speeds.

The **deformation rate** in a tension test is the speed at which a specimen is being stretched, in units such as m/s. The **strain rate**, on the other hand, is a function of the specimen's length. For example, consider two rubber bands, one 20 mm and the other 100 mm long, respectively, that are stretched by 10 mm within a period of 1 s. The engineering strain in the shorter specimen is $\frac{10}{20} = 0.5$; the strain in the longer is $\frac{10}{100} = 0.1$. Thus, the strain rates are $0.5\ \text{s}^{-1}$ and $0.1\ \text{s}^{-1}$, respectively; thus, the short band is being subjected to a strain rate five times higher than that for the long band, even though they are both being stretched at the same deformation rate.

Deformation rates typically employed in various testing as well as metalworking processes, and the true strains involved, are given in Table 2.4. Because of the wide range encountered in practice, strain rates are usually stated in terms of orders of magnitude, such as $10^2\ \text{s}^{-1}$, $10^4\ \text{s}^{-1}$, etc.

The typical effects that temperature and strain rate jointly have on the strength of metals are shown in Fig. 2.7. Note that increasing the strain rate increases the

TABLE 2.4

Typical Ranges of Strain and Deformation Rate in Manufacturing Processes

Process	True Strain	Deformation rate (m/s)
Cold working		
Forging, rolling	0.1–0.5	0.1–100
Wire and tube drawing	0.05–0.5	0.1–100
Explosive forming	0.05–0.2	10–100
Hot working and warm working		
Forging, rolling	0.1–0.5	0.1–30
Extrusion	2–5	0.1–1
Machining	1–10	0.1–100
Sheet-metal forming	0.1–0.5	0.05–2
Superplastic forming	0.2–3	10^{-4}–10^{-2}

strength of the material, called **strain-rate hardening**. The slope of these curves is called the **strain-rate sensitivity exponent,** m. The value of m is obtained from log–log plots, provided that the vertical and horizontal scales are the same (unlike those shown in Fig. 2.7). A slope of 45° would therefore indicate a value of $m = 1$. The relationship is given by the equation

$$\sigma = C\dot{\epsilon}^{m}, \tag{2.9}$$

where C is the **strength coefficient** and $\dot{\epsilon}$ is the *true strain rate*, defined as the true strain that the material undergoes per unit time. Note that C has the units of stress and is similar to, but not to be confused with, the strength coefficient K in Eq. (2.8).

From Fig. 2.7, it can be seen that the sensitivity of strength to strain rate increases with temperature; in other words, m increases with increasing temperature. Also note that the slope is relatively flat at room temperature; that is, m is very low. This condition is true for most metals, but not for those that recrystallize at room temperature, such as lead and tin. Typical ranges of m for metals are up to 0.05 for cold-working, 0.05 to 0.4 for hot-working, and 0.3 to 0.85 for superplastic materials (see below).

The magnitude of the strain-rate sensitivity exponent significantly influences necking in a tension test. With increasing m, the material stretches farther before it fails; thus, increasing m delays necking. Ductility enhancement caused by the high strain-rate sensitivity of some materials has been exploited in **superplastic forming** of sheet metal, as described in Section 16.10.

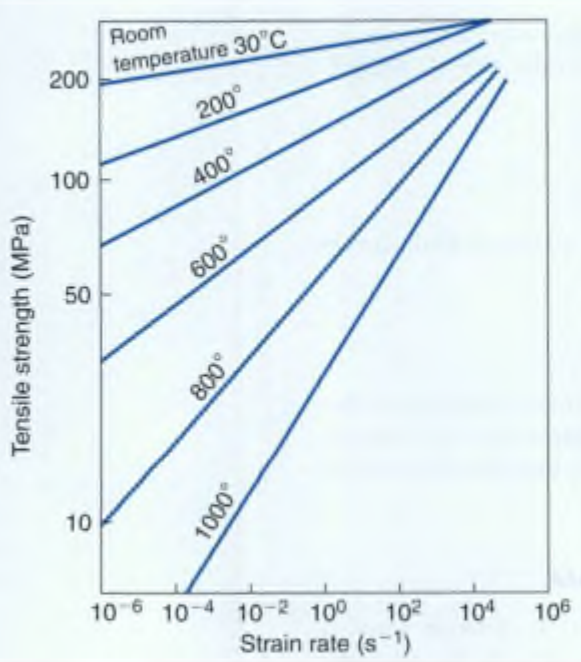


FIGURE 2.7 The effect of strain rate on the ultimate tensile strength for aluminum. Note that, as the temperature increases, the slopes of the curves increase; thus, strength becomes more and more sensitive to strain rate as temperature increases. *Source:* J.H. Hollomon.

Superplasticity. The term *superplasticity* refers to the capability of some materials to undergo large uniform elongation prior to necking and fracture in tension. The elongation ranges from a few hundred percent to as much as 2000%. Common nonmetallic materials exhibiting superplastic behavior are bubble gum, glass (at elevated temperatures), and thermoplastics; as a result, glass and thermoplastics can successfully be formed into a wide variety of complex shapes. Among metals exhibiting superplastic behavior are very fine grained (10 to 15 μm) titanium alloys and zinc–aluminum alloys; when heated, they can elongate to several times their original length.

2.2.8 Hydrostatic Pressure Effects

Various tests have been performed to determine the effect of hydrostatic pressure on mechanical properties of materials. Test results at pressures up to 3.5 GPa indicate that increasing the hydrostatic pressure substantially increases the strain at fracture, both for ductile and for brittle materials. This beneficial effect of hydrostatic pressure has been exploited in metalworking processes, particularly in hydrostatic extrusion (Section 15.4.2) and in compaction of metal powders (Section 17.3).

2.2.9 Radiation Effects

In view of the use of various metals and alloys in nuclear applications, extensive studies have been conducted on radiation's effects on mechanical properties. Typical changes in the properties of steels and other metals exposed to doses of high radiation are increased yield stress, tensile strength, and hardness, and decreased ductility and toughness.

2.3 Compression

Numerous operations in manufacturing, such as forging, rolling, and extrusion (Part III), are performed with the workpiece subjected to compressive forces. The **compression test**, in which the specimen is subjected to a compressive load, gives information that is helpful in estimating forces and power requirements in these processes. This test is usually carried out by compressing a solid cylindrical specimen between two well-lubricated flat dies (platens). Because of friction between the specimen and the platens, the specimen's cylindrical surface bulges, called **barreling** (Fig. 2.8). The height-to-diameter ratio of the specimen is typically less than 3:1 in order to avoid buckling during the test. (See also Section 14.4 on *heading*.)

Because of barreling, the specimen's cross-sectional area varies along its height, and thus obtaining the stress–strain curves in compression can be difficult. Furthermore, since friction dissipates energy, the compressive force is higher than it otherwise would be in order to overcome friction. With effective lubrication, however, friction can be minimized and thus a reasonably constant cross-sectional area can be maintained during the test.

When the results of compression and tension tests on *ductile* metals are compared, it will be seen that the true stress–true strain curves coincide. This behavior, however, does not hold true for *brittle* materials, which are generally stronger and more ductile in compression than in tension. (See Table 8.2.)

If a specimen is first subjected to tension and deformed plastically and then the load is released and a compressive load is applied, the yield stress in compression is found to be lower than that in tension. This behavior is known as the **Bauschinger effect** (after the German engineer J. Bauschinger, reported in 1881); it is exhibited in varying

FIGURE 2.8 Barreling in compressing a round solid cylindrical specimen (7075-O aluminum) between flat dies. Barreling is caused by friction at the die–specimen interfaces, which retards the free flow of the material. See also Fig. 14.3.

degrees by all metals and alloys. The phenomenon is also called **strain softening** or **work softening**, because of the lowered yield stress in the direction opposite that of the original load application.

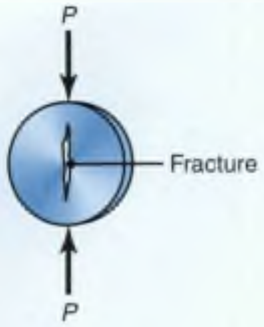


FIGURE 2.9 Disk test on a brittle material, showing the direction of loading and the fracture path.

Disk Test. For brittle materials such as ceramics and glasses (Chapter 8), the **disk test** can be used, in which a disk is subjected to diametral compression forces between two hardened flat platens (Fig. 2.9). When the specimen is loaded as shown, tensile stresses develop perpendicular to the vertical centerline along the disk; fracture initiates and the disk splits vertically in half.

The *tensile stress*, σ, in the disk is uniform along the centerline and can be calculated from the formula

$$\sigma = \frac{2P}{\pi d t}, \tag{2.10}$$

where P is the load at fracture, d is the diameter of the disk, and t is its thickness. In order to avoid premature failure at the contact points, thin strips of soft metal are placed between the disk and the two platens; these strips also protect the platens from being damaged during the test. The phenomenon of fracture at the center of the specimen has been utilized in the manufacture of *seamless tubing* (Section 13.5).

2.4 Torsion

In addition to undergoing tensile and compressive forces, a workpiece may also be subjected to shear strains (Fig. 2.10), such as in the punching of holes in sheet metals (Section 16.2), swaging (Section 14.4), and machining (Section 21.2). The method generally used to determine properties of materials in shear is the **torsion test**. This test is usually performed on a thin tubular specimen in order to obtain an approximately uniform stress and strain distribution along its cross-section.

The test specimen usually has a reduced cross-section in order to confine the deformation to a narrow zone. The **shear stress**, τ, can be calculated from the formula

$$\tau = \frac{T}{2\pi r^2 t}, \tag{2.11}$$

where T is the torque applied, r is the average radius of the tube, and t is the thickness of the tube at its narrow section.

The **shear strain**, γ, can be calculated from the formula

$$\gamma = \frac{r\phi}{l}, \tag{2.12}$$

where l is the length of the tube section and ϕ the **angle of twist** in radians.

The ratio of the shear stress to the shear strain in the elastic range is known as the **shear modulus**, or **modulus of rigidity**, G. The shear modulus is a quantity related to the modulus of elasticity, E, by the formula

$$G = \frac{E}{2(1+\nu)}. \tag{2.13}$$

The *angle of twist*, ϕ, to fracture in the torsion of solid round bars at elevated temperatures has been found to be useful in estimating the forgeability of metals (Section 14.5). The greater the number of twists prior to failure, the better is the forgeability.

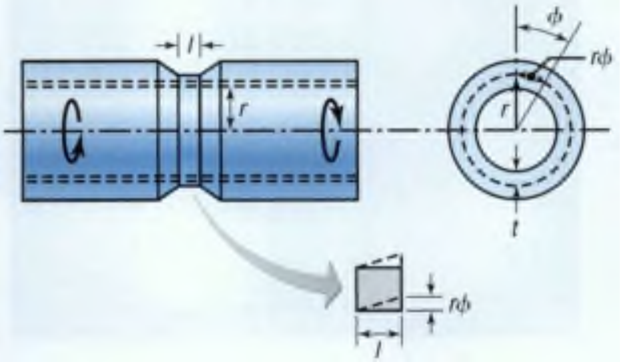


FIGURE 2.10 A typical torsion-test specimen; it is mounted between the two heads of a testing machine and twisted; note the shear deformation of an element in the reduced section of the specimen.

2.5 Bending (Flexure)

Preparing specimens from brittle materials can be challenging because of the difficulties involved in shaping or machining them to proper dimensions. Furthermore, the specimens are sensitive to surface defects (such as scratches and notches), and clamping brittle specimens for testing is difficult. Also, improper alignment of the test specimen can result in a nonuniform stress distribution along its cross-section.

A commonly used test method for brittle materials is the **bend** or **flexure test**, which typically involves a specimen that has a rectangular cross-section and is supported in a manner shown in Fig. 2.11. The load is applied vertically, at either one point or two points; consequently, these tests are referred to as **three-point** and **four-point bending**, respectively. The longitudinal stresses in the specimens are tensile at their lower surfaces and compressive at their upper surfaces; these stresses can be calculated using simple beam equations described in texts on the mechanics of solids.

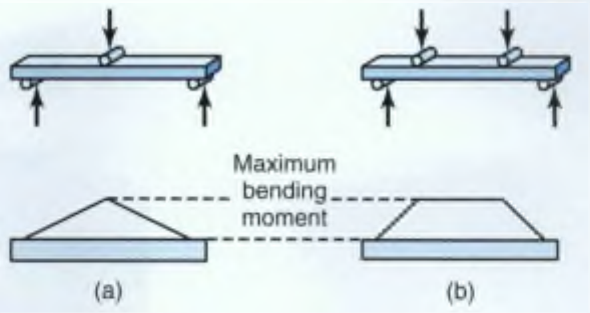


FIGURE 2.11 Two bend-test methods for brittle materials: (a) three-point bending and (b) four-point bending. The areas over the beams represent the bending-moment diagrams, described in texts on the mechanics of solids. Note the region of constant maximum bending moment in (b); by contrast, the maximum bending moment occurs only at the center of the specimen in (a).

The stress at fracture in bending is known as the **modulus of rupture**, or **transverse rupture strength** (see Table 8.2). Note that, because of the larger volume of material subjected to the same bending moment in Fig. 2.11b, there is a higher probability that defects exist within this volume than in that shown in Fig. 2.11a. Consequently, the four-point test gives a lower modulus of rupture than the three-point test.

QR Code 2.1 Instron 5544 3-point bend test. (*Source:* Courtesy of Instron®)

2.6 Hardness

Hardness is generally defined as *resistance to permanent indentation*; thus, steel is harder than aluminum and aluminum is harder than lead. Hardness, however, is not a fundamental property, because the resistance to indentation depends on the shape of the indenter and on the load applied. Hardness is a commonly used property; it gives a general indication of the strength of the material and of its resistance to scratching and wear.

2.6.1 Hardness Tests

Several test methods, using different indenter materials and shapes (Fig. 2.12), have been developed to measure the hardness of materials. The most commonly used hardness tests are described below.

Brinell Test. Introduced by J.A. Brinell in 1900, this test involves pressing a steel or tungsten-carbide ball 10 mm in diameter against a surface, with a load of 500, 1500, or 3000 kg (Fig. 2.13). The *Brinell hardness number* (HB) is defined as the ratio of the applied load, P, to the curved surface area of the indentation. The harder the material tested, the smaller the impression; a 1500-kg or 3000-kg load is usually recommended in order to obtain impressions sufficiently large for accurate measurement of hardness.

Depending on the condition of the material tested, one of two types of impression develops on the surface after the performance of a hardness test (Fig. 2.14). The impressions in annealed metals generally have a rounded profile along the periphery (Fig. 2.14a); in cold-worked metals, they usually have a sharp profile

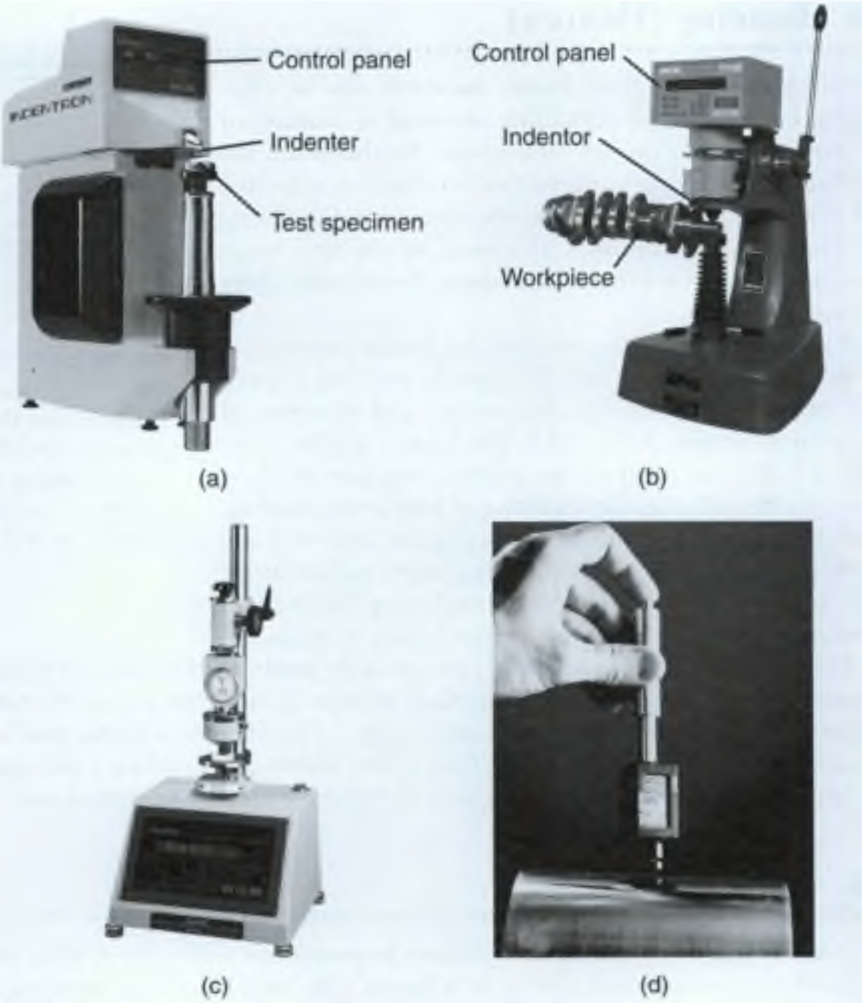


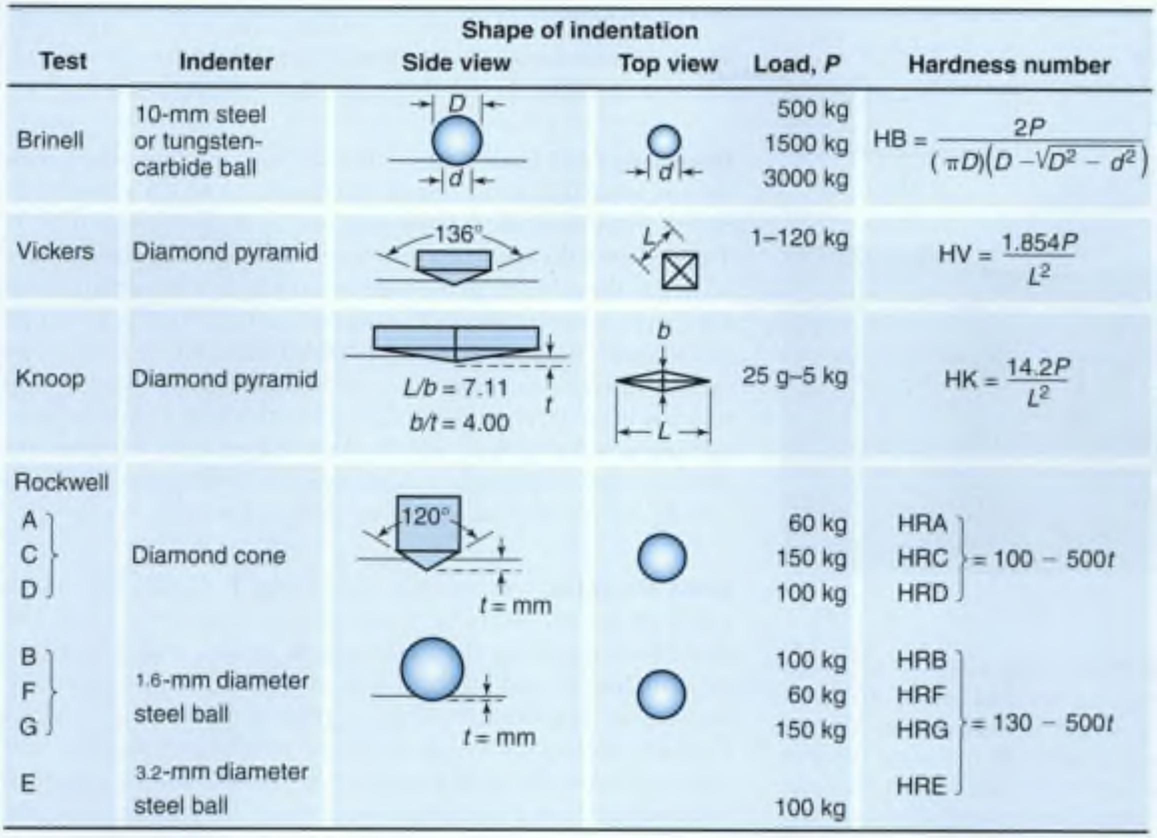
FIGURE 2.12 A selection of hardness testers. (a) A Micro Vickers hardness tester, (b) Rockwell hardness tester (the support for the part has been removed for clarity), (c) Durometer, and (d) Leeb tester. *Source:* (a) through (c) Courtesy of Newage Testing Instruments, Inc. (d) Courtesy of Wilson® Instruments.

(Fig. 2.14b). The correct method of measuring the indentation diameter, d, is shown in the figure.

The indenter has a finite elastic modulus, and thus undergoes *elastic* deformation under the applied load; as a result, hardness measurements may not be as accurate as expected, depending on the indenter material. One method for minimizing this effect is using tungsten-carbide balls (Section 22.4); because of their higher modulus of elasticity, they distort less than steel balls do. These indenters are usually recommended for materials with a Brinell hardness number higher than 500.

QR Code 2.2 Video of a Rockwell hardness test. (*Source:* Courtesy of Instron®)

Rockwell Test. Developed by S.P. Rockwell in 1922, this test measures the *depth* of penetration instead of the diameter of the indentation. The indenter is pressed onto the surface, first with a *minor load* and then with a *major load*; the difference in the depths of penetration is a measure of the hardness of the material. Figure 2.13 shows some of the more common Rockwell hardness scales and the indenters used



Test	Indenter	Shape of indentation Side view	 Top view	Load, P	Hardness number
Brinell	10-mm steel or tungsten-carbide ball	D d	d	500 kg 1500 kg 3000 kg	$HB = \frac{2P}{(\pi D)(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid	136°	L	1–120 kg	$HV = \frac{1.854P}{L^2}$
Knoop	Diamond pyramid	$L/b = 7.11$ $b/t = 4.00$ t	b L	25 g–5 kg	$HK = \frac{14.2P}{L^2}$
Rockwell					
A	Diamond cone	120° t = mm		60 kg	HRA $= 100 - 500t$
C				150 kg	HRC $= 100 - 500t$
D				100 kg	HRD $= 100 - 500t$
B	1.6-mm diameter steel ball	t = mm		100 kg	HRB $= 130 - 500t$
F				60 kg	HRF $= 130 - 500t$
G				150 kg	HRG $= 130 - 500t$
E	3.2-mm diameter steel ball			100 kg	HRE $= 130 - 500t$

FIGURE 2.13 General characteristics of hardness-testing methods and formulas for calculating hardness.

in practice. Rockwell **superficial hardness** tests, using the same type of indenters but at lighter loads, also have been developed.

Vickers Test. This test, developed by the Vickers Ltd. company in 1922 and formerly known as the *diamond pyramid hardness* test, uses a pyramid-shaped diamond indenter (Fig. 2.13) and a load that ranges from 1 to 120 kg. The *Vickers hardness number* is indicated by HV. The impressions obtained are typically less than 0.5 mm on the diagonal, and penetration depths can be as low as 20 nm. This test gives essentially the same hardness number regardless of the load, and is suitable for testing materials with a wide range of hardness, including heat-treated steels. Test procedures also have been developed to perform tests using atomic force microscopes and nanoindenters.

Knoop Test. This test, developed by F. Knoop in 1939, uses a diamond indenter in the shape of an elongated pyramid (Fig. 2.13); the applied loads range generally from 25 g to 5 kg. The *Knoop hardness number* is indicated by HK. Because of the light loads applied, this test is a **microhardness** test, and is therefore suitable for very small or very thin specimens and for brittle materials such as carbides, ceramics, and glass.

This test is also used for measuring the hardness of the individual grains and components in a metal alloy. The size of the indentation is generally in the range from

0.01 to 0.10 mm; consequently, surface preparation is important. Because the hardness number obtained depends on the applied load, Knoop test results should always cite the load employed.

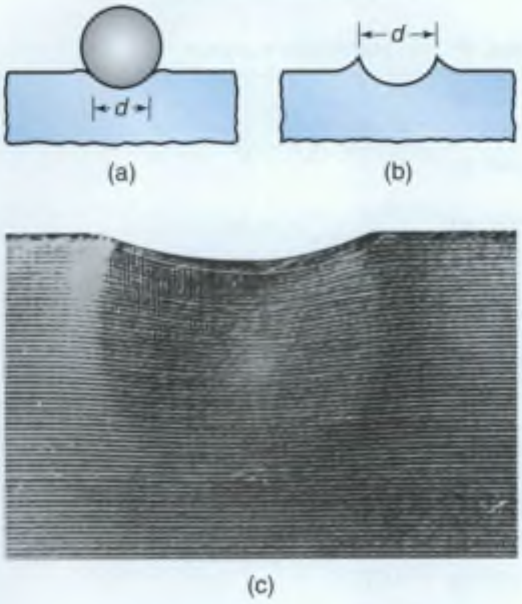


FIGURE 2.14 Indentation geometry in Brinell hardness testing: (a) annealed metal, (b) work-hardened metal, and (c) deformation of mild steel under a spherical indenter. Note that the depth of the permanently deformed zone is about one order of magnitude larger than the depth of indentation; for a hardness test to be valid, this zone should be fully developed in the material. *Source:* After M.C. Shaw and C.T. Yang.

Scleroscope and Leeb Tests. The *scleroscope* (from the Greek *skleros*, meaning "hard") is an instrument in which a diamond-tipped indenter (called *hammer*), enclosed in a glass tube, is dropped onto the specimen from a certain height. The hardness is related to the *rebound* of the indenter: the higher the rebound, the harder the material tested. The impression made by a scleroscope is very small. Because obtaining reliable results with a scleroscope can be difficult, an electronic version, called a *Leeb* or Equotip test, has been developed (Fig. 2.12d). In this test, a carbide hammer impacts the surface, and incident and rebound velocities are electronically measured. A *Leeb number* is then calculated and usually converted to Rockwell or Vickers hardness.

Mohs Hardness. Developed in 1822 by F. Mohs, this test is based on the capability of one material to scratch another. The Mohs hardness is based on a scale from 1 to 10, with 1 being the measure for talc and 10 that for diamond (the hardest substance known; see Section 8.7). Thus, a material with a higher Mohs hardness number always scratches one with a lower number. Soft materials typically have a number between 2 and 3, hardened steels about 6, and aluminum oxide (used for cutting tools and as an abrasive in grinding wheels) of 9. Although the Mohs scale is qualitative and is used mainly by mineralogists, it correlates well with Knoop hardness.

Shore Test and Durometer. The hardness of materials such as rubbers, plastics, and similar soft and elastic nonmetallic materials is generally measured by a Shore test, with an instrument called a *durometer* (from the Latin *durus*, meaning "hard"). An indenter is first pressed against the surface and then a constant load is rapidly applied. The *depth* of penetration is measured after one second; the hardness is inversely related to the penetration. There are two different scales for this test. Type A has a blunt indenter and an applied load of 1 kg; the test is typically used for softer materials. Type D has a sharper indenter and a load of 5 kg, and is used for harder materials. The hardness numbers in these tests range from 0 to 100.

Hot Hardness. The hardness of materials at elevated temperatures (see Fig. 22.1) is important in applications such as cutting tools in machining and dies in hot-working and casting operations. Hardness tests can be performed at elevated temperatures with conventional testers, with some modifications such as enclosing the specimen and indenter in a small electric furnace.

2.6.2 Hardness and Strength

Because hardness is the resistance to *permanent* indentation, it can be likened to performing a compression test on a small volume on the surface of a material (Fig. 2.14c). Studies have shown that the hardness of a cold-worked metal is about three times

Video Solution 2.2 Hardness Test Indentation Dimensions its yield stress Y (in the same units); for annealed metals, the hardness is about five times Y.

A relationship has been established between the UTS and the Brinell hardness (HB) for steels, measured for a load of 3000 kg. In SI units, the relationship is given by

$$\text{UTS} = 3.5(\text{HB}), \tag{2.14}$$

where UTS is in MPa. In traditional units,

$$\text{UTS} = 500(\text{HB}), \tag{2.15}$$

where UTS is in psi.

2.6.3 Hardness-testing Procedures

For a hardness test to be meaningful and reliable, the **zone of deformation** under the indenter (see Fig. 2.14c) must be allowed to develop freely. Consequently, the *location* of the indenter (with respect to the location of the *edges* of the specimen to be tested) and the *thickness* of the specimen are important considerations. Generally, the location should be at least two diameters of the indentation from the edge of the specimen, and the thickness of the specimen should be at least 10 times the depth of penetration of the indenter. Also, successive indentations on the same surface of the workpiece should be far enough apart so as not to interfere with each other.

Moreover, the indentation should be sufficiently large to give a representative hardness value for the bulk material. If hardness variations need to be detected in a small area, or if the hardness of individual constituents in a matrix or an alloy is to be determined, the indentations should be very small, such as those obtained in Knoop or Vickers tests, using light loads. While *surface preparation* is not critical for the Brinell test, it is important for the Rockwell test and even more important for the other hardness tests, because of the small sizes of the indentations. Surfaces may have to be polished to allow correct measurement of the impression's dimensions.

The values obtained from different hardness tests, on different scales, can be interrelated and can be converted using Fig. 2.15. Care should be exercised in using these charts because of the variables in material characteristics and in the shape of the indentation.

EXAMPLE 2.2 Calculation of Modulus of Resilience from Hardness

Given: A piece of steel is highly deformed at room temperature; its hardness is found to be 300 HB.

Find: Estimate the area of the elastic portion of the stress–strain curve up to the yield point (that is, the *resilience*) for this material if the yield strength is one-third the Brinell hardness.

Solution: Since the steel has been subjected to large strains at room temperature, it may be assumed that its stress–strain curve has flattened considerably, thus approaching the shape of a perfectly-plastic curve. Since the yield strength is one-third the Brinell hardness,

$$Y = \frac{300}{3} = 100 \text{ kg/mm}^2.$$

The area under the stress–strain curve is

$$\text{Modulus of resilience} = \frac{Y^2}{2E}.$$

From Table 2.2, $E = 210$ GPa for steel. Hence,

$$\begin{aligned}\text{Modulus of resilience} &= \frac{(100)^2}{2(210000)} \times 9.81 \\ &= 0.2336 \text{ mm-kg}^{3}\text{/mn}\end{aligned}$$

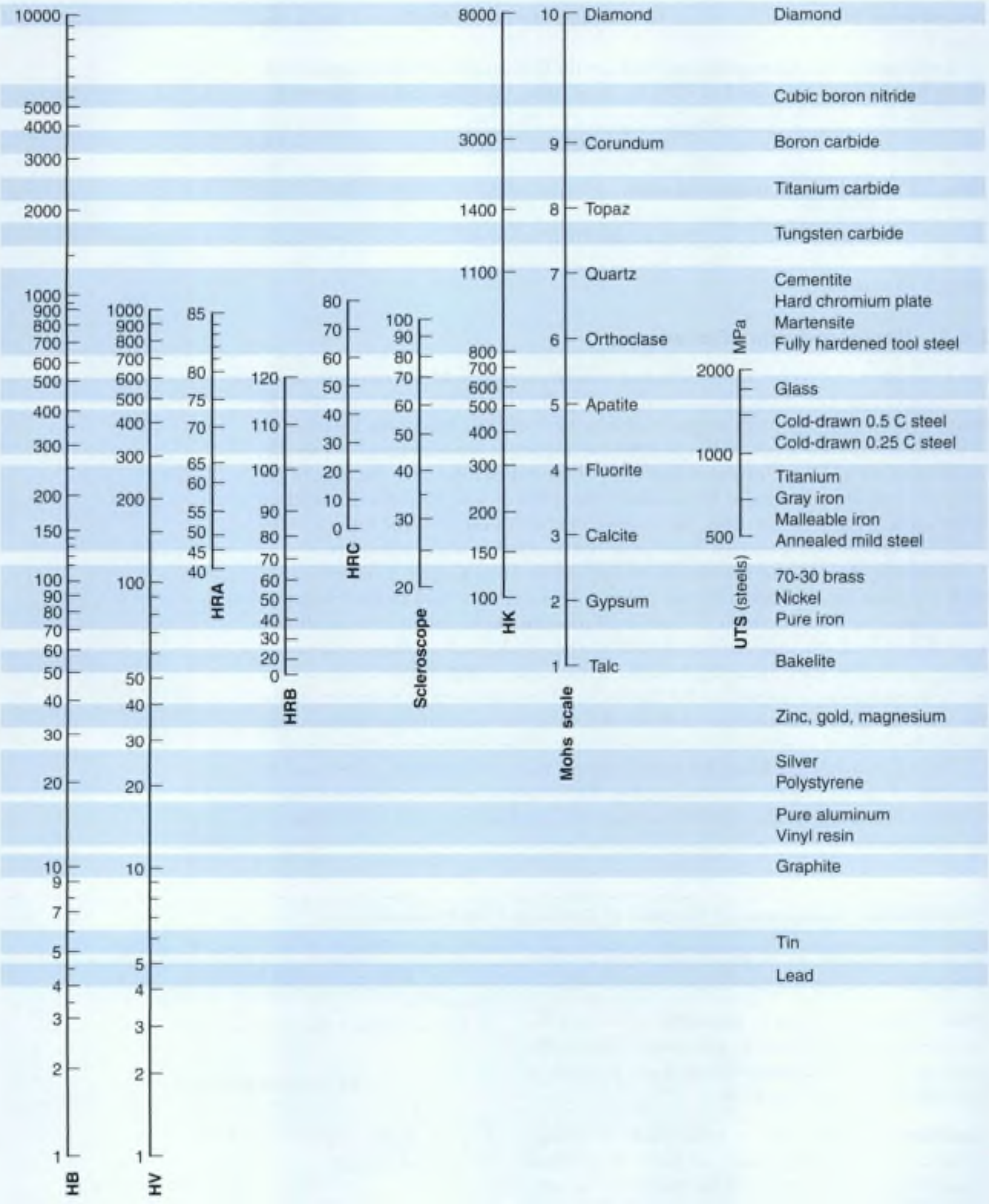


FIGURE 2.15 Chart for converting various hardness scales; note the limited range of most of the scales. Because of the many factors involved, these conversions are approximate.

2.7 Fatigue

Numerous components, such as tools, dies, gears, cams, shafts, and springs, are subjected to rapidly fluctuating (cyclic or periodic) loads, in addition to static loads. **Cyclic stresses** may be caused by fluctuating mechanical loads, such as (a) on gear teeth or reciprocating sliders, (b) by rotating machine elements under constant bending stresses, as is commonly encountered in shafts, or (c) by thermal stresses, as when a room-temperature die comes into repeated contact with hot workpieces, and then begins to cool between successive contacts. Under these conditions, the component fails at a stress level *below* that at which failure would occur under static loading. Upon inspection, failure is found to be associated with cracks that grow with every stress cycle and that propagate through the material until a critical crack length is reached when the material fractures. Known as **fatigue failure**, this phenomenon is responsible for the majority of failures in mechanical components.

Fatigue test methods involve testing specimens under various states of stress, usually in a combination of tension and bending. The test is carried out at various *stress amplitudes* (S), and the number of cycles (N) it takes to cause total failure of the specimen or part is then recorded. Stress amplitude is defined as the maximum stress, in tension and compression, to which the specimen is subjected. Typical plots, called **S–N curves**, are shown in Fig. 2.16. These curves are based on complete reversal of the stress—that is, maximum tension, then maximum compression, then maximum tension, and so on—such as that imposed by bending a rectangular eraser or a piece of wire alternately in one direction and then the other.

Tests can also be performed on a rotating shaft in four-point bending (see Fig. 2.11b). With some materials, the S–N curve becomes horizontal at low stress levels, indicating that the material will not fail at stresses below this limit. The maximum stress to which the material can be subjected without fatigue failure, regardless of the number of cycles, is known as the **endurance limit** or **fatigue limit**.

Although many materials, especially steels, have a definite endurance limit, others, such as aluminum alloys, do not have one and the S–N curve continues its downward trend. For metals exhibiting such behavior, the fatigue strength is specified at a certain number of cycles, such as 10^7; in this way, the useful service life of the component can be specified. The endurance limit for metals can be approximately related to their

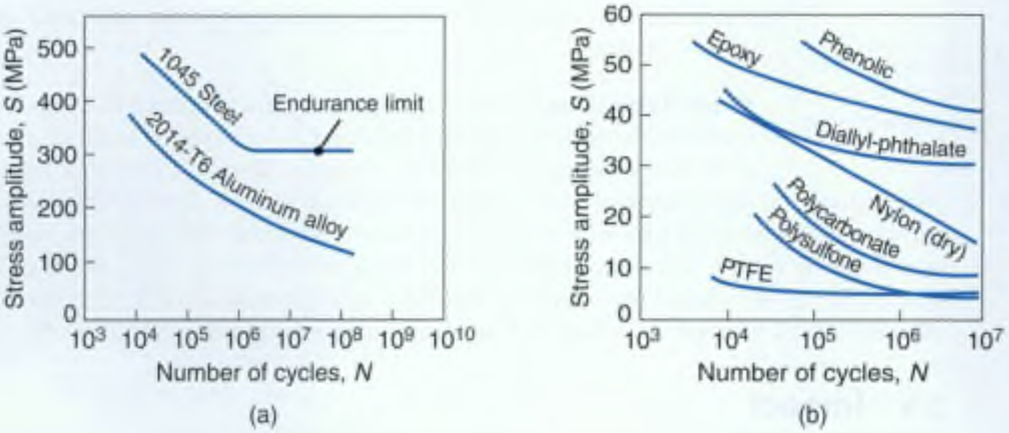


FIGURE 2.16 (a) Typical S–N curves for two metals; note that, unlike steel, aluminum does not have an endurance limit. (b) S–N curves for some polymers.

UTS (Fig. 2.17). For carbon steels, the endurance limit is usually 0.4–0.5 times the tensile strength.

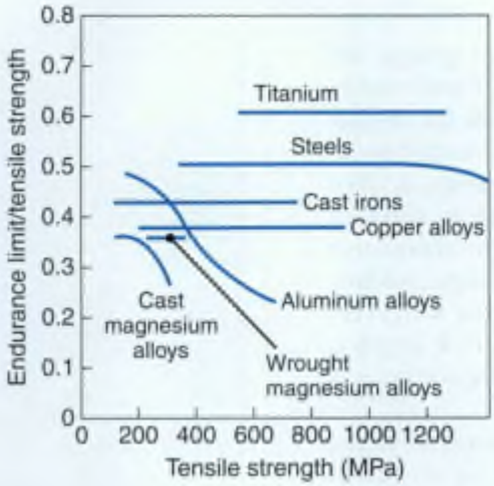


FIGURE 2.17 Ratio of endurance limit to tensile strength for various metals, as a function of tensile strength. Because aluminum does not have an endurance limit, the correlations for aluminum are based on a specific number of cycles, as is seen in Fig. 2.16.

2.8 Creep

Creep is the permanent deformation of a component under a static load maintained for a period of time. This phenomenon occurs in metals and some nonmetallic materials, such as thermoplastics and rubbers, and it can occur at any temperature; lead, for example, creeps under a constant tensile load at room temperature. However, for metals and their alloys, creep of any significance occurs at elevated temperatures, beginning at about 200°C for aluminum alloys and at about 1500°C for refractory alloys. The mechanism of creep at elevated temperature in metals is generally attributed to **grain-boundary sliding** (Section 1.5).

Creep is especially important in high-temperature applications, such as gas-turbine blades and components in jet engines and rocket motors. High-pressure steam lines, nuclear-fuel elements, and furnace components are likewise subject to creep. Creep can also occur in tools and dies that are subjected to high stresses at elevated temperatures during hot-working operations, such as forging and extrusion.

The *creep test* typically consists of subjecting a specimen to a constant tensile load (hence, constant engineering stress) at elevated temperature and measuring the changes in length at various time increments. A creep curve usually consists of *primary, secondary,* and *tertiary stages* (Fig. 2.18). During the test, the specimen eventually fails by necking and fracture, called *rupture* or *creep rupture.* As expected, the creep rate increases with specimen temperature and applied load.

Design against creep usually requires knowledge of the secondary (linear) range and its slope, because the creep rate can be determined reliably only when the curve has a constant slope. Generally, resistance to creep increases with the melting temperature of a material. Stainless steels, superalloys, and refractory metals and alloys are thus commonly used in applications where resistance to creep is required.

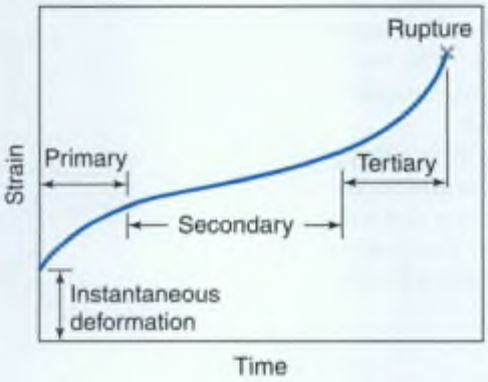


FIGURE 2.18 Schematic illustration of a typical creep curve; the linear segment of the curve (secondary) is used in designing components for a specific creep life.

Stress Relaxation. *Stress relaxation* is closely related to creep. In stress relaxation, the stresses resulting from external loading of a structural component decrease in magnitude over a period of time, even though the dimensions of the component remain constant. An example is the decrease in tensile stress of a wire in tension between two fixed ends (as in the wires in a piano or violin). Other examples include stress relaxation in rivets, bolts, guy wires, and various similar parts under either tension, compression, or flexure. Stress relaxation is particularly common and important in thermoplastics (Section 7.3).

2.9 Impact

In numerous machinery components and manufacturing operations, materials are subjected to **impact**, or **dynamic, loading**; for example, in high-speed metalworking processes such as heading to shape nails and bolt heads (Section 14.4).

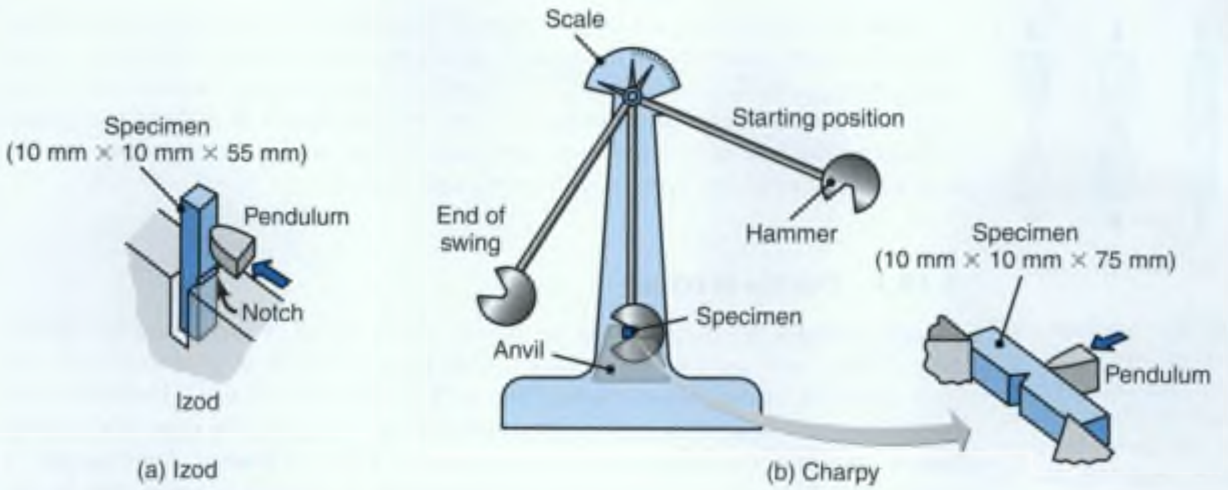


FIGURE 2.19 Impact test specimens.

A typical *impact test* for determining impact properties of materials consists of placing a *notched* specimen in an impact tester and breaking the specimen with a swinging pendulum (Fig. 2.19).

In the **Charpy test** (after the French scientist G. Charpy), the specimen is supported at both ends, while in the **Izod test** (after the English engineer E.G. Izod), it is supported at one end like a cantilever beam. From the swing of the pendulum, the energy dissipated in breaking the specimen can be obtained; this energy is the **impact toughness** of the material. Unlike hardness-test conversions (Fig. 2.15), no quantitative relationships have yet been established between Charpy and the Izod tests. Materials that have high impact resistance generally have high strength, high ductility, and, hence, high toughness. Sensitivity to surface defects (**notch sensitivity**) is important, as it significantly lowers impact toughness, particularly in heat-treated metals, ceramics, and glasses. Impact tests are particularly useful in determining the ductile–brittle transition temperature of materials (Section 2.10.1).

2.10 Failure and Fracture of Materials

Failure is one of the most important aspects of material behavior, because it directly influences the selection of a material for a particular application and the method(s) of manufacturing, and determining the service life of the component. Because of the several factors involved, failure and fracture of materials is a complex area of study. This section focuses only on those aspects of failure that are of particular significance to selecting and processing materials.

There are two general types of failure:

1. **Fracture**, through either internal or external cracking; fracture is further subclassified into two general categories: *ductile* and *brittle* (Figs. 2.21 and 2.22).
2. **Buckling**, as shown in Fig. 2.20b.

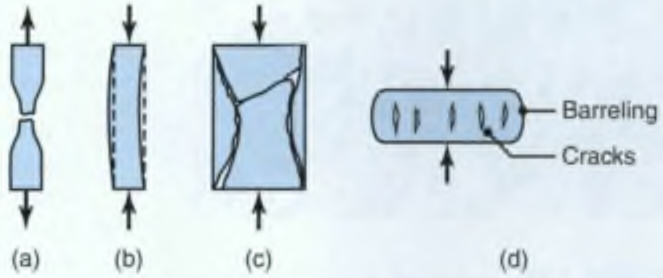


FIGURE 2.20 Schematic illustration of types of failures in materials: (a) necking and fracture of ductile materials, (b) buckling of ductile materials under a compressive load, (c) fracture of brittle materials in compression, and (d) cracking on the barreled surface of ductile materials in compression.

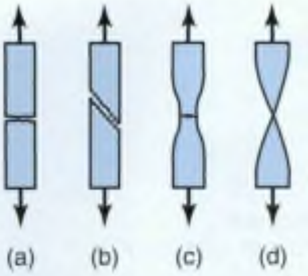


FIGURE 2.21 Schematic illustration of the types of fracture in tension: (a) brittle fracture in polycrystalline metals, (b) shear fracture in ductile single crystals—see also Fig. 1.6a, (c) ductile cup-and-cone fracture in polycrystalline metals, and (d) complete ductile fracture in polycrystalline metals, with 100% reduction of area.

Although failure of materials is generally regarded as undesirable, it should be noted that some products are designed in such a way that failure is essential for their functioning. Typical examples are (a) food and beverage containers with tabs or entire tops which are removed by tearing; (b) shear pins on shafts to prevent machinery damage in the case of overloads; (c) perforated sheet to ease tearing along a path; and (d) metal or plastic screw caps for beverage bottles.

2.10.1 Ductile Fracture

Ductile fracture is characterized by *plastic deformation*, which precedes failure (Fig. 2.20a). In a tension test, highly ductile materials such as gold and lead may neck down to a point before failing (Fig. 2.21d); most metals and alloys, however, neck down to a finite area and then fail. Ductile fracture generally takes place along planes on which the shear stress is a maximum. Thus, in torsion, for example, a ductile metal fractures along a plane perpendicular to the axis of twist; that is, the plane on which the shear stress is a maximum. Fracture in shear, by contrast, is a result of extensive slip along slip planes within the grains (see Fig. 1.7).

Close examination of the surface of ductile fracture (Fig. 2.22) shows a *fibrous* pattern with *dimples*, as if a number of very small tension tests have been carried out over the fracture surface. Failure is initiated with the formation of tiny *voids*, usually around small inclusions or pre-existing voids, which, in turn, *grow* and *coalesce*, developing into microcracks which then grow in size and eventually lead to fracture.

In a tension-test specimen, fracture begins at the center of the necked region resulting in the growth and coalescence of cavities (Fig. 2.23). The central region becomes one large crack, as can be seen in the midsection of the tension-test specimen in Fig. 2.23d; this crack then propagates to the periphery of the necked region and results in total failure. Because of its appearance, the fracture surface of a tension-test ductile specimen is called a **cup-and-cone fracture.**

Effects of Inclusions. Because they are nucleation sites for voids, *inclusions* have an important influence on ductile fracture and, consequently, on the workability of metals. Inclusions typically consist of impurities of various kinds and of second-phase particles, such as oxides, carbides, and sulfides. The extent of their influence depends on such factors as their shape, hardness, distribution, and their fraction of the total volume; the higher the volume fraction of inclusions, the lower will be the ductility of the material.

Voids and porosity can also develop during processing of metals, such as porosity in casting (Section 10.6.1), and metalworking processes such as drawing and extrusion, described in Chapter 15. Two factors affect void formation:

1. The strength of the bond at the interface between an inclusion and the matrix. If the bond is strong, there is less tendency for void formation during plastic deformation.
2. The hardness of the inclusion. If the inclusion is soft, such as manganese sulfide, it will conform to the overall shape change of the workpiece during plastic deformation. If the inclusion is hard, as, for example, in carbides and oxides (see also Section 8.2), it could lead to void formation (Fig. 2.24). Hard inclusions may also break up into smaller particles during plastic deformation, because of their brittle nature.

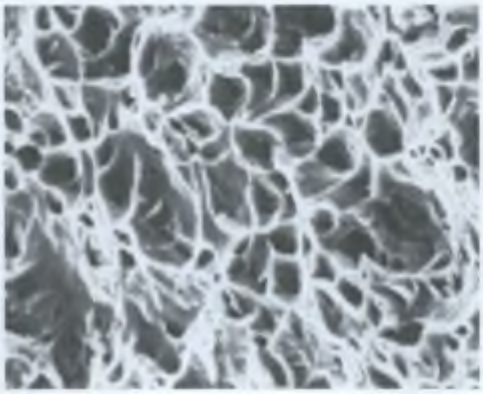


FIGURE 2.22 Surface of ductile fracture in low-carbon steel, showing dimples. Fracture is usually initiated at impurities, inclusions, or pre-existing voids (microporosity) in the metal. *Source:* Courtesy of K.-H. Habig and D. Klaffke.

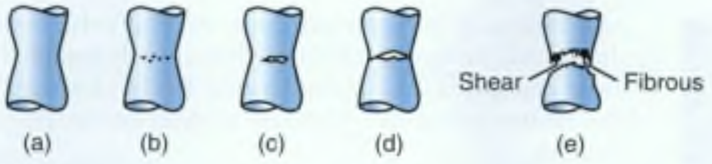


FIGURE 2.23 Sequence of events in the necking and fracture of a tensile-test specimen: (a) early stage of necking; (b) small voids begin to form within the necked region; (c) voids coalesce, producing an internal crack; (d) the rest of the cross-section begins to fail at the periphery, by shearing; and (e) the final fracture, known as a cup- (top fracture surface) and cone- (bottom surface) fracture, surfaces.

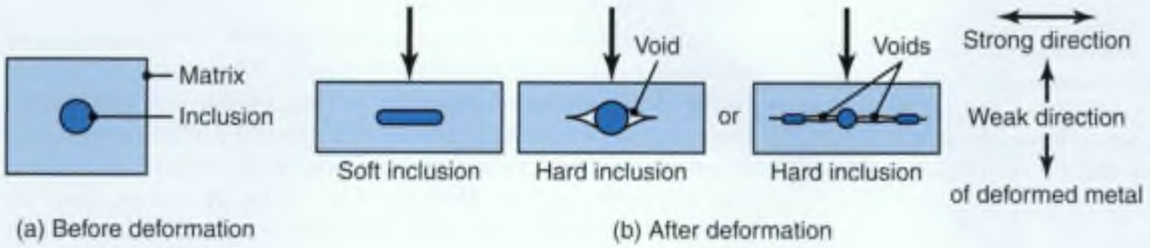


FIGURE 2.24 Schematic illustration of the deformation of soft and hard inclusions and of their effect on void formation in plastic deformation. Note that, because they do not conform to the overall deformation of the ductile matrix, hard inclusions can cause internal voids.

The alignment of inclusions during plastic deformation leads to **mechanical fibering** (Section 1.6). Subsequent processing of such a material must therefore involve considerations of the proper direction of working the material, in order to develop maximum ductility and strength.

Transition Temperature. Metals may undergo a sharp change in ductility and toughness across a narrow temperature range, called the *transition temperature* (Fig. 2.25). This phenomenon occurs mostly in body-centered cubic and in some hexagonal close-packed metals; it is rarely exhibited by face-centered cubic metals. The transition temperature depends on such factors as (a) the composition, microstructure, and grain size of the material, (b) surface finish and shape of the specimen, and (c) the deformation rate. High rates, abrupt changes in workpiece shape, and the presence of surface notches raise the transition temperature.

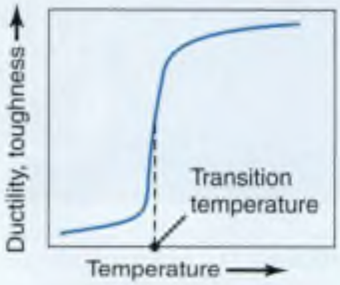


FIGURE 2.25 Schematic illustration of transition temperature in metals.

Strain Aging. *Strain aging* is a phenomenon in which carbon atoms in steels segregate to dislocations, thereby pinning the dislocations and, in this way, increasing the resistance to their movement; the result is increased strength and reduced ductility. Instead of taking place over several days at room temperature, strain aging can occur in just a few hours at a higher temperature; it is then called *accelerated strain aging*. An example of accelerated strain aging in steels is **blue brittleness**, so named because it occurs in the blue-heat range where the steel develops a bluish oxide film. Blue brittleness causes a significant decrease in ductility and toughness, and an increase in the strength of plain-carbon and some alloy steels.

2.10.2 Brittle Fracture

Brittle fracture occurs with little or no gross plastic deformation. In tension, fracture takes place along the crystallographic plane (**cleavage plane**) on which the normal tensile stress is a maximum. Face-centered cubic metals usually do not fail by brittle fracture, whereas body-centered cubic and some hexagonal close-packed metals fail by cleavage. In general, low temperature and a high rate of deformation promote brittle fracture.

In a polycrystalline metal under tension, the fracture surface has a bright granular appearance (unlike the fibrous appearance in ductile fracture) because of the changes in the direction of the cleavage planes as the crack propagates from one grain to another (Fig. 2.26). Brittle fracture in compression is more complex; fracture may even follow a path that is theoretically at an angle of 45° to the direction of the applied force.

Examples of fracture along a cleavage plane are the splitting of rock salt and the peeling of layers of mica. Tensile stresses normal to the cleavage plane, caused by pulling, initiate and control the propagation of fracture. Another example is the behavior of brittle materials, such as chalk, gray cast iron, and concrete; in tension, they fail in the manner shown in Fig. 2.21a; in torsion, they fail along a plane at an angle of 45° to the axis of twist (Fig. 2.10)—that is, along a plane on which the tensile stress is a maximum.

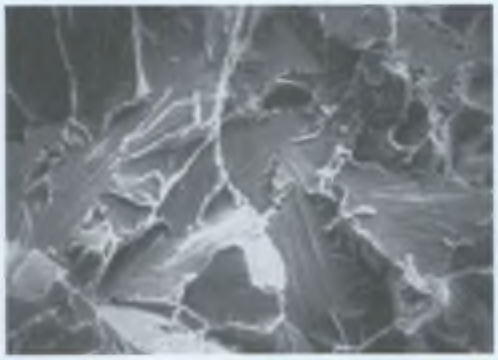


FIGURE 2.26 Fracture surface of steel that has failed in a brittle manner; the fracture path is transgranular (through the grains). Magnification: 200×. *Source:* Courtesy of B.J. Schulze and S.L. Meiley and Packer Engineering Associates, Inc.

Defects. An important factor in fracture is the presence of *defects*, such as scratches, flaws, and pre-existing external or internal cracks. Under tension, the sharp tip of a crack is subjected to high tensile stresses, which then lead the crack to propagate rapidly.

The presence of defects explains why brittle materials exhibit weakness in tension as compared with their strength in compression. (See Table 8.2.) For example, the ratio of compressive to tensile strength is on the order of 10 for rocks and similar materials, about 5 for glass, and about 3 for gray cast iron. Under tensile stresses, cracks propagate rapidly, causing what is known as *catastrophic failure*.

In polycrystalline metals, the fracture paths most commonly observed are **transgranular** (*transcrystalline* or *intragranular*); that is, the crack propagates through the grain. In **intergranular** fracture, the crack propagates along the grain boundaries (Fig. 2.27); it generally occurs when the grain boundaries are soft, contain a brittle phase, or they have been weakened by liquid- or solid-metal embrittlement (Section 1.5.2).

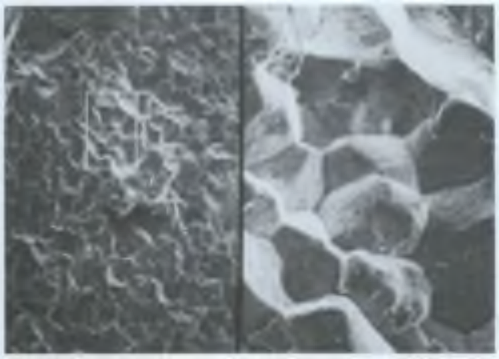


FIGURE 2.27 Intergranular fracture, at two different magnifications; grains and grain boundaries are clearly visible in this micrograph. The fracture path is along the grain boundaries. Magnification: left, 100×; right, 500×. *Source:* Courtesy of B.J. Schulze and S.L. Meiley and Packer Engineering Associates, Inc.

Fatigue Fracture. *Fatigue fracture* typically occurs in a brittle manner. Minute external or internal cracks develop at pre-existing flaws or defects in the material; these cracks then propagate over time and eventually lead to sudden and total failure of the part. The surface in fatigue fracture is generally characterized by the term **beach marks**, because of its appearance (Fig. 2.28). Under high magnification (typically more than 1000×), however, a series of **striations** can be seen on fracture surfaces, each beach mark consisting of several striations.

Improving Fatigue Strength. Fatigue life is greatly influenced by the method of preparation of the surfaces of the part (Fig. 2.29). The fatigue strength of manufactured products can be improved overall by the following methods:

1. Inducing compressive residual stresses on surfaces—for example, by shot peening or by roller burnishing (Section 34.2).
2. Case hardening (surface hardening) by various means (Section 4.10).
3. Providing a fine surface finish, thereby reducing the detrimental effects of notches and other surface imperfections.
4. Selecting appropriate materials and ensuring that they are free from significant amounts of inclusions, voids, and impurities.

FIGURE 2.28 Typical fatigue-fracture surface on metals, showing beach marks. Magnification: left, 500×; right, 1000×. *Source:* Courtesy of B.J. Schulze and S.L. Meiley and Packer Engineering Associates, Inc.

Conversely, the following factors and processes can *reduce* fatigue strength:

1. Tensile residual stresses on the surface
2. Decarburization
3. Surface pits (such as due to corrosion), that act as stress raiser
4. Hydrogen embrittlement
5. Galvanizing
6. Electroplating

Stress–corrosion Cracking. An otherwise ductile metal can fail in a brittle manner by *stress–corrosion cracking* (also called **stress cracking** or **season cracking**). Parts that are free from defects may develop cracks, either over time or even soon after being manufactured. Crack propagation may be either intergranular or transgranular. The susceptibility of metals to stress–corrosion cracking depends mainly on the material, the presence and magnitude of *tensile residual stresses*, and the environment (corrosive media such as salt water or chemicals).

Brass and austenitic stainless steels are among metals that are highly susceptible to stress cracking. The usual procedure to avoid stress–corrosion cracking is to *stress relieve* the part just after it is formed. Full annealing (Section 4.11) may also be done, but this treatment reduces the strength of cold-worked parts.

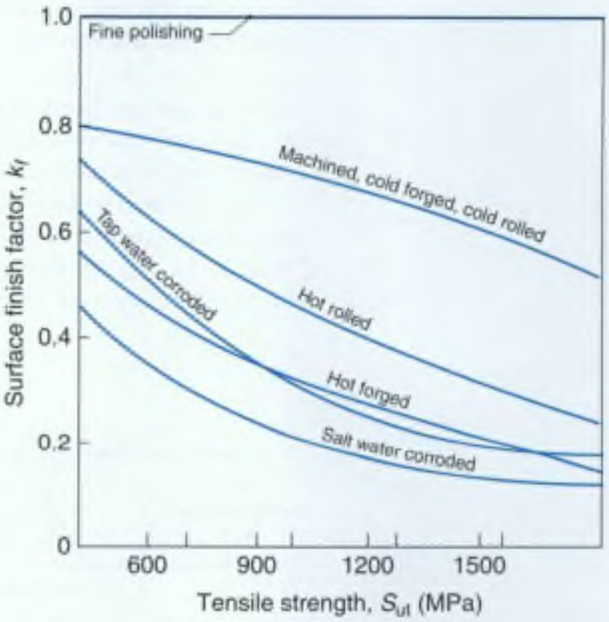


FIGURE 2.29 Reductions in the fatigue strength of cast steels subjected to various surface-finishing operations. Note that the reduction becomes greater as the surface roughness and the strength of the steel increase. *Source:* Reprinted by permission of CRC Press, Inc. *Fundamentals of Machine Elements*, 3rd edition by Schmidt, Hamrock and Jacobson; © 2013 Taylor & Francis LLC.

Hydrogen Embrittlement. The presence of hydrogen can reduce ductility and cause severe embrittlement and premature failure in metals, alloys, and nonmetallic materials. Called *hydrogen embrittlement*, this phenomenon is especially severe in high-strength steels. Possible sources of hydrogen arise during melting of the metal for casting, pickling (removing of surface oxides by chemical or electrochemical reaction), and electrolysis in electroplating. Other sources of hydrogen are water vapor in the atmosphere and moisture on electrodes and in fluxes used during welding. Oxygen can also cause embrittlement, particularly in copper alloys.

2.11 Residual Stresses

Residual stresses may develop when workpieces are subjected to plastic deformation that is not uniform throughout the part; these are stresses that remain within a part after it has been formed and all the external forces (applied through tools and dies) are removed. A typical example is the bending of a metal bar (Fig. 2.30). Note that the external bending moment first produces a linear elastic stress distribution (Fig. 2.30a); as the moment is increased, the outer fibers in the bar reach a stress level high enough to cause yielding. For a typical strain-hardening material, the stress distribution shown in Fig. 2.30b is eventually reached, and the bar has now undergone permanent bending.

Let's now remove the external bending moment on the bar. This operation is equivalent to applying an equal but opposite moment to the bar; thus, the moments of the areas *oab* and *oac* in Fig. 2.30c must be equal. Line *oc*, which represents the opposite bending moment, is linear, because all unloading and recovery are *elastic* (see Fig. 2.3). The difference between the two stress distributions gives the residual stress pattern within the bar, as shown in Fig. 2.30d.

Note the presence of compressive residual stresses in layers *ad* and *oe*, and tensile residual stresses in layers *do* and *ef*. Because there are now no external forces applied to the bar, the internal forces resulting from these residual stresses must be in static equilibrium. It should be noted that although this example involves residual stresses in the longitudinal direction of the bar only, in most cases residual stresses are three dimensional and hence more difficult to analyze.

The removal of a layer of material from the surfaces of the bar, such as by machining or grinding, will disturb the equilibrium of the residual stresses shown in Fig. 2.30d. The bar will then acquire a new radius of curvature in order to balance the internal forces. Such disturbances of residual stresses cause **warping** of parts (Fig. 2.31). The equilibrium of residual stresses may also be disturbed by *relaxation* of these stresses over a period of time; see below.

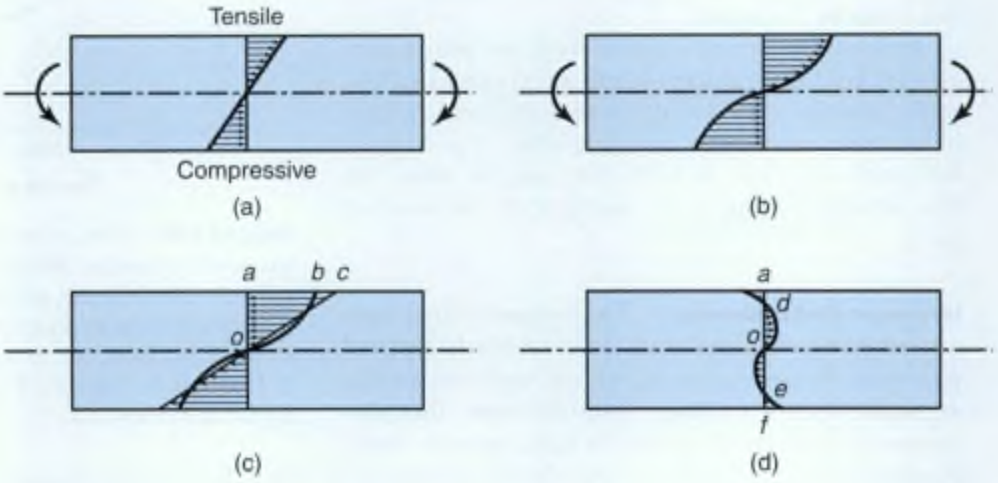


FIGURE 2.30 Residual stresses developed in bending a beam having a rectangular cross-section; note that the horizontal forces and moments caused by residual stresses in the beam must be balanced internally. Because of nonuniform deformation, especially during cold-metalworking operations, most parts develop residual stresses.

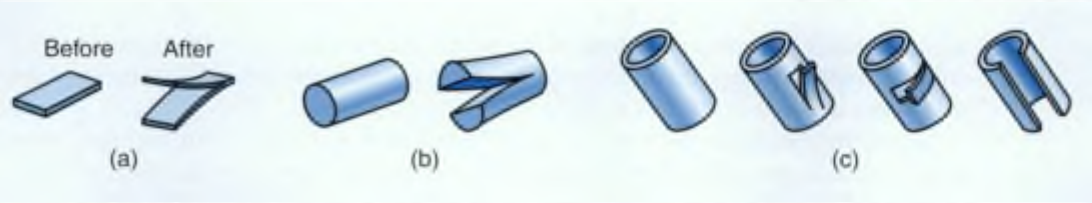


FIGURE 2.31 Distortion of parts with residual stresses after cutting or slitting: (a) flat sheet or plate, (b) solid round rod, and (c) thin-walled tubing or pipe.

Residual stresses can also be developed by *temperature gradients* within the part, such as occur during cooling of a casting or a hot forging. The local expansions and contractions caused by temperature gradients within the part will produce a nonuniform deformation, such as described in the permanent bending of a beam.

Tensile residual stresses on the surface of a part are generally undesirable, as they lower the fatigue life and fracture strength of the part. This is because a surface with tensile residual stresses cannot sustain additional tensile stresses (from external forces) as high as those that a surface free from residual stresses can. This reduction in strength is particularly characteristic of brittle or less ductile materials, in which fracture takes place with little or no plastic deformation preceding fracture.

Tensile residual stresses can also lead, over a period of time, to *stress cracking* or *stress–corrosion cracking* of parts (Section 2.10.2). Compressive residual stresses on a surface, on the other hand, are generally desirable. In fact, in order to increase the fatigue life of components, compressive residual stresses can be imparted to surfaces by such techniques as shot peening and surface rolling (Section 34.2).

Reduction and Elimination of Residual Stresses. Residual stresses can be reduced or eliminated either by *stress-relief annealing* (Section 4.11) or by a further *plastic deformation* of the part, such as stretching it. Given sufficient time, residual stresses may also diminish at room temperature, by *relaxation* of residual stresses. The time required for relaxation can be greatly reduced by raising the temperature of the workpiece.

2.12 Work, Heat, and Temperature

Almost all the mechanical work in plastic deformation is converted into **heat**. However, this conversion is not complete, because a portion of this work is stored within the deformed material as elastic energy, known as **stored energy** (Section 1.7). This is generally 5–10% of the total energy input; in some alloys, however, it may be as high as 30%.

In a simple frictionless deformation process, and assuming that the work is completely converted into heat, the theoretical (adiabatic) *temperature rise*, ΔT, in the workpiece is given by

$$\Delta T = \frac{u}{\rho c}, \tag{2.16}$$

where u is the **specific energy** (work of deformation per unit volume), ρ is the density, and c is the specific heat of the material. It can be seen that higher temperatures are associated with large areas under the stress–strain curve and with smaller values of specific heat. However, such physical properties as specific heat and thermal conductivity (Chapter 3) may themselves also depend on temperature; thus, they must be taken into account in the calculations.

The temperature rise for a true strain of 1 (such as occurs in a 27-mm-high specimen when it is compressed down to 10 mm) can be calculated to be: for aluminum, 75°C; copper, 140°C; low-carbon steel, 280°C; and titanium 570°C. In actual metalworking operations, heat is lost to the environment, to tools and dies, and to lubricants or coolants used, if any, in the process. If deformation is performed rapidly, the heat losses will be relatively small over that brief period; if, on the other hand, the process is carried out slowly, the actual temperature rise will be only a fraction of the calculated value.

SUMMARY

- Numerous manufacturing processes involve shaping materials by plastic deformation; consequently, such mechanical properties as strength (yield strength, Y, and ultimate tensile strength, UTS); modulus of elasticity, E; ductility (total elongation and reduction of area); hardness; and the energy required for plastic deformation are important factors. These properties depend, to various extents, on the particular material and on its condition, temperature, deformation rate, surface condition, and the environment.
- Because of its relative simplicity, the tensile test is the most commonly used to determine mechanical properties. From these tests, true stress–true strain curves are constructed that are needed to determine the strength coefficient (K), the strain-hardening exponent (n), the strain-rate sensitivity exponent (m), and the toughness of materials.
- Compression tests are subject to inaccuracy due to the presence of friction and to resulting barreling of the specimen. Torsion tests are conducted on tubular specimens and subjected to twisting. Bending or flexure tests are commonly used for brittle materials to determine their modulus of rupture or the transverse rupture strength.
- Several hardness tests may be used to determine the resistance of a material to permanent indentation or to scratching. Hardness is related to strength and wear resistance of a material, but it is not a fundamental property.
- Fatigue tests indicate the endurance limit or fatigue limit of materials—that is, the maximum stress to which a material can be subjected without fatigue failure, regardless of the number of cycles. Some materials have no endurance limit; their allowable stress must be reported with respect to the number of loading cycles.
- Creep is the permanent deformation of a component under a static load maintained for a period of time. In tension, the specimen eventually fails by rupture (necking and fracturing).
- Impact tests determine the energy required to completely break a specimen, called the impact toughness of the material. Impact tests are also useful for determining the transition temperature of materials.
- Failure and fracture constitute an important aspect of a material's behavior when it is subjected to deformation during metalworking operations. Ductile fracture

is characterized by plastic deformation preceding fracture, and it requires a considerable amount of energy. Brittle fracture can be catastrophic, because it is not preceded by plastic deformation; however, it requires much less energy than does ductile fracture. Impurities, inclusions, and voids play a major role in the fracture of materials.

- Residual stresses are those that remain in a workpiece after it has been plastically deformed and then has had all external forces removed. Surface tensile residual stresses are generally undesirable; they may be reduced or eliminated by stress-relief annealing, further plastic deformation, or by relaxation over a period of time.

KEY TERMS

Bauschinger effect
Blue brittleness
Brittle fracture
Buckling
Charpy test
Compression
Creep
Defects
Deformation rate
Disk test
Ductile fracture
Ductility
Durometer
Elongation
Engineering strain
Engineering stress
Fatigue
Fatigue failure
Flexural strength
Fracture
Hardness
Impact loading
Inclusions
Izod test
Leeb test
Microhardness
Modulus of elasticity
Modulus of rigidity
Modulus of rupture
Poisson's ratio
Reduction of area
Residual stresses
Rupture
Shear
Shear modulus
Shore test
Strain aging
Strain-hardening exponent
Strain rate
Strain-rate sensitivity exponent
Strain softening
Strength coefficient
Stress–corrosion cracking
Stress relaxation
Superplasticity
Tension
Torsion test
Toughness
Transition temperature
True strain
True stress
Ultimate tensile strength
Yield stress

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REVIEW QUESTIONS

2.1 Distinguish between engineering stress and true stress.

2.2 In a stress–strain curve, what is the proportional limit? Is it different than the yield point?

2.3 Describe the events that take place when a specimen undergoes a tension test. Sketch a plausible stress–strain curve, and identify all significant regions and points between them. Assume that loading continues up to fracture.

2.4 What is ductility, and how is it measured?

2.5 In the equation $\sigma = K\epsilon^n$, which represents the true stress–strain curve for a material, what is the significance of the exponent n?

2.6 What is strain-rate sensitivity, and how is it measured?

2.7 What test can measure the properties of a material undergoing shear strain?

2.8 What testing procedures can be used to measure the properties of brittle materials, such as ceramics and carbides?

2.9 Describe the differences between brittle and ductile fracture.

2.10 What is hardness? Explain.

2.11 Describe the features of a Rockwell hardness test.

2.12 What is a Leeb test? How is it different from a Rockwell A test?

2.13 Differentiate between stress relaxation and creep.

2.14 Describe the difference between elastic and plastic behavior.

2.15 Explain what uniform elongation means in tension testing.

2.16 Describe the difference between deformation rate and strain rate. What unit does each one have?

2.17 Describe the difficulties involved in conducting a compression test.

2.18 What is Hooke's law? Young's modulus? Poisson's ratio?

2.19 Describe the difference between transgranular and intergranular fracture.

2.20 What is the reason that yield strength is generally defined as a 0.2% offset strength?

2.21 Why does the fatigue strength of a specimen or part depend on its surface finish?

2.22 If striations are observed under microscopic examination of a fracture surface, what do they suggest regarding the mode of fracture?

2.23 What is an Izod test? Why are Izod tests useful?

2.24 Why does temperature increase during plastic deformation?

2.25 What is residual stress? How can residual stresses be removed?

QUALITATIVE PROBLEMS

2.26 On the same scale for stress, the tensile true stress–true strain curve is higher than the engineering stress–engineering strain curve. Explain whether this condition also holds for a compression test.

2.27 What are the similarities and differences between deformation and strain?

2.28 Can a material have a negative Poisson's ratio? Give a rationale for your answer.

2.29 It has been stated that the higher the value of m, the more diffuse the neck is, and likewise, the lower the value of m, the more localized the neck is. Explain the reason for this behavior.

2.30 Explain why materials with high m values, such as hot glass and Silly Putty®, when stretched slowly, undergo large elongations before failure. Consider events taking place in the necked region of the specimen.

2.31 With a simple sketch, explain whether it is necessary to use the offset method to determine the yield stress, Y, of a material that has been highly cold worked.

2.32 Explain why the difference between engineering strain and true strain becomes larger as strain increases. Does this difference occur for both tensile and compressive strains? Explain.

2.33 Consider an elastomer, such as a rubber band. This material can undergo a large elastic deformation before failure, but after fracture it recovers completely to its original shape. Is this material brittle or ductile? Explain.

2.34 If a material (such as aluminum) does not have an endurance limit, how then would you estimate its fatigue life?

2.35 What role, if any, does friction play in a hardness test? Explain.

2.36 Which hardness tests and scales would you use for very thin strips of metal, such as aluminum foil? Explain.

2.37 Consider the circumstance where a Vickers hardness test is conducted on a material. Sketch the resulting indentation shape if there is a residual stress on the surface.

2.38 Which of the two tests, tension or compression, would require a higher capacity of testing machine, and why?

2.39 List and explain briefly the conditions that induce brittle fracture in an otherwise ductile metal.

2.40 List the factors that you would consider in selecting a hardness test. Explain why.

2.41 On the basis of Fig. 2.5, can you calculate the percent elongation of the materials listed? Explain.

2.42 If a metal tension-test specimen is rapidly pulled and broken, where would the temperature be highest, and why?

2.43 Comment on your observations regarding the contents of Table 2.2.

2.44 Will the disk test be applicable to a ductile material? Why or why not?

2.45 What hardness test is suitable for determining the hardness of a thin ceramic coating on a piece of metal?

2.46 Wire rope consists of many wires that bend and unbend as the rope is run over a sheave. A wire-rope failure is investigated, and it is found that some of the wires, when examined under a scanning electron microscope, display cup-and-cone failure surfaces, while others display transgranular fracture surfaces. Comment on these observations.

2.47 A statistical sampling of Rockwell C hardness tests are conducted on a material, and it is determined that the material is defective because of insufficient hardness. The supplier claims that the tests are flawed because the diamond-cone indenter was probably dull. Is this a valid claim? Explain.

2.48 In a Brinell hardness test, the resulting impression is found to be elliptical. Give possible explanations for this result.

2.49 Some coatings are extremely thin—some as thin as a few nanometers. Explain why even the Knoop test is not able to give reliable results for such coatings. Recent investigations have attempted to use highly polished diamonds (with a tip radius around 5 nm) to indent such coatings in atomic force microscopes. What concerns would you have regarding the appropriateness of the test results?

2.50 Select an appropriate hardness test for each of the following materials, and justify your answer:

- **a.** Cubic boron nitride
- **b.** Lead
- **c.** Cold-drawn 0.5%C steel
- **d.** Diamond
- **e.** Caramel candy
- **f.** Granite

QUANTITATIVE PROBLEMS

2.51 A paper clip is made of wire 0.5 mm in diameter. If the original material from which the wire is made is a rod 25 mm in diameter, calculate the longitudinal engineering and true strains that the wire has undergone during processing.

2.52 A 250-mm-long strip of metal is stretched in two steps, first to 300 mm and then to 400 mm. Show that the total true strain is the sum of the true strains in each step; in other words, the true strains are additive. Show that, in the case of engineering strains, the strains cannot be added to obtain the total strain.

2.53 Identify the two materials in Fig. 2.5 that have the lowest and the highest uniform elongations. Calculate these quantities as percentages of the original gage lengths.

2.54 Plot the ultimate strength vs. stiffness for the materials listed in Table 2.2, and prepare a three-dimensional plot for these materials where the third axis is their maximum elongation in 50 mm.

2.55 If you remove the layer of material *ad* from the part shown in Fig. 2.30d (for instance, by machining or grinding), which way will the specimen curve? (*Hint:* Assume that the part shown in sketch *d* in the figure is composed of four horizontal springs held at the ends. Thus, from the top down, you have compression, tension, compression, and tension springs.)

2.56 Prove that the true strain at necking equals the strain hardening exponent.

2.57 Percent elongation is always defined in terms of the original gage length, such as 50 mm. Explain how percent elongation would vary as the gage length of the tensile-test specimen increases. (*Hint:* Recall that necking is a *local* phenomenon.)

2.58 Make a sketch showing the nature and distribution of residual stresses in Fig. 2.31a and b, prior to the material's being cut. (*Hint:* Assume that the split parts are free from any stresses; then force these parts back to the shape they originally had.)

2.59 You are given the K and n values of two different metals. Is this information sufficient to determine which metal is tougher? If not, what additional information do you need?

2.60 A cable is made of two strands of different materials, A and B, and cross-sections, as follows:

$$\text{For material } A,\ K = 415 \text{ MPa},\ n = 0.5,\ A_o = 380 \text{ mm}^2;$$

$$\text{For material } B,\ K = 210 \text{ MPa},\ n = 0.5,\ A_o = 190 \text{ mm}^2.$$

Calculate the maximum tensile force that this cable can withstand prior to necking.

2.61 On the basis of the information given in Fig. 2.5, calculate the ultimate tensile strength (engineering) of 304 stainless steel.

2.62 In a disk test performed on a specimen 25 mm in diameter and 6 mm thick, the specimen fractures at a stress of 275 MPa. What was the load on it?

2.63 A piece of steel has a hardness of 300 HB. Calculate its tensile strength, in MPa and in psi.

2.64 A metal has the following properties: UTS = 480 MPa and $n = 0.20$. Calculate its strength coefficient, K.

2.65 Using only Fig. 2.5, calculate the maximum load in tension testing of an annealed copper specimen with an original diameter of 5 mm.

2.66 Estimate the modulus of resilience for a highly cold worked piece of steel having a hardness of 250 HB, and for a piece of highly cold-worked copper with a hardness of 100 HRB.

2.67 A metal has a strength coefficient $K = 690$ MPa and $n = 0.25$. Assuming that a tensile-test specimen made from this metal begins to neck at a true strain of 0.25, show that the ultimate tensile strength is 409 MPa.

2.68 Plot the true stress–true strain curves for the materials listed in Table 2.3.

2.69 The design specification for a metal requires a minimum hardness of 80 HRA. If a Rockwell test is performed and the depth of penetration is 60 μm, is the material acceptable?

2.70 Calculate the major and minor pyramid angles for a Knoop indenter, and compare your results with those obtained from Vickers and Rockwell A indenters.

2.71 If a material has a target hardness of 300 HB, what is the expected indentation diameter?

2.72 A Rockwell A test was conducted on a material and a penetration depth of 0.15 mm was recorded. What is the hardness of the material? What material would typically have such a hardness value? If a Brinell hardness test were to be conducted on this material, give an estimate of the indentation diameter if the load used was 1500 kg.

2.73 For a cold-drawn 0.5% carbon steel, will a Rockwell C test or a Brinell test at 500 kg result in a deeper penetration?

2.74 A material is tested in tension. Over a 25-mm. gage length, the engineering strain measurements are 0.01, 0.02, 0.03, 0.04, 0.05, 0.1, 0.15, 0.2, 0.5, and 1.0. Plot the true strain versus engineering strain for these readings.

2.75 A horizontal rigid bar *c–c* is subjecting specimen *a* to tension and specimen *b* to frictionless compression such that the bar remains horizontal. (See Fig. P2.75.) The force *F* is located at a distance ratio of 2:1. Both specimens have an original cross-sectional area of 645 mm^2 and the original lengths are $a = 203$ mm. and $b = 114$ mm. The material for specimen *a* has a true stress–true strain curve of $\sigma = 100{,}000\epsilon^{0.5}$. Plot the true stress–true strain curve that the material for specimen *b* should have for the bar to remain horizontal.

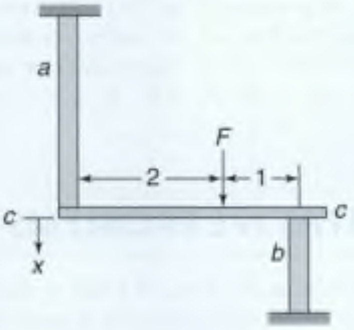

FIGURE P2.75

SYNTHESIS, DESIGN, AND PROJECTS

2.76 List and explain the desirable mechanical properties of (a) an elevator cable, (b) a paper clip, (c) a leaf spring for a truck, (d) a bracket for a bookshelf, (e) piano wire, (f) a wire coat hanger, (g) the clip for a pen, and (h) a staple.

2.77 When making a hamburger, you may have observed the type of cracks shown in Fig. 2.20d. What would you do to avoid such cracks? [*Note:* Test hamburger patties by compressing them at different temperatures, and observe the crack path (i.e., the path through the fat particles, the meat particles, or their interface).]

2.78 An inexpensive claylike material called Silly Putty is generally available in stores that sell toys and games. Obtain a sample and perform the following experiments: (a) Shape it into a ball, and drop it onto a flat surface. (b) Reround the ball and place a heavy book on it for one minute. (c) Shape the putty into a long rod, and pull on it—first slowly, then very quickly. Describe your observations, referring to the specific sections in this chapter where each particular observation is relevant.

2.79 Make individual sketches of the mechanisms of testing machines that, in your opinion, would be appropriate for tension, for torsion, and for compression testing of specimens at different rates of deformation. What modifications would you make on these machines to include the effects of temperature on material properties?

2.80 In tension testing of specimens, mechanical and electronic instruments are typically used to measure elongation. Make sketches of instruments that would be suitable for this purpose, commenting on their accuracy. What modifications would you make to these instruments to include the use of specimens at elevated temperatures?

2.81 Obtain small pieces of different metallic and nonmetallic materials, including stones. Rub them against each other, observe the scratches made, and order them in a manner similar to the Mohs hardness numbering system.

2.82 Demonstrate the stress-relaxation phenomenon by tightly stretching thin plastic strings between two nails placed at the ends of a long piece of wood. Pluck the strings frequently, to test the tension as a function of time. Repeat the test at a higher temperature by placing the fixture in an oven set on low.

2.83 Demonstrate the impact toughness of a piece of round chalk by first using a triangular file to produce a V-notch on the cylindrical surface (as shown in Fig. 2.19a) and then bending the chalk to break it.

2.84 Using a large rubber band and a set of weights, obtain the force–displacement curve for the rubber band. Is the result different from the stress–strain curves shown in Fig. 2.4? Comment.

2.85 Design a test protocol to obtain the work of plastic deformation by measuring the temperature rise in a workpiece, assuming that there is no heat loss and that the temperature distribution is uniform throughout. If the specific heat of the material decreases with increasing temperature, will the work of deformation calculated using the specific heat at room temperature be higher or lower than the actual work done? Explain.

2.86 Find or prepare some solid circular pieces of brittle materials, such as chalk, ceramics, etc. and subject them to the type of test shown in Fig. 2.9 by using the jaws of a simple vise. Describe your observations as to how the materials fracture. Repeat the tests, using ductile materials, such as clay, soft metals, etc., and describe your observations.

2.87 Take several rubber bands and pull them at different temperatures, including from a frozen state. Comment on their behavior, such as ductile or brittle.

2.88 Devise a simple fixture for conducting the bend tests shown in Fig. 2.11. Test sticks of various brittle materials by loading them with dead weights until they break. Verify the statement in the text that the specimens on the right in the figure will fracture sooner than the ones on the left.

2.89 By pressing a small ball bearing against the top surfaces of various materials, such as clay and dough, observe the shape of the indentation with a magnifier, referring to those shapes shown in Fig. 2.14a and b.

2.90 Describe your observations regarding Fig. 2.14c.

2.91 Embed a small steel ball in a soft block of material such as clay, and compress the clay as shown in Fig. 2.24a. Then slice the clay carefully along the center plane and observe the deformation of the material. Repeat the experiment by embedding a small round jelly bean in the clay and deforming the material. Comment on your observations.

2.92 Devise a simple experiment, and perform tests on materials commonly found around the house by bending them at different temperatures, for a qualitative assessment of their transition temperature, as shown in Fig. 2.25.

2.93 Obtain some solid and some tubular metal pieces, and slit them as shown in Fig. 2.31. Comment on whether there were any residual stresses in the parts prior to slitting them.

2.94 Explain how you would obtain an estimate of the hardness for a carbon nanotube. (See Section 8.6.2.)

2.95 Without using the words "stress" or "strain," define elastic modulus.

2.96 We know that it is relatively easy to subject a specimen to hydrostatic compression, such as by using a chamber filled with a liquid. Devise a means whereby the specimen (say, in the shape of a cube or a round disk) can be subjected to hydrostatic tension, or one approaching this state of stress. (Note that a thin-walled, internally pressurized spherical shell is not a correct answer, because it is subjected only to a state of plane stress.)

CHAPTER

3 Physical Properties of Materials

- Physical properties can have several significant roles in the selection, processing, and use of materials. They can be key factors in determining a material's suitability for specific applications, especially when considered simultaneously with mechanical properties.
- Strength-to-weight and stiffness-to-weight ratios, as examples, are discussed in the context of lightweight design, an important consideration in aerospace and automotive industries.
- Thermal, electrical, magnetic, and optical properties are then presented.
- The importance of corrosion and corrosion-resistant materials are described.
- Design and manufacturing implications of all physical properties are considered, with various specific examples given.

3.1 Introduction

Why is electrical wiring generally made of copper? Why are aluminum, stainless steel, and copper commonly used in cookware? Why are the handles of cookware usually made of wood or plastic, while other types of handles are made of metal? What type of material should be chosen for the heating elements in toasters? Why does aluminum feel colder to the touch than plastic, when both are at room temperature? Why are the metallic components in some machines being replaced with ceramics? Why are commercial airplane bodies generally made of aluminum, and why are some now being replaced gradually with various composite materials, including reinforced plastics?

It is apparent from these questions that an important criterion in material selection is consideration of **physical properties**, such as density, melting point, specific heat, thermal conductivity, thermal expansion, electrical and magnetic properties, and resistance to oxidation and corrosion. Combinations of mechanical and physical properties, such as the strength-to-weight and stiffness-to-weight ratios of materials, are equally important, particularly for aircraft and aerospace structures. Also, high-speed equipment, such as textile and printing machinery, and forming and cutting machines for high-speed operations, require lightweight components to reduce inertial forces, and thus prevent the machines from being subjected to excessive vibration. Several other examples of the importance of physical properties are described in this chapter.

3.2 Density

The **density** of a material is its mass per unit volume. Another term is **specific gravity**, which expresses a material's density relative to that of water, therefore specific gravity has no units. The range of densities for a variety of materials at room temperature, along with other properties, is given in Tables 3.1 and 3.2.

Weight saving is particularly important for aircraft and aerospace structures, automotive bodies and components, and for various other products where energy

TABLE 3.1

Physical Properties of Selected Materials at Room Temperature

Material	Density (kg/m^3)	Melting point (°C)	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)	Coefficient of thermal expansion (μm/m-°C)	Electrical resistivity (Ω-m)
Metallic						
Aluminum	2700	660	900	222	23.6	2.8×10^{-8}
Aluminum alloys	2630–2820	476–654	880–920	121–239	23.0–23.6	$2.8\text{–}4.0 \times 10^{-8}$
Beryllium	1854	1278	1884	146	8.5	4.0×10^{-8}
Niobium(columbium)	8580	2468	272	52	7.1	15×10^{-8}
Copper	8970	1082	385	393	16.5	1.7×10^{-8}
Copper alloys	7470–8940	885–1260	377–435	219–234	16.5–20	$1.7\text{–}5.9 \times 10^{-8}$
Gold	19,300	1063	129	317	19.3	2.4×10^{-8}
Iron	7860	1537	460	74	11.5	9.5×10^{-8}
Lead	11,350	327	130	35	29.4	20.6×10^{-8}
Lead alloys	8850–11,350	182–326	126–188	24–46	27.1–31.1	$20.6\text{–}24 \times 10^{-8}$
Magnesium	1745	650	1025	154	26.0	4.5×10^{-8}
Magnesium alloys	1770	610–621	1046	75–138	26.0	$4.5\text{–}15.9 \times 10^{-8}$
Molybdenum alloys	10,210	2610	276	142	5.1	5.3×10^{-8}
Nickel	8910	1453	440	92	13.3	6.2×10^{-8}
Nickel alloys	7750–8850	1110–1454	381–544	12–63	12.7–18.4	$6.2\text{–}110 \times 10^{-8}$
Platinum	2145	1768	133	71.6	8.8	10.5×10^{-8}
Silicon	2330	1423	712	148	7.63	1.0×10^{-3}
Silver	10,500	961	235	429	19.3	1.6×10^{-8}
Steels	6920–9130	1371–1532	448–502	15–52	11.7–17.3	17.0×10^{-8}
Tantalum alloys	16,600	2996	142	54	6.5	13.5×10^{-8}
Tin	7310	232	217	67	22	11.5×10^{-8}
Titanium	4510	1668	519	17	8.35	42×10^{-8}
Titanium alloys	4430–4700	1549–1649	502–544	8–12	8.1–9.5	$40\text{–}171 \times 10^{-8}$
Tungsten	19,290	3410	138	166	4.5	5.0×10^{-8}
Zinc	7140	419	385	113	32.5	5.45×10^{-8}
Zinc alloys	6640–7200	386–525	402	105–113	32.5–35	$6.06\text{–}6.89 \times 10^{-8}$
Nonmetallic						
Ceramics	2300–5500	—	750–950	10–17	5.5–13.5	—
Glasses	2400–2700	580–1540	500–850	0.6–1.7	4.6–70	—
Graphite	1900–2200	—	840	5–10	7.86	—
Plastics	900–2000	110–330	1000–2000	0.1–0.4	72–200	—
Wood	400–700	—	2400–2800	0.1–0.4	2–60	—

TABLE 3.2

Physical Properties of Materials (in Descending Order)

Density	Melting point	Specific heat	Thermal conductivity	Thermal expansion	Electrical conductivity
Platinum	Tungsten	Wood	Silver	Plastics	Silver
Gold	Tantalum	Beryllium	Copper	Lead	Copper
Tungsten	Molybdenum	Porcelain	Gold	Tin	Gold
Tantalum	Niobium	Aluminum	Aluminum	Magnesium	Aluminum
Lead	Titanium	Graphite	Magnesium	Aluminum	Magnesium
Silver	Iron	Glass	Graphite	Copper	Tungsten
Molybdenum	Beryllium	Titanium	Tungsten	Steel	Beryllium
Copper	Copper	Iron	Beryllium	Gold	Steel
Steel	Gold	Copper	Zinc	Ceramics	Tin
Titanium	Silver	Molybdenum	Steel	Glass	Graphite
Aluminum	Aluminum	Tungsten	Tantalum	Tungsten	Ceramics
Beryllium	Magnesium	Lead	Ceramics		Glass
Glass	Lead		Titanium		Plastics
Magnesium	Tin		Glass		Quartz
Plastics	Plastics		Plastics		

consumption and power limitations are major concerns. Substitution of materials for weight savings and economy is a major factor in the design of advanced equipment and machinery and consumer products, such as automobiles, aircraft, sporting goods, laptop computers, and bicycles.

A significant role that density plays is in the **strength-to-weight ratio (specific strength)** and **stiffness-to-weight ratio (specific stiffness)** of materials. Figure 3.1 shows the ratio of maximum yield stress to density for a variety of metal alloys.

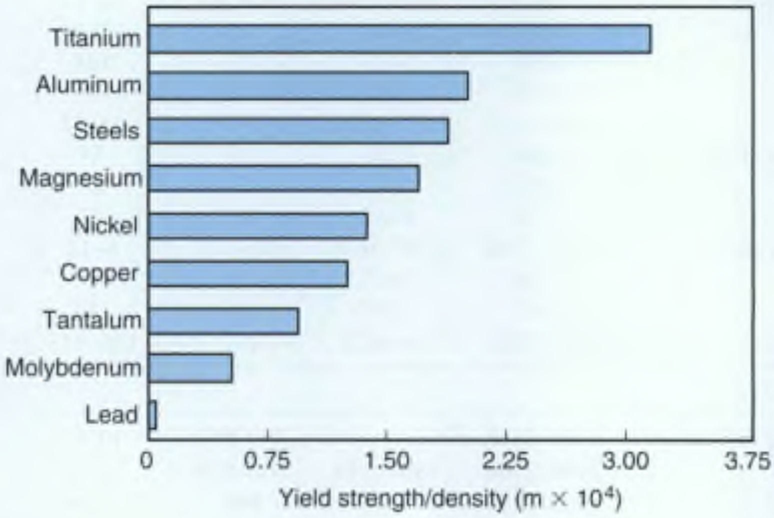

FIGURE 3.1 Ratio of maximum yield stress to density for selected metal alloys.

Note that titanium and aluminum are at the top of the list; consequently, and as described in Chapter 6, they are among the most commonly used metals for various applications.

The specific tensile strength and specific stiffness at room temperature for a variety of metallic and nonmetallic materials is given in Fig. 3.2. Note the positions of composite materials, as compared with those of metals, with respect to these properties; these advantages have led composites to become among the most important materials, as described in Chapter 9. At elevated temperatures, specific strength and specific stiffness are likewise important considerations, especially for components operating at these temperatures, such as automotive and jet engines, gas turbines, and furnaces. Typical ranges for a variety of materials as a function of temperature are given in Fig. 3.3.

Density is also an important factor in the selection of materials for high-speed equipment, such as magnesium in printing and textile machinery, many components of which typically operate at very high speeds. To obtain exposure times of 1/4000 s in cameras without sacrificing accuracy, the focal plane shutters of some high-quality digital cameras are made of titanium. Aluminum is used with some digital cameras for better performance in cold weather. Because of their low density, ceramics (Chapter 8) are being used for components in high-speed automated machinery and in machine tools.

On the other hand, there are applications where weight is desirable. Examples are counterweights for various mechanisms (using lead or steel), flywheels, ballasts on yachts and aircraft, and weights on golf clubs (using high-density materials such as tungsten).

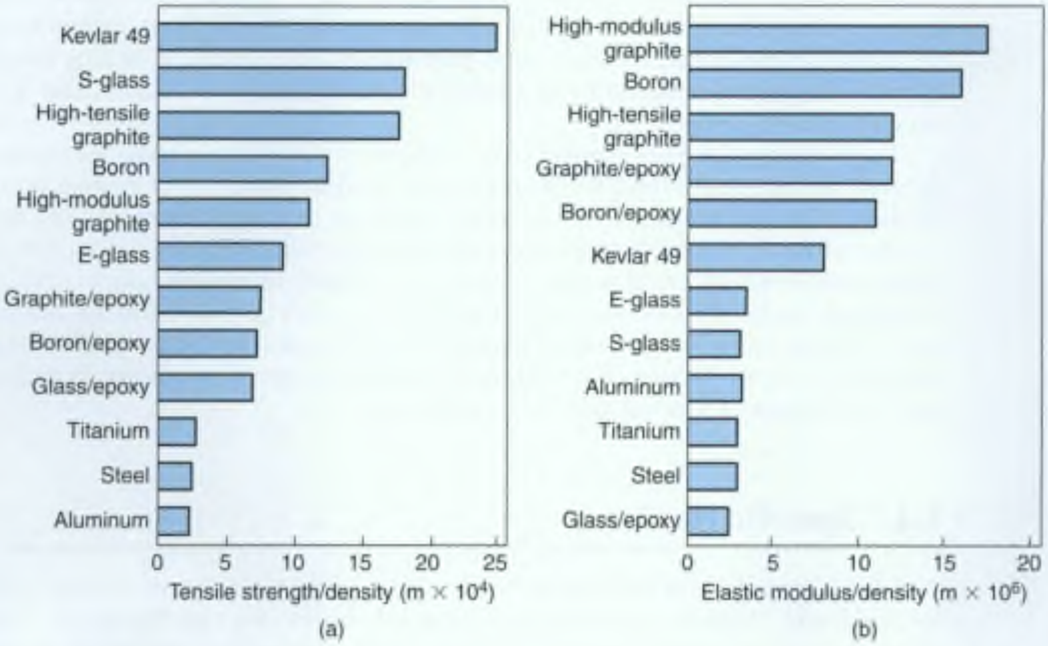

FIGURE 3.2 Specific strength (tensile strength/density) and specific stiffness (elastic modulus/density) for various materials at room temperature. (See also Chapter 9.)

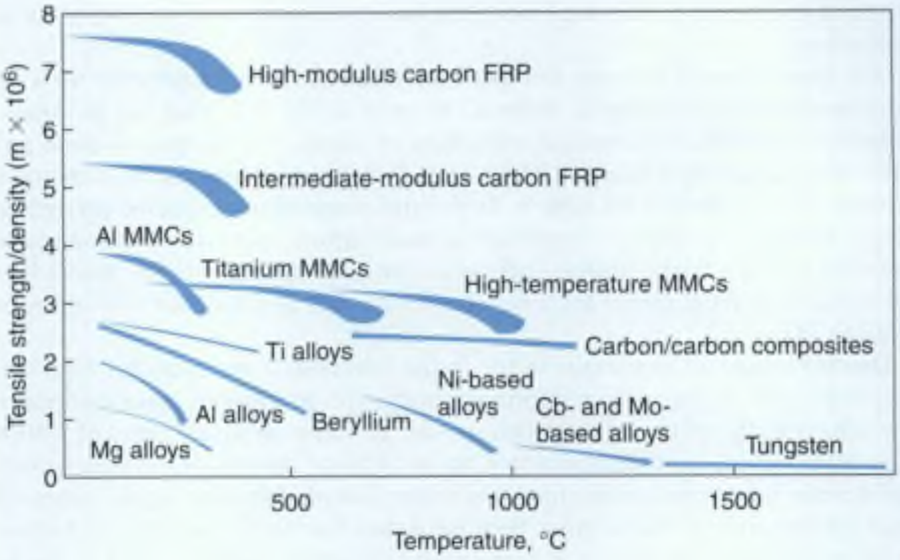

FIGURE 3.3 Specific strength (tensile strength/density) for a variety of materials as a function of temperature; note the useful temperature range for these materials and the high values for composite materials. MMC = metal-matrix composite; FRP = fiber-reinforced plastic.

3.3 Melting Point

The temperature range within which a component or structure is designed to function is an important consideration in the selection of materials. Plastics, for example, have the lowest useful temperature range, while graphite and refractory-metal alloys have the highest useful range. Note also that pure metals have a definite melting point, whereas the melting temperature of a metal alloy can have a wide range (Table 3.1) depending on its composition.

The melting point has a number of indirect effects on manufacturing operations. Because the recrystallization temperature of a metal is related to its melting point (Section 1.7), operations such as annealing and heat treating (Chapter 4) and hot working (Part III) require a knowledge of the melting points of the materials involved. These considerations are also important in the selection of tool and die materials. Melting point also plays a major role in the selection of the equipment and the melting practice employed in metal-casting operations (Part II) and in the electrical-discharge machining process (Section 27.5), where the melting points of metals are related to the rate of material removal and of electrode wear.

3.4 Specific Heat

A material's **specific heat** is the energy required to raise the temperature of a unit mass by one degree. Alloying elements have a relatively minor effect on the specific heat of metals. The temperature rise in a workpiece, such as those resulting from forming or machining operations (Parts III and IV, respectively), is a function of the work done and of the specific heat of the workpiece material (Section 2.12). An excessive temperature rise in a workpiece can

a. Decrease product quality by adversely affecting its surface finish and dimensional accuracy
b. Cause excessive tool and die wear
c. Result in undesirable metallurgical changes in the material

3.5 Thermal Conductivity

Thermal conductivity indicates the rate at which heat flows within and through a material. Metallically bonded materials (metals) generally have high thermal conductivity, while ionically or covalently bonded materials (ceramics and plastics) have poor conductivity (Table 3.2). Alloying elements can have a significant effect on the thermal conductivity of alloys, as can be seen by comparing pure metals with their alloys in Table 3.1. In general, materials with high electrical conductivity also have high thermal conductivity.

Thermal conductivity is an important consideration in many applications. For example, high thermal conductivity is desirable in cooling fins, cutting tools, and die-casting molds, to extract heat faster. In contrast, materials with low thermal conductivity are used, for instance, in furnace linings, insulation, coffee cups, and handles for pots and pans. One function of a lubricant in hot metalworking is to serve as an insulator to keep the workpiece hot and thus formable.

Video Solution 3.1 Selection of Materials for Thermal Insulation

3.6 Thermal Expansion

The **thermal expansion** of materials can have several significant effects, particularly the relative expansion or contraction of different materials in assemblies, such as electronic and computer components, glass-to-metal seals, struts on jet engines, coatings on cutting tools (Section 22.5), and moving parts in machinery that require certain clearances for proper functioning. The use of ceramic components in cast-iron engines, for example, also requires consideration of their relative expansion during their operation. *Shrink fits* utilize thermal expansion and contraction; a shrink fit is a part, often a sleeve or a hub, that is to be installed over a shaft. The part is first heated and then slipped over the shaft or spindle; when allowed to cool, the hub shrinks and the assembly becomes an integral component.

Typical coefficients of thermal expansion are given in Table 3.1 (see also *Invar* below). Generally, the coefficient of thermal expansion is inversely proportional to the melting point of the material. Alloying elements have a relatively minor effect on the thermal expansion of metals.

Thermal expansion, in conjunction with thermal conductivity, plays the most significant role in the development of **thermal stresses** (due to *temperature gradients*), both in manufactured components and in tools and dies, and molds for casting operations. This consideration is particularly important in, for example, a forging operation during which hot workpieces are repeatedly placed over a relatively cool die, thus subjecting the die surfaces to thermal cycling. To reduce thermal stresses, a combination of high thermal conductivity and low thermal expansion is desirable. Thermal stresses can also be caused by **anisotropy of thermal expansion**; that is, the material expands differently in different directions. This property is generally observed in hexagonal close-packed metals, ceramics, and composite materials.

Thermal expansion and contraction can lead to cracking, warping, or loosening of components during their service life, as well as cracking of ceramic parts and in tools and dies made of relatively brittle materials. **Thermal fatigue** results from thermal cycling and causes a number of surface cracks, especially in tools and dies for casting and metalworking operations (*heat checking*). **Thermal shock** is the term generally used to describe development of a crack or cracks after being subjected to a single thermal cycle.

To alleviate some of the problems caused by thermal expansion, a family of iron–nickel alloys with very low thermal expansion coefficients are available, called **low-expansion alloys**. The low thermal-expansion characteristic of these alloys is often referred to as the **Invar effect**, after the metal *Invar*. Their thermal coefficient of expansion is generally in the range of 2×10^{-6} to 9×10^{-6} per °C (compare with those given in Table 3.1). Typical compositions are 64% Fe–36% Ni for Invar and 54% Fe–28% Ni–18% Co for Kovar.

Low-expansion alloys also have good thermal-fatigue resistance, and because of their good ductility, they can easily be formed into various shapes. Applications include (a) bimetallic strips, consisting of a low-expansion alloy metallurgically bonded to a high-expansion alloy (the strip bends when subjected to temperature variations) and (b) glass-to-metal seals, in which the thermal expansions of the two materials are matched.

3.7 Electrical, Magnetic, and Optical Properties

Electrical conductivity and the *dielectric* properties of materials are important not only in electrical equipment and machinery but also in such manufacturing processes as magnetic-pulse forming (Section 16.12), resistance welding (Section 31.5), and the electrical-discharge machining and electrochemical grinding of hard and brittle materials (Chapter 27). The units of electrical conductivity are mho/m, where mho is the reverse of ohm, the unit of electrical resistance. Alloying elements have a major effect on the electrical conductivity of metals; the higher the conductivity of the alloying element, the higher is the electrical conductivity of the alloy.

Dielectric Strength. An electrically insulating material's *dielectric strength* is the largest electric field to which it can be subjected without degrading or losing its insulating properties. This property is defined as the voltage required per unit distance for electrical breakdown and has the units of V/m.

Conductors. Materials with high electrical conductivity, such as metals, are generally referred to as *conductors*. **Electrical resistivity** is the inverse of electrical conductivity; materials with high electrical resistivity are referred to as **dielectrics** or **insulators**.

Superconductors. *Superconductivity* is the phenomenon of near-zero electrical resistivity that occurs in some metals and alloys below a critical temperature, often near absolute zero (0 K, –273°C). The highest temperature at which superconductivity has been exhibited to date is for a mercury–barium–calcium–copper compound ($HgBa_2Ca_2Cu_3O_x$), which may be as high as –109°C, under pressure; advances in high temperature superconductivity continue to be made.

The main application of superconductors is for high-power magnets, and are the enabling technology for magnetic resonance imaging used for medical imaging. Other applications proposed for superconductors include magnetic levitation (maglev) trains, efficient power transmission lines, and components for extremely fast computers.

Semiconductors. The electrical properties of *semiconductors*, such as single-crystal silicon, germanium, and gallium arsenide, are extremely sensitive to temperature and the presence and type of minute impurities. Thus, by controlling the concentration and type of impurities (called **dopants**), such as phosphorus and boron in silicon, electrical conductivity can be controlled. This property is utilized in semiconductor (solid-state) devices, used extensively in miniaturized electronic circuitry (Chapter 28).

Ferromagnetism and Ferrimagnetism. *Ferromagnetism* is a phenomenon characterized by high permeability and permanent magnetization that are due to the alignment of iron, nickel, and cobalt atoms. It is important in such applications as electric motors, electric generators, electric transformers, and microwave devices. *Ferrimagnetism* is a permanent and large magnetization exhibited by some ceramic materials, such as cubic ferrites.

Piezoelectric Effect. The *piezoelectric effect* (*piezo* from Greek, meaning "to press") is exhibited by what are called **smart materials**. Two basic behaviors are involved: (a) When subjected to an electric current, these materials undergo a reversible change in shape, by as much as 4% and (b) when deformed by an external force, the materials emit a small electric current. Piezoelectric materials include quartz crystals and some ceramics and polymers. The piezoelectric effect is utilized in making transducers, which are devices that convert the strain from an external force into electrical energy. Typical applications are sensors, force or pressure transducers, inkjet printers, strain gages, sonar detectors, and microphones. As an example, an air bag in an automobile has a sensor that, when subjected to an impact force, sends an electric charge which deploys the bag.

Magnetostriction. The phenomenon of expansion or contraction of a material when it is subjected to a magnetic field is called *magnetostriction*. Materials such as pure nickel and some iron–nickel alloys exhibit this behavior. Magnetostriction is the principle behind ultrasonic machining equipment (Section 26.6).

Magnetorheostatic and Electrorheostatic Effects. When subjected to magnetic or electric fields, some fluids undergo a major and reversible change in their viscosity within a fraction of a second, turning from a liquid to an almost solid state. For example, magnetorheostatic behavior is attained by mixing very fine iron filings with oil. Called **smart fluids**, these materials are being developed for such applications as vibration dampeners, engine mounts, prosthetic devices, clutches, and valves.

Optical Properties. Among various other properties, color and opacity are particularly relevant to polymers and glasses. These two properties are described in Sections 7.2.2 and 8.4.3, respectively.

3.8 Corrosion Resistance

Metals, ceramics, and plastics are all subject to forms of **corrosion**. The word *corrosion* itself usually refers to the deterioration of metals and ceramics, while similar phenomena in plastics (Chapter 7) are generally called **degradation**. Corrosion not only leads to surface deterioration of components and structures, such as bridges and ships, but also reduces their strength and structural integrity. The direct cost of corrosion to the U.S. economy alone has been estimated to be over $400 billion per year, approximately 3% of the gross domestic product. Indirect costs of corrosion are estimated at twice this amount.

Corrosion resistance is an important aspect of material selection for applications in the chemical, food, and petroleum industries, as well as in manufacturing operations. In addition to various possible chemical reactions from the elements and compounds present, the environmental oxidation and corrosion of components and structures is a major concern, particularly at elevated temperatures and in automobiles and other transportation vehicles.

Resistance to corrosion depends on the composition of the material and on the particular environment. Corrosive media may be chemicals (acids, alkalis, and salts) and the environment (oxygen, moisture, pollution, and acid rain), including water (fresh or salt water). Nonferrous metals, stainless steels, and nonmetallic materials generally have high corrosion resistance, whereas steels and cast irons generally have poor resistance and must be protected by various coatings and surface treatments (Chapter 34).

Corrosion can occur over an entire surface or it can be *localized*, called **pitting**, a term that is also used for fatigue wear or failure of gears and in forging; see Section 33.2. Corrosion can also occur along grain boundaries of metals as intergranular corrosion, and at the interface of bolted or riveted joints as **crevice corrosion.**

Two dissimilar metals may form a **galvanic cell** (after the Italian physician L. Galvani, 1737–1798); that is, two electrodes in an electrolyte in a corrosive environment that includes moisture and cause **galvanic corrosion**. Two-phase alloys (Chapter 4) are more susceptible to galvanic corrosion (because of the physical separation of the two different metals involved) than are single-phase alloys or pure metals; as a result, heat treatment can have a significant beneficial influence on corrosion resistance.

Stress-corrosion cracking (Section 2.10.2) is an example of the effect of a corrosive environment on the integrity of a product that, as manufactured, had residual stresses. Likewise, cold-worked metals are likely to have residual stresses, hence they are more susceptible to corrosion than are hot worked or annealed metals.

Tool and die materials also can be susceptible to chemical attack by lubricants and by coolants; the chemical reaction alters their surface finish and adversely influences the metalworking operation. One example is that of carbide tools and dies having cobalt as a binder (Section 22.4); the cobalt is attacked by elements in the metalworking fluid (**selective leaching**). Thus, compatibility of the tool, die, and workpiece materials with the metalworking fluid, under actual operating conditions is an important consideration in the selection of materials.

However, chemical reactions should not be regarded as having only adverse effects. Advanced machining processes such as chemical and electrochemical machining (Chapter 27) are indeed based on controlled chemical reactions. These processes remove material by chemical action, in a manner similar to the etching of metallurgical specimens.

The usefulness of some level of **oxidation** is demonstrated by the corrosion resistance of aluminum, titanium, and stainless steel (Section 33.2). Aluminum develops a thin (a few atomic layers), strong, and adherent hard-oxide film (Al_2O_3) that better protects the surface from further environmental corrosion. Titanium develops a film of titanium oxide (TiO_2). A similar phenomenon occurs in stainless steels which, because of the chromium present in the alloy, develop a protective chromium oxide film on their surfaces. These processes are known as **passivation**. When the protective film is scratched and exposes the metal underneath, a new oxide film begins to form.

CASE STUDY 3.1 Selection of Materials for Coins

There are six general criteria in the selection of materials for coins (Fig. 3.4).

1. *Subjective factors*, such as the *appearance* of the coin, its color, weight, and its ring (the sound made when striking). Also included in this criterion is the *feel* of the coin, a term that is similar in effect to the feel of a fine piece of wood, polished stone, or tableware. It is difficult to quantify because it combines several human factors.
2. The intended *life* of the coin is also a consideration; this duration will reflect resistance to corrosion and wear (Chapter 33) while the coin is in circulation. These two factors basically determine the span over which the surface imprint of the coin will remain identifiable, as well as the ability of the coin to retain its original luster.
3. *Manufacturing* of the coin includes factors such as the formability of the candidate coin materials, the life of the dies used in the coining operation (Section 14.4), and the capability of the materials and processes to resist counterfeiting.
4. Another consideration is the *suitability for use* in coin-operated devices, such as vending machines and turnstiles. These machines are generally equipped with detection devices that test the coins—first, for proper diameter, thickness, and surface condition, and second, for electrical conductivity and density. The coin is rejected if it fails any of these tests.
5. *Health* issues must be considered. For example, given the large portion of the population with nickel allergies, Euro coins are minted from nickel-free alloys.
6. A final consideration is the *cost* of raw materials and processing, and whether there is a sufficient *supply* of the coin materials. For example, Canada recently decided it would eliminate the penny because of the high cost of production and its limited currency value. The United States has similar concerns, since a penny (one cent) costs around 1.6 cents to manufacture.

FIGURE 3.4 A selection of U.S. coins, manufactured from different metal alloys of copper, nickel, tin, zinc, and aluminum. Valuable metals such as gold and silver are used for coins, but are not used for general currency.

SUMMARY

- Physical properties can have several important influences on materials selection, manufacturing, and on the service life of components. These properties and other relevant material characteristics must be considered because of their possible effects on product design, service requirements, and compatibility with other materials, including tools, dies, and workpieces.
- The combined properties of strength-to-weight and stiffness-to-weight ratios are important factors in selecting materials for lightweight and high-performance structures.
- Thermal conductivity and thermal expansion are major factors in the development of thermal stresses and thermal fatigue and shock, effects that are important in tool and die life in manufacturing operations.
- Chemical reactions, including oxidation and corrosion, are important factors in material selection, design, and manufacturing, as well as in the service life of

components. Passivation and stress-corrosion cracking are two other phenomena to be considered.

- Certain physical properties are utilized in manufacturing processes and their control, such as the magnetostriction effect (for ultrasonic machining of materials) and the piezoelectric effect (for force transducers and various sensors).

KEY TERMS

Conductors
Corrosion
Degradation
Density
Dielectric
Electrical conductivity
Electrical resistivity
Electrorheostatic
Ferromagnetism
Galvanic corrosion
Heat checking
Invar effect
Magnetorheostatic
Magnetostriction
Melting point
Oxidation
Passivation
Piezoelectric effect
Selective leaching
Semiconductors
Smart fluids
Smart materials
Specific heat
Specific stiffness
Specific strength
Stress-corrosion cracking
Superconductivity
Thermal conductivity
Thermal expansion
Thermal fatigue
Thermal stresses

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REVIEW QUESTIONS

3.1 List several reasons that density is an important material property.

3.2 Explain why the melting point of a material can be an important factor in material selection.

3.3 What adverse effects can be caused by thermal expansion of materials? Give some examples.

3.4 Is thermal cracking the same as thermal shock? Why or why not?

3.5 What is the piezoelectric effect?

3.6 Describe the factors that can lead to the corrosion of a metal.

3.7 What is a superconductor? Describe two applications of superconducting materials.

3.8 What is the difference between thermal conductivity and thermal expansion?

3.9 What is corrosion? How can it be prevented or accelerated?

3.10 Explain stress-corrosion cracking. Why is it also called season cracking?

3.11 What is the difference between a superconductor and a semiconductor?

3.12 What are smart materials?

QUALITATIVE PROBLEMS

3.13 What is the fundamental difference between mechanical properties of materials discussed in Chapter 2, and physical properties of materials, described in this chapter?

3.14 Describe the significance of structures and machine components made of two materials with different coefficients of thermal expansion.

3.15 Which of the properties described in this chapter are important for (a) pots and pans, (b) cookie sheets for baking, (c) rulers, (d) paper clips, (e) music wire, and (f) beverage cans? Explain your answers.

3.16 Note in Table 3.1 that the properties of the alloys of metals have a wide range compared with the properties of the pure metals. Explain why.

3.17 Rank the following in order of increasing thermal conductivity: aluminum, copper, silicon, titanium, ceramics, and plastics. Comment on how this ranking influences applications of these materials.

3.18 Does corrosion have any beneficial effects? Explain.

3.19 Explain how thermal conductivity can play a role in the development of residual stresses in metals.

3.20 What material properties are desirable for heat shields such as those placed on the space shuttle?

3.21 List examples of products where materials that are transparent are desired. List applications for opaque materials.

3.22 Refer to Fig. 3.2 and explain why the trends seen are to be expected.

3.23 Two physical properties that have a major influence on the cracking of workpieces, tools, or dies during thermal cycling are thermal conductivity and thermal expansion. Explain why.

3.24 Which of the materials described in this chapter has the highest (a) density, (b) electrical conductivity, (c) thermal conductivity, (d) specific heat, (e) melting point, and (f) cost.

3.25 Which properties described in this chapter can be affected by applying a coating?

QUANTITATIVE PROBLEMS

3.26 If we assume that all the work done in plastic deformation is converted into heat, the temperature rise in a workpiece is (1) directly proportional to the work done per unit volume and (2) inversely proportional to the product of the specific heat and the density of the workpiece. Using Fig. 2.5, and letting the areas under the curves be the unit work done, calculate the temperature rise for (a) 8650 steel, (b) 304 stainless steel, and (c) 1100-H14 aluminum.

3.27 The natural frequency, f, of a cantilever beam is given by

$$f = 0.56\sqrt{\frac{EIg}{wL^4}},$$

where E is the modulus of elasticity, I is the moment of inertia, g is the gravitational constant, w is the weight of the beam per unit length, and L is the length of the beam. How does the natural frequency of the beam change, if at all, as its temperature is increased? Assume that the material is steel.

3.28 Plot the following for the materials described in this chapter: elastic modulus versus density, yield stress versus density, thermal conductivity versus density. Comment on the implications of these plots.

3.29 It can be shown that thermal distortion in precision devices is low for high values of thermal conductivity divided by the thermal expansion coefficient. Rank the materials in Table 3.1 according to their ability to resist thermal distortion.

3.30 Add a column to Table 3.1 that lists the volumetric heat capacity of the materials listed, expressed in units of J/cm^3-K. Compare the results to the value for liquid water (4.184 J/cm^3-K). Note that the volumetric heat capacity of a material is the product of its density and specific heat.

SYNTHESIS, DESIGN, AND PROJECTS

3.31 Conduct a literature search and add the following materials to Table 3.1: cork, cement, ice, sugar, lithium, graphene, and chromium.

3.32 From your own experience, make a list of parts, components, or products that have corroded and have had to be replaced or discarded.

3.33 List applications where the following properties would be desirable: (a) high density, (b) low density, (c) high melting point, (d) low melting point, (e) high thermal conductivity, and (f) low thermal conductivity.

3.34 Describe several applications in which both specific strength and specific stiffness are important.

3.35 Design several mechanisms or instruments based on utilizing the differences in thermal expansion of materials, such as bimetallic strips that develop a curvature when heated.

3.36 For the materials listed in Table 3.1, determine the specific strength and specific stiffness. Describe your observations.

3.37 The maximum compressive force that a lightweight column can withstand before buckling depends on the ratio of the square root of the stiffness to the density for the material. For the materials listed in Table 2.2, determine (a) the ratio of tensile strength to density and (b) the ratio of elastic modulus to density. Comment on the suitability of each for being made into lightweight columns.

3.38 Describe possible applications and designs using alloys exhibiting the Invar effect of low thermal expansion.

3.39 Collect some pieces of different metallic and nonmetallic materials listed in Table 3.2. Using simple tests and/or instruments, determine the validity of the descending order of the physical properties shown in the table.

3.40 Design an actuator to turn on a switch when the temperature drops below a certain level. Use two materials with different coefficients of thermal expansion in your design.

3.41 Conduct an Internet and technical literature review and write a one-page paper highlighting applications of piezoelectric materials.

3.42 It has been widely reported that mechanical properties such as strength and ductility can be very different for micro-scale devices than are measured at normal length scales. Explain whether or not you would expect the physical properties described in this chapter to be scale dependent.

3.43 If you were given a metal (not an alloy) and asked to identify it, list (in order) the experiments or measurements you would perform. Explain what influence the shape of the metal would have on your prioritization.

Metal Alloys: Their Structure and Strengthening by Heat Treatment

CHAPTER 4

- This chapter examines the structures of metal alloys, including solid solutions, intermetallic compounds, and two-phase systems.
- Phase diagrams show graphically the various phases that develop as a function of alloy composition and temperature.
- The system of iron and carbon and the phases involved are described in detail.
- Heat treatment of metals is a common method to improve mechanical properties; it involves establishing a desired phase at elevated temperatures, followed by controlled cooling before the microstructure can transform into a different phase.
- Some metals, such as aluminum and stainless steels, can be heat treated only by precipitation hardening or aging.
- Improving the ductility of a material is at the expense of properties such as strength or hardness.
- The chapter ends with a discussion of the characteristics of heat-treating equipment.

4.1 Introduction

The properties and behavior of metals and alloys during manufacturing into a product and their performance during their service life depend on their composition, structure, and their processing history and the heat treatment to which they have been subjected. Important properties such as strength, hardness, ductility, toughness, and resistance to wear are greatly influenced by alloying elements and the heat-treatment processes employed. The properties of non-heat-treatable alloys are improved by mechanical working, such as rolling, forging, and extrusion (Part III).

The most common example of a process that improves properties is *heat treatment* (Sections 4.7–4.10), which modifies microstructures. Several mechanical properties that are important to manufacturing then develop, such as improved formability, machinability, or increased strength and hardness for better performance of tools and dies. These properties also enhance the service performance of gears (Fig. 4.1), cams, shafts, tools, dies, and molds.

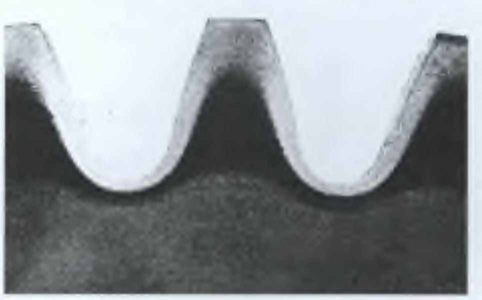


FIGURE 4.1 Cross-section of gear teeth showing induction-hardened surfaces. *Source:* TOCCO Div., Park-Ohio Industries, Inc.

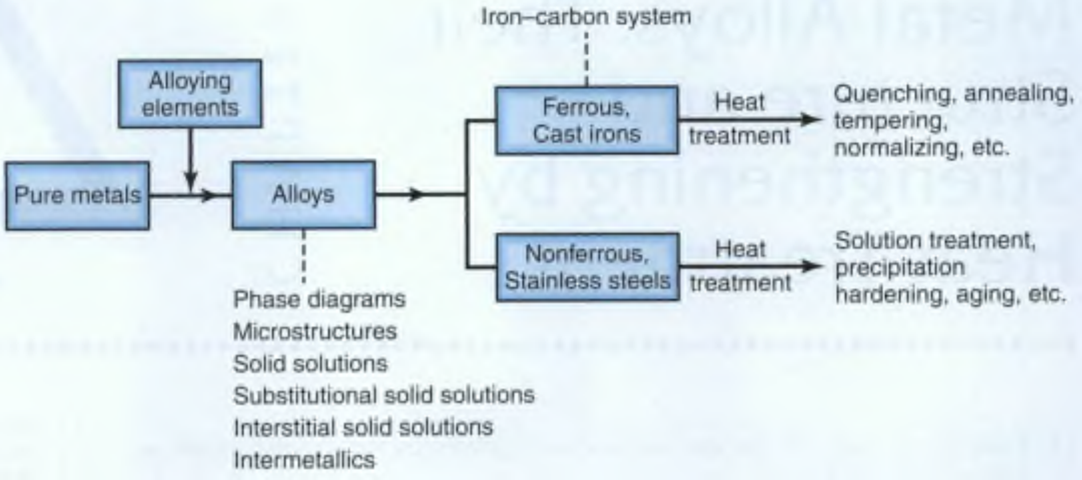


FIGURE 4.2 Outline of topics described in this chapter.

This chapter follows the outline shown in Fig. 4.2, beginning with the role of various alloying elements, the solubility of one element in another, phases, equilibrium phase diagrams, and the influence of composition, temperature, and time. The chapter also discusses methods and techniques of heating, quenching, tempering, and annealing of metals and alloys, and describes the characteristics of the equipment involved.

4.2 Structure of Alloys

When describing the basic crystal structure of metals in Chapter 1, it was noted that the atoms are all of the *same* type, except for the presence of rare impurity atoms; these metals are known as **pure metals**, even though they may not be completely pure. *Commercially pure* metals are used for various purposes, such as aluminum for foil, copper for electrical conductors, nickel or chromium for plating, and gold for electrical contacts. Pure metals have somewhat limited properties but they can be enhanced and modified by **alloying**. An **alloy** consists of two or more chemical elements, at least one of which is a metal; the majority of metals used in engineering applications are some form of alloy. Alloying consists of two basic forms: *solid solutions* and *intermetallic compounds*.

4.2.1 Solid Solutions

Two terms are essential in describing alloys: **solute** and **solvent**. The solute is the *minor* element (such as salt or sugar) that is added to the solvent, which is the *major* element (such as water). In terms of the elements in a crystal structure, the solute (composed of *solute atoms*) is the element that is added to the solvent (composed of *host atoms*). When the particular crystal structure of the solvent is maintained during alloying, the alloy is called a *solid solution*.

Substitutional Solid Solutions. If the size of the solute atom is similar to that of the solvent atom, the solute atoms can replace solvent atoms and form a *substitutional solid solution* (see Fig. 1.8). An example is brass, which is an alloy of zinc and copper in which zinc (the solute atom) is introduced into the lattice of copper (solvent atoms). The properties of brass can thus be altered by controlling the amount of zinc in copper.

Interstitial Solid Solutions. If the size of the solute atom is much smaller than that of the solvent atom, each solute atom can occupy an *interstitial* position; such a process forms an *interstitial solid solution*.

An important family of interstitial solid solutions is **steel** (Chapter 5), an alloy of iron and carbon in which the carbon atoms are present in interstitial positions between iron atoms. The atomic radius of carbon is 0.071 nm, which is very small compared to the 0.124-nm radius of the iron atom. The properties of carbon steels can be varied over a wide range by adjusting the ratio of carbon to iron. The ability to control this ratio is a major reason why steel is such a versatile and useful material, with a very wide variety of properties and applications.

4.2.2 Intermetallic Compounds

Intermetallic compounds are complex structures consisting of two metals in which solute atoms are present among solvent atoms in certain proportions. Typical examples are the aluminides of titanium (Ti_3Al), nickel (Ni_3Al), and iron (Fe_3Al). Some intermetallic compounds have solid solubility, and the type of atomic bond may range from metallic to ionic. Intermetallic compounds are strong, hard, and brittle. Because of their high melting points, strength at elevated temperatures, good oxidation resistance, and relatively low density, they are candidate materials for such applications as advanced gas-turbine engines.

4.2.3 Two-phase Systems

Recall that a solid solution is one in which two or more elements form a single homogeneous solid phase, in which the elements are uniformly distributed throughout the solid mass. Such a system has a maximum concentration of solute atoms in the solvent-atom lattice, just as there is a solubility limit for sugar in water. Most alloys consist of two or more solid phases and may be regarded as mechanical mixtures; such a system with two solid phases is known as a *two-phase system*.

A **phase** is defined as a physically distinct and homogeneous portion in a material. Each phase is a homogeneous part of the total mass, and has its own characteristics and properties. Consider a mixture of sand and water as an example of a two-phase system. These two different components have their own distinct structures, characteristics, and properties; there is a clear boundary in this mixture between the water (one phase) and the sand particles (the second phase). Another example is ice in water: the two phases are the same chemical compound of exactly the same chemical elements (hydrogen and oxygen), even though their properties are very different. Note that it is not necessary that one phase be a liquid; for example, sand suspended in ice is also a two-phase system.

A typical example of a two-phase system in metals occurs when lead is added to copper in the molten state. After the mixture solidifies, the structure consists of two phases: one having a small amount of lead in solid solution in copper, the other having lead particles (roughly spherical in shape) *dispersed* throughout the structure (Fig. 4.3a). The lead particles are analogous to the sand particles in water, described above. This copper–lead alloy has properties that are different from those of either copper or lead alone.

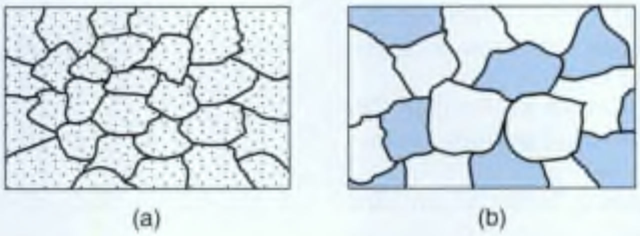

(a) (b)

FIGURE 4.3 (a) Schematic illustration of grains, grain boundaries, and particles dispersed throughout the structure of a two-phase system, such as a lead–copper alloy. The grains represent lead in solid solution in copper, and the particles are lead as a second phase. (b) Schematic illustration of a two-phase system consisting of two sets of grains: dark and light. The colored and white grains have different compositions and properties.

Alloying with finely dispersed particles (**second-phase particles**) is an important method of strengthening metal alloys and controlling their properties. In two-phase alloys, the second-phase particles become obstacles to dislocation movement and thus increase the strength of the alloy. Another example of a two-phase alloy is the aggregate structure shown in Fig. 4.3b, where there are two sets of grains, each with its own composition and properties. The darker grains in the figure may have a different structure from the lighter grains; they may, for example, be brittle, while the lighter grains are ductile.

Defects may develop during metalworking operations such as forging or extrusion (as described in Chapters 14 and 15, respectively). Such flaws may be due to the lack of ductility of one of the phases in the alloy. In general, two-phase alloys are stronger and less ductile than solid solutions.

4.3 Phase Diagrams

Pure metals have clearly defined melting or freezing points, and solidification takes place at a *constant temperature*. When the temperature of a molten metal is reduced to the freezing point, the energy or the *latent heat of solidification* is given off while the temperature remains constant. Eventually, solidification is complete and the solid metal continues cooling to ambient (room) temperature.

Unlike pure metals, alloys solidify over a range of temperatures (Fig. 4.4). Solidification begins when the temperature of the molten metal drops below the **liquidus**; it is completed when the temperature reaches the **solidus**. Within this temperature range, the alloy is in a *mushy* or *pasty* state; its composition and state are then described by the particular alloy's phase diagram.

A phase diagram, also called an **equilibrium** or constitutional diagram, shows the relationships among temperature, composition, and the phases present in a particular alloy system at equilibrium. *Equilibrium* means that the state of a system does not vary with time; the word *constitutional* indicates the relationships among the structure, the composition, and the physical makeup of the alloy. As described in detail below, types of phase diagrams include those for (a) complete solid solutions; (b) eutectics, such as cast irons; and (c) eutectoids, such as steels.

One example of a phase diagram is shown in Fig. 4.4 for the copper–nickel alloy; it is called a **binary phase diagram** because there are two elements (copper and nickel) present in the system. The left boundary of this phase diagram (100% Ni) indicates the melting point of pure nickel; the right boundary (100% Cu) indicates the melting point of pure copper. (All percentages are by weight, not by number of atoms.)

Lever Rule. The composition of various phases in a phase diagram can be determined by a procedure called the *lever rule*. As shown in the lower portion of Fig. 4.4, we first construct a lever between the solidus and liquidus lines (called *tie line*), which is balanced (on the triangular support) at the nominal weight composition C_0 of the alloy. The left end of the lever represents the composition C_S of the solid phase and the right end of the composition C_L of the liquid phase. Note from the graduated scale in the figure that the liquid fraction is also indicated along this tie line, ranging from 0 at the left (fully solid) to 1 at the right (fully liquid).

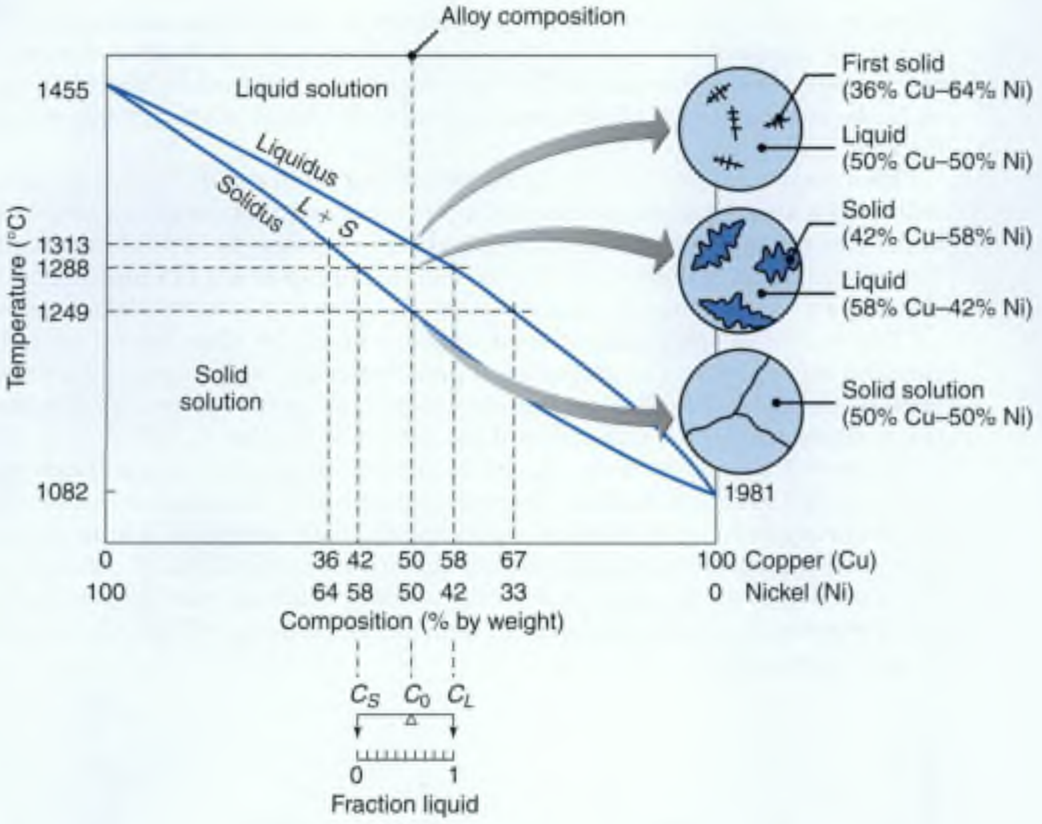


FIGURE 4.4 Phase diagram for copper–nickel alloy system obtained at a slow rate of solidification. Note that pure nickel and pure copper each have one freezing or melting temperature. The top circle on the right depicts the nucleation of crystals. The second circle shows the formation of dendrites (see Section 10.2.2). The bottom circle shows the solidified alloy, with grain boundaries.

The lever rule states that the **weight fraction of solid** is proportional to the distance between C_o and C_L:

$$\frac{S}{S+L} = \frac{C_o - C_L}{C_S - C_L}. \tag{4.1}$$

Likewise, the **weight fraction of liquid** is proportional to the distance between C_S and C_o, hence

$$\frac{L}{S+L} = \frac{C_S - C_o}{C_S - C_L}. \tag{4.2}$$

Note that these quantities are fractions and must be multiplied by 100 to obtain percentages.

From inspection of the tie line in Fig. 4.4 (and for a nominal alloy composition of $C_o = 50\%$ Cu–50% Ni) it can be noted that, because C_o is closer to C_L than it is to C_S, the solid phase contains less copper than does the liquid phase. By measuring on the phase diagram and using the lever-rule equations, it can be seen that the composition of the solid phase is 42% Cu and of the liquid phase is 58% Cu, as stated in the middle circle at the right in Fig. 4.4. These calculations refer to copper. If we now reverse the phase diagram in the figure, so that the left boundary is 0% nickel (whereby nickel now becomes the alloying element in copper), these calculations will give us the compositions of the solid and liquid phases in terms of nickel. The lever rule is also known as the *inverse lever rule* because, as indicated by Eqs. (4.1) and (4.2), the amount of each phase is proportional to the length of the opposite end of the lever.

The *completely solidified* alloy in the phase diagram shown in Fig. 4.4 is a *solid solution*, because the alloying element, Cu (the solute atom), is completely dissolved in the host metal, Ni (the solvent atom), and each grain has the same composition. The atomic radius of copper is 0.128 nm and that of nickel is 0.125 nm, and both elements are of face-centered cubic structure; thus, they readily form solid solutions.

The mechanical properties of solid solutions of Cu–Ni alloy depend on their composition (Fig. 4.5). The properties of pure copper are, up to a point, improved upon by increasing the nickel content; thus, there is an optimal percentage of nickel that gives the highest strength and hardness to the Cu–Ni alloy.

Figure 4.5 also shows how zinc, as an alloying element in copper, affects the mechanical properties of the alloy. Note the maximum of 40% solid solubility for zinc (solute) in copper (solvent), whereas copper and nickel are completely soluble in each other. The improvements in properties are due to *pinning* (blocking) of dislocations (Section 1.4.1) at substitutional nickel or zinc atoms, which may also be regarded as impurity atoms. As a result, dislocations cannot move as freely and thus the strength of the alloy increases.

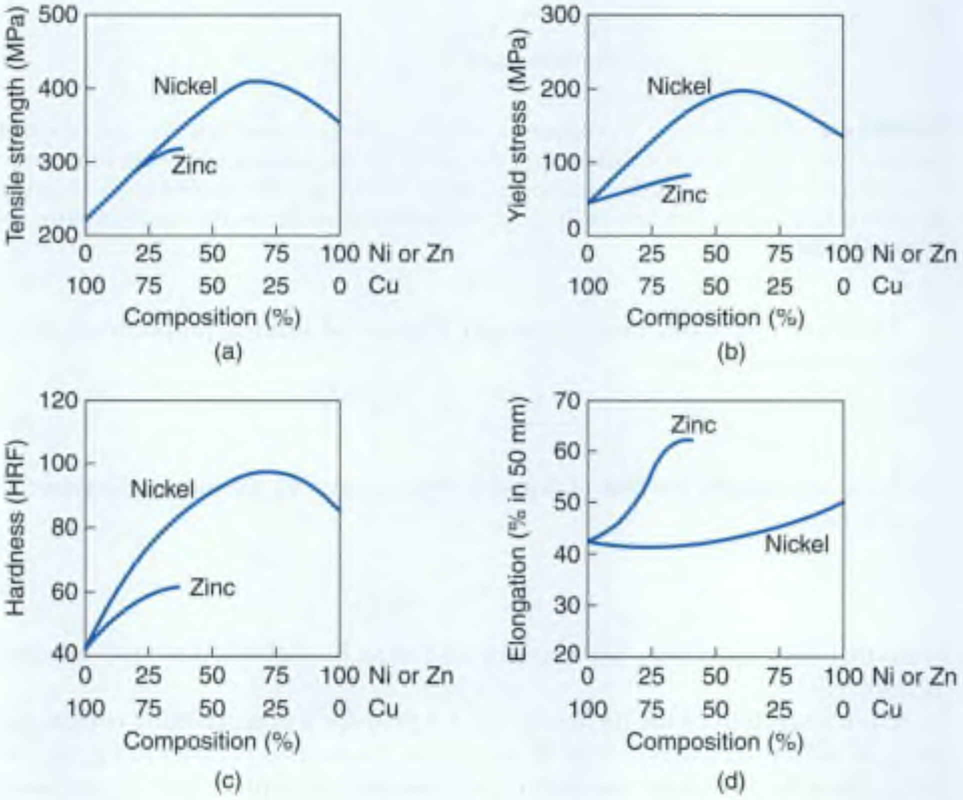


FIGURE 4.5 Mechanical properties of copper–nickel and copper–zinc alloys as a function of their composition. The curves for zinc are short, because zinc has a maximum solid solubility of 40% in copper.

4.4 The Iron–carbon System

Steels and cast irons are represented by the iron–carbon binary system. Commercially pure iron contains up to 0.008% C, steels up to 2.11% C, and cast irons up to 6.67% C, although most cast irons contain less than 4.5% C. In this section, the iron–carbon system is described, including the techniques employed to evaluate and modify the properties of these important materials for specific applications.

The **iron–iron-carbide phase diagram** is shown in Fig. 4.6. Although this diagram can be extended to the right—to 100% C (pure graphite; see Fig. 4.10)—the range that is significant to engineering applications is up to 6.67% C, because Fe_3C is a stable phase. Pure iron melts at a temperature of 1538°C, as shown at the left boundary in Fig. 4.6. As iron cools, it first forms delta ferrite, then austenite, and finally alpha ferrite.

Ferrite. **Alpha ferrite,** also denoted α-ferrite or simply **ferrite,** is a solid solution of body-centered cubic (bcc) iron; it has a maximum solid solubility of 0.022% C at a temperature of 727°C. Just as there is a solubility limit for salt in water (with any extra amount precipitating as solid salt at the bottom of a container), there is a solid solubility limit for carbon in iron as well.

Ferrite is relatively soft and ductile; it is magnetic from room temperature to 768°C, the so-called *Curie temperature* (after the Polish physicist and chemist M.Curie, 1867–1934). Although very little carbon can dissolve interstitially in bcc iron, the amount of carbon can significantly affect the mechanical properties of ferrite. Furthermore, significant amounts of chromium, manganese, nickel, molybdenum, tungsten, and silicon can be contained in iron in solid solution, imparting special properties.

Austenite. As shown in Fig. 4.6, within a certain temperature range iron undergoes a **polymorphic transformation** from a bcc to an fcc structure, becoming *gamma iron*

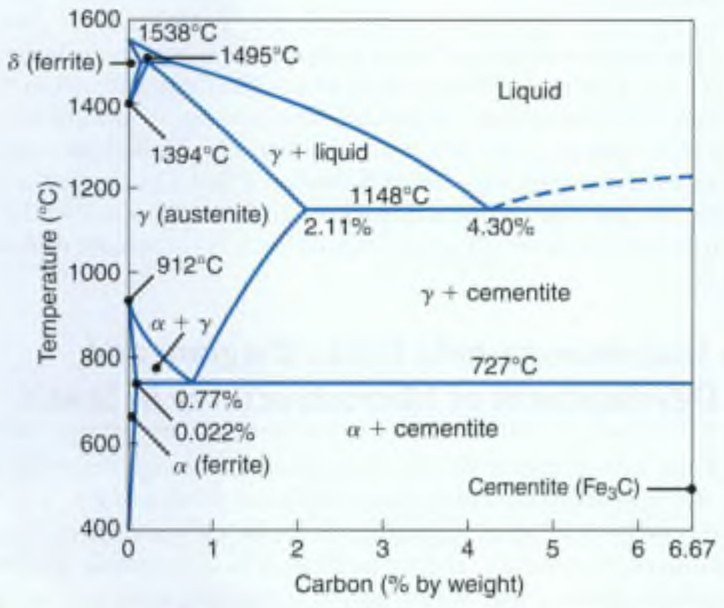
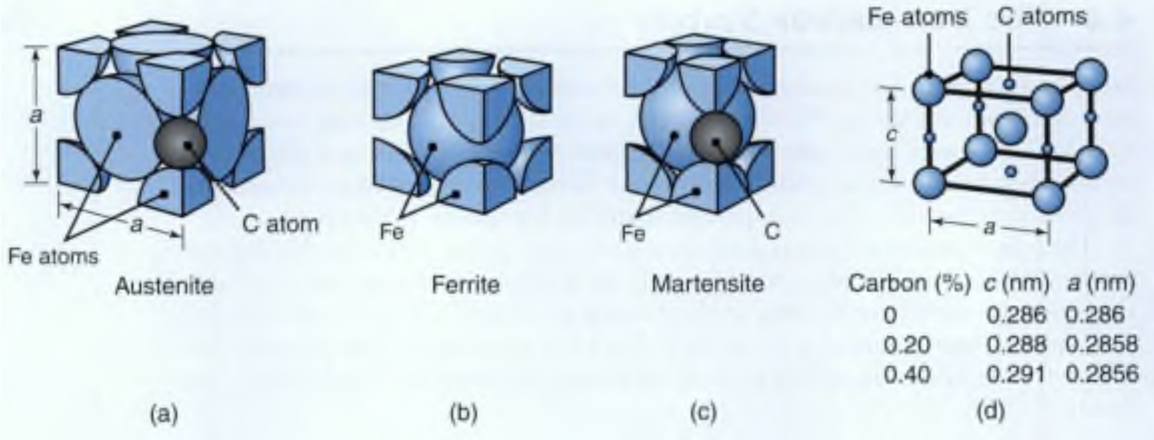


FIGURE 4.6 The iron–iron-carbide phase diagram.



Carbon (%)	c (nm)	a (nm)
0	0.286	0.286
0.20	0.288	0.2858
0.40	0.291	0.2856

FIGURE 4.7 The unit cells for (a) austenite, (b) ferrite, and (c) martensite. The effect of percentage of carbon (by weight) on the lattice dimensions for martensite is shown in (d); note the interstitial position of the carbon atoms. (See Fig. 1.8.) Note also the increase in dimension c with increasing carbon content; this effect causes the unit cell of martensite to be in the shape of a rectangular prism.

(γ-iron), or, more commonly, **austenite** (after the British metallurgist W.C. Roberts–Austen, 1843–1902). This structure has a solid solubility of up to 2.11% C at 1148°C. Because the fcc structure has more interstitial positions, the solid solubility of austenite is about two orders of magnitude higher than that of ferrite, with the carbon occupying interstitial positions, as shown in Fig. 4.7a.

Austenite is an important phase in the heat treatment of steels (Section 4.7). It is denser than ferrite, and its single-phase fcc structure is ductile at elevated temperatures; consequently, it possesses good formability. Large amounts of nickel and manganese can also be dissolved in fcc iron to impart various properties. Steel is nonmagnetic in the austenitic form, either at high temperatures or, for austenitic stainless steels, at room temperature.

Cementite. The right boundary of Fig. 4.6 represents **cementite**, which is 100% iron carbide (Fe_3C), having a carbon content of 6.67%. Cementite (from the Latin *caementum*, meaning "stone chips") is also called **carbide**, but should not be confused with other carbides used as dies, cutting tools, and abrasives, such as tungsten carbide, titanium carbide, and silicon carbide (Chapters 8 and 22). Cementite is a very hard and brittle intermetallic compound, with a significant influence on the properties of steels. It can include other alloying elements, such as chromium, molybdenum, and manganese.

4.5 The Iron–iron-carbide Phase Diagram and the Development of Microstructures in Steels

The region of the iron–iron-carbide phase diagram that is significant for steels is shown in Fig. 4.8 (an enlargement of the lower left-hand portion of Fig. 4.6). Various microstructures can be developed, depending on the (a) carbon content, (b) amount of plastic deformation (working), and (c) method of heat treatment. For example, consider the **eutectic point** of iron with a 0.77% C content, while it is being cooled very slowly from a temperature of, say, 1100°C in the austenite phase. The reason for very slow cooling is to maintain equilibrium.

At 727°C, a reaction takes place in which austenite is transformed into alpha ferrite (bcc) and cementite. Because the solid solubility of carbon in ferrite is only 0.022%, the extra carbon forms cementite. This reaction is called a **eutectoid** (meaning *eutecticlike*) reaction, which means that, at a certain temperature, a single solid phase (austenite) is transformed into two other solid phases (ferrite and cementite).

The structure of eutectoid steel is called pearlite because, at low magnifications, it resembles mother of pearl (Fig. 4.9). The microstructure of pearlite consists of alternating layers (lamellae) of ferrite and cementite; consequently, the mechanical properties of pearlite are intermediate between those of ferrite (soft and ductile) and cementite (hard and brittle).

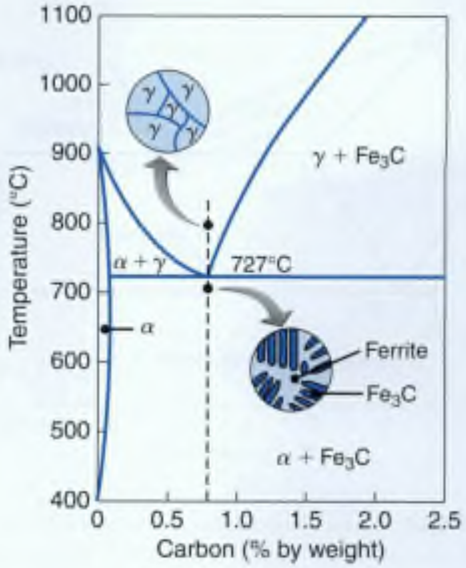


FIGURE 4.8 Schematic illustration of the microstructures for an iron–carbon alloy of eutectoid composition (0.77% carbon), above and below the eutectoid temperature of 727°C.

4.5.1 Effects of Alloying Elements in Iron

Although carbon is the basic element that transforms iron into steel, other elements are also added to impart a variety of desirable properties. The main effect of these alloying elements on the iron–iron-carbide phase diagram is to shift the eutectoid temperature and eutectoid composition (percentage of carbon in steel at the eutectoid point); these elements shift other phase boundaries as well.

The eutectoid temperature may be raised or lowered, from 727°C, depending on the particular alloying element. On the other hand, alloying elements always lower the eutectoid composition; that is, its carbon content is lower than 0.77%. Lowering the eutectoid temperature means increasing the austenite range; as a result, an alloying element such as nickel is known as an **austenite former**. Because nickel has an fcc structure, it favors the fcc structure of austenite. Conversely, chromium and molybdenum have a bcc structure, thus favoring the bcc structure of ferrite; these elements are known as **ferrite stabilizers**.

FIGURE 4.9 Microstructure of pearlite in 1080 steel, formed from austenite of eutectoid composition. In this lamellar structure, the lighter regions are ferrite and the darker regions are carbide. Magnification: 2500×.

4.6 Cast Irons

The term **cast iron** refers to a family of ferrous alloys composed of iron, carbon (ranging from 2.11% to about 4.5%), and silicon (up to about 3.5%). Cast irons are usually classified according to their solidification morphology from the eutectic temperature (see also Section 12.3.2):

1. Gray cast iron, or gray iron
2. Ductile cast iron, also called nodular cast iron or spheroidal graphite cast iron
3. White cast iron
4. Malleable iron
5. Compacted graphite iron

Cast irons are also classified by their structure: ferritic, pearlitic, quenched and tempered, or austempered.

The equilibrium phase diagram relevant to cast irons is shown in Fig. 4.10, in which the right boundary is 100% C—that is, pure graphite. Because the eutectic

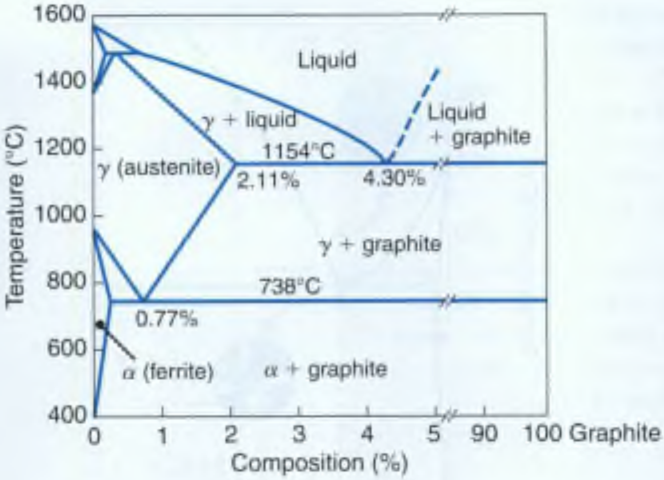


FIGURE 4.10 Phase diagram for the iron–carbon system with graphite (instead of cementite) as the stable phase; note that this figure is an extended version of Fig. 4.6.

temperature is 1154°C, cast irons are completely liquid at temperatures lower than those required for liquid steels. Consequently, iron with high carbon content can be cast (see Part II) at lower temperatures than can steels.

Cementite is not completely stable; it is **metastable**, with an extremely low rate of decomposition. It can, however, be made to decompose into alpha ferrite and graphite. The formation of graphite (**graphitization**) can be controlled, promoted, and accelerated by modifying the composition, the rate of cooling, and by the addition of silicon.

Gray Cast Iron. In this structure, graphite exists largely in the form of *flakes* (Fig. 4.11a). It is called **gray cast iron**, or **gray iron** because, when it is broken, the fracture path is along the graphite flakes and has a gray, sooty appearance. These flakes act as stress raisers; as a result, gray iron has negligible ductility and is weak in tension, although strong in compression. On the other hand, the presence of graphite flakes gives this material the capacity to dampen vibrations (by internal friction). This capacity makes gray cast iron a suitable and commonly used material for constructing machine-tool bases and machinery structures (Section 25.3).

Three types of gray cast iron are **ferritic, pearlitic,** and **martensitic**; because of the different structures, each has different properties and applications. In ferritic gray iron (also known as *fully gray iron*), the structure consists of graphite flakes in an alpha-ferrite matrix. Pearlitic gray iron has a structure of graphite in a matrix of pearlite, and although still brittle, it is stronger than fully gray iron. Martensitic gray iron is obtained by austenitizing a pearlitic gray iron and then quenching it rapidly to produce a structure of graphite in a martensite matrix; as a result, this cast iron is very hard.

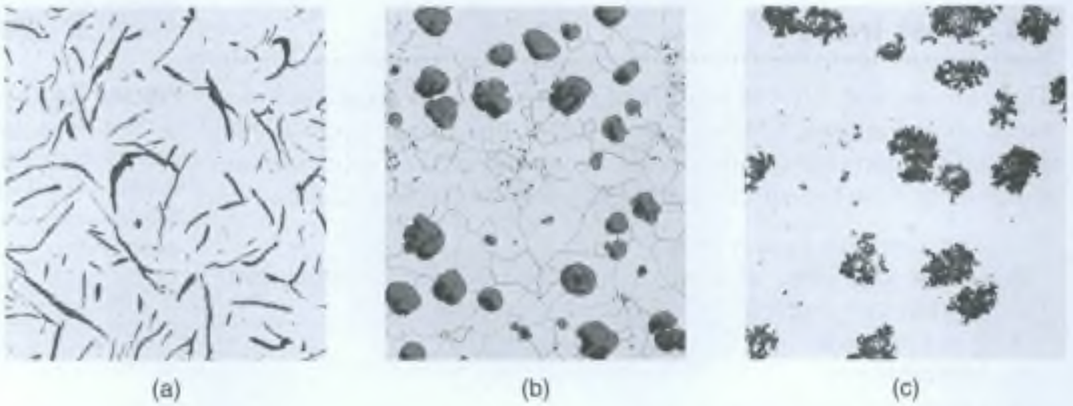

(a) (b) (c)

FIGURE 4.11 Microstructure for cast irons. Magnification: 100×. (a) Ferritic gray iron with graphite flakes. (b) Ferritic ductile iron (nodular iron), with graphite in nodular form. (c) Ferritic malleable iron; this cast iron solidified as white cast iron, with the carbon present as cementite, and was heat treated to graphitize the carbon.

Ductile (Nodular) Iron. In the ductile-iron structure, graphite is in a **nodular** or **spheroid** form (Fig. 4.11b), which permits the material to be somewhat ductile and shock resistant. The shape of graphite flakes can be changed into nodules (spheres), by small additions of magnesium and/or cerium to the molten metal prior to pouring. Ductile iron can be made ferritic or pearlitic by heat treatment; it can also be heat treated to obtain a structure of tempered martensite (Section 4.7).

White Cast Iron. *White cast iron* is obtained either by cooling gray iron rapidly or by adjusting the composition by keeping the carbon and silicon content low; it is also called *white iron* because of the white crystalline appearance of the fracture surface. The white cast iron structure is very hard, wear resistant, and brittle, because of the presence of large amounts of iron carbide (instead of graphite).

Malleable Iron. *Malleable iron* is obtained by annealing white cast iron in an atmosphere of carbon monoxide and carbon dioxide, at between 800°C and 900°C for up to several hours, depending on the size of the part. During this process, the cementite decomposes (*dissociates*) into iron and graphite. The graphite exists as *clusters* or *rosettes* (Fig. 4. 11c) in a ferrite or pearlite matrix; consequently, malleable iron has a structure similar to that of nodular iron. This structure promotes good ductility, strength, and shock resistance—hence, the term *malleable* (from the Latin *malleus* meaning "it can be hammered").

Compacted-graphite Iron. The graphite in this structure is in the form of short, thick, interconnected flakes having undulating surfaces and rounded extremities. The mechanical and physical properties of this cast iron are intermediate between those of flake-graphite and nodular-graphite cast irons.

4.7 Heat Treatment of Ferrous Alloys

The various microstructures described thus far can be modified by **heat-treatment** techniques—that is, by controlled heating and cooling of the alloys at various rates. These treatments induce **phase transformations**, which greatly influence such mechanical properties as strength, hardness, ductility, toughness, and wear resistance. The effects of thermal treatment depend on the particular alloy, its composition and microstructure, the degree of prior cold work, and the rates of heating and cooling during heat treatment.

This section focuses on the microstructural changes in the iron–carbon system. Because of their technological significance, the structures considered are pearlite, spheroidite, bainite, martensite, and tempered martensite. The heat-treatment processes described are annealing, quenching, and tempering.

Pearlite. If the ferrite and cementite lamellae in the pearlite structure of the eutectoid steel, shown in Fig. 4.9, are thin and closely packed, the microstructure is called **fine pearlite**; if they are thick and widely spaced, it is called **coarse pearlite**. The difference between the two depends on the rate of cooling through the eutectoid temperature, which is the site of a reaction in which austenite is transformed into pearlite. If the rate of cooling is relatively high (as in air), fine pearlite is produced; if cooling is slow (as in a furnace), coarse pearlite is produced.

Spheroidite. When pearlite is heated to just below the eutectoid temperature and then held at that temperature for a period of time, such as at 700°C for a

QR Code 4.1 Hardening chains with induction heating. (*Source:* Courtesy of GH Induction Atmospheres)

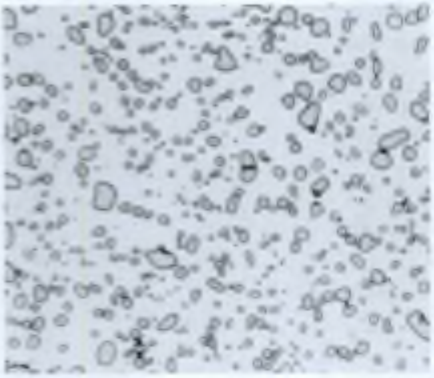


FIGURE 4.12 Microstructure of eutectoid steel. Spheroidite is formed by tempering the steel at 700°C. Magnification: 1000×.

day, the cementite lamellae transform to roughly spherical shapes (Fig. 4.12). Unlike the lamellar shapes of cementite, which act as stress raisers, **spheroidites** (spherical particles) have smaller stress concentrations because of their rounded shapes. Consequently, this structure has higher toughness and lower hardness than the pearlite structure. It can be cold worked, because the ductile ferrite has high toughness and the spheroidal carbide particles prevent the initiation of cracks within the material.

Bainite. Visible only through electron microscopy, *bainite* is a very fine microstructure, consisting of ferrite and cementite, similar to pearlite, but having a different morphology. Bainite can be produced in steels with alloying elements and at cooling rates that are higher than those required for pearlite. This structure, called **bainitic steel** (after the American metallurgist E.C. Bain, 1891–1971), is generally stronger and more ductile than pearlitic steels at the same hardness level.

Martensite. When austenite is cooled at a high rate, such as by quenching in water, its fcc structure is transformed into a **body-centered tetragonal** (bct) structure, which can be described as a body-centered rectangular prism that is slightly elongated along one of its principal axes (see Fig. 4.7d). This microstructure is called *martensite* (after the German metallurgist A. Martens, 1850–1914). Because martensite does not have as many slip systems as a bcc structure, and the carbon is in interstitial positions, it is extremely hard and brittle (Fig. 4.13). Martensite transformation takes place almost instantaneously, because it involves not the diffusion process but a slip mechanism and thus involves plastic deformation. This is a time-dependent phenomenon that is the mechanism in other transformations as well.

Retained Austenite. If the temperature to which the alloy is quenched is not sufficiently low, only a portion of the structure is transformed to martensite. The rest is *retained austenite*, which is visible as white areas in the structure, along with the dark, needlelike martensite. Retained austenite can cause dimensional instability and cracking, and lower the hardness and strength of the alloy.

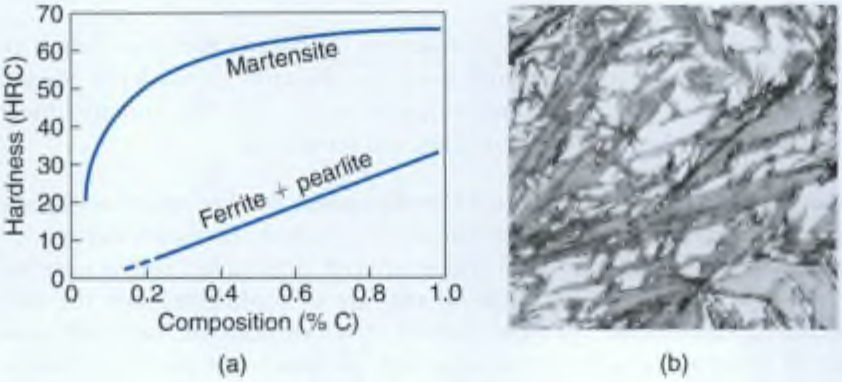


FIGURE 4.13 (a) Hardness of martensite as a function of carbon content. (b) Micrograph of martensite containing 0.8% carbon. The gray platelike regions are martensite; they have the same composition as the original austenite (white regions). Magnification: 1000×.

Tempered Martensite. Martensite is tempered in order to improve its mechanical properties. *Tempering* is a heating process by which hardness is reduced and toughness is increased. The body-centered tetragonal martensite is heated to an intermediate temperature, typically 150°–650°C, where it decomposes to a two-phase microstructure, consisting of bcc alpha ferrite and small particles of cementite.

With increasing tempering time and temperature, the hardness of tempered martensite decreases (Fig. 4.14). The reason is that the cementite particles coalesce and grow, and the distance between the particles in the soft ferrite matrix increases as the less stable and smaller carbide particles dissolve.

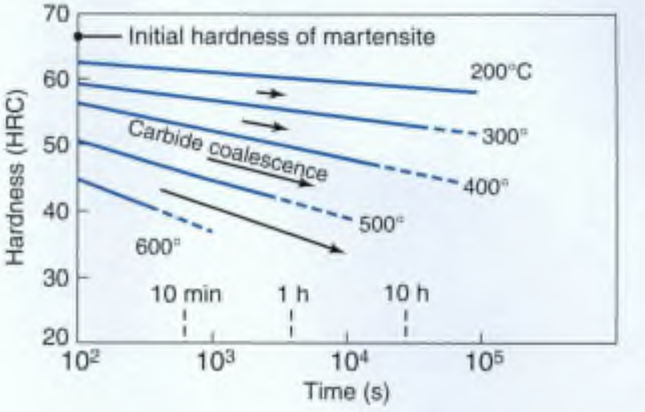


FIGURE 4.14 Hardness of tempered martensite as a function of tempering time for 1080 steel quenched to 65 HRC. Hardness decreases because the carbide particles coalesce and grow in size, thereby increasing the interparticle distance of the softer ferrite.

4.7.1 Time–temperature–transformation Diagrams

The percentage of austenite transformed into pearlite is a function of temperature and time (Fig. 4.15a). This transformation is best illustrated by Figs. 4.15b and c in diagrams called **isothermal transformation (IT) diagrams,** or *time–temperature–transformation* (TTT) *diagrams*, constructed from the data given in Fig. 4.15a. The higher the temperature or the longer the time, the more austenite is transformed into pearlite. Note that, for each temperature, there is a minimum time for the transformation to begin. This time period defines the critical cooling rate; with longer times, austenite begins to transform into pearlite, as can be traced in Figs. 4.15b and c.

Video Solution 4.1 Application of TTT Diagrams

The TTT diagrams shown allow the design of heat-treatment schedules to obtain desirable microstructures. For example, consider the TTT curves shown in Fig. 4.15c; the steel can be raised to a very high temperature (above the eutectic temperature) to start with a state of austenite. If the material is cooled rapidly, it can follow the 140°C/s cooling rate trajectory shown, resulting in complete martensite. On the other hand, it can be more slowly cooled (in a molten salt bath) to develop pearlite- or bainite-containing steels. If tempered martensite is desired, the heat treat and quench stages is followed by a tempering process.

The differences in hardness and toughness of the various structures obtained are shown in Fig. 4.16. Fine pearlite is harder and less ductile than coarse pearlite. The effects of various percentages of carbon, cementite, and pearlite on other mechanical properties of steels are shown in Fig. 4.17.

4.8 Hardenability of Ferrous Alloys

The capability of an alloy to be hardened by heat treatment is called its **hardenability,** and is a measure of the *depth* of hardness that can be obtained by heating and subsequent quenching. The term "hardenability" should not be confused with "hardness," which is the resistance of a material to indentation or scratching (Section 2.6). From the discussion thus far, it can be seen that hardenability of ferrous alloys depends on the (a) carbon content, (b) grain size of the austenite, (c) alloying elements present in the material, and (d) cooling rate.

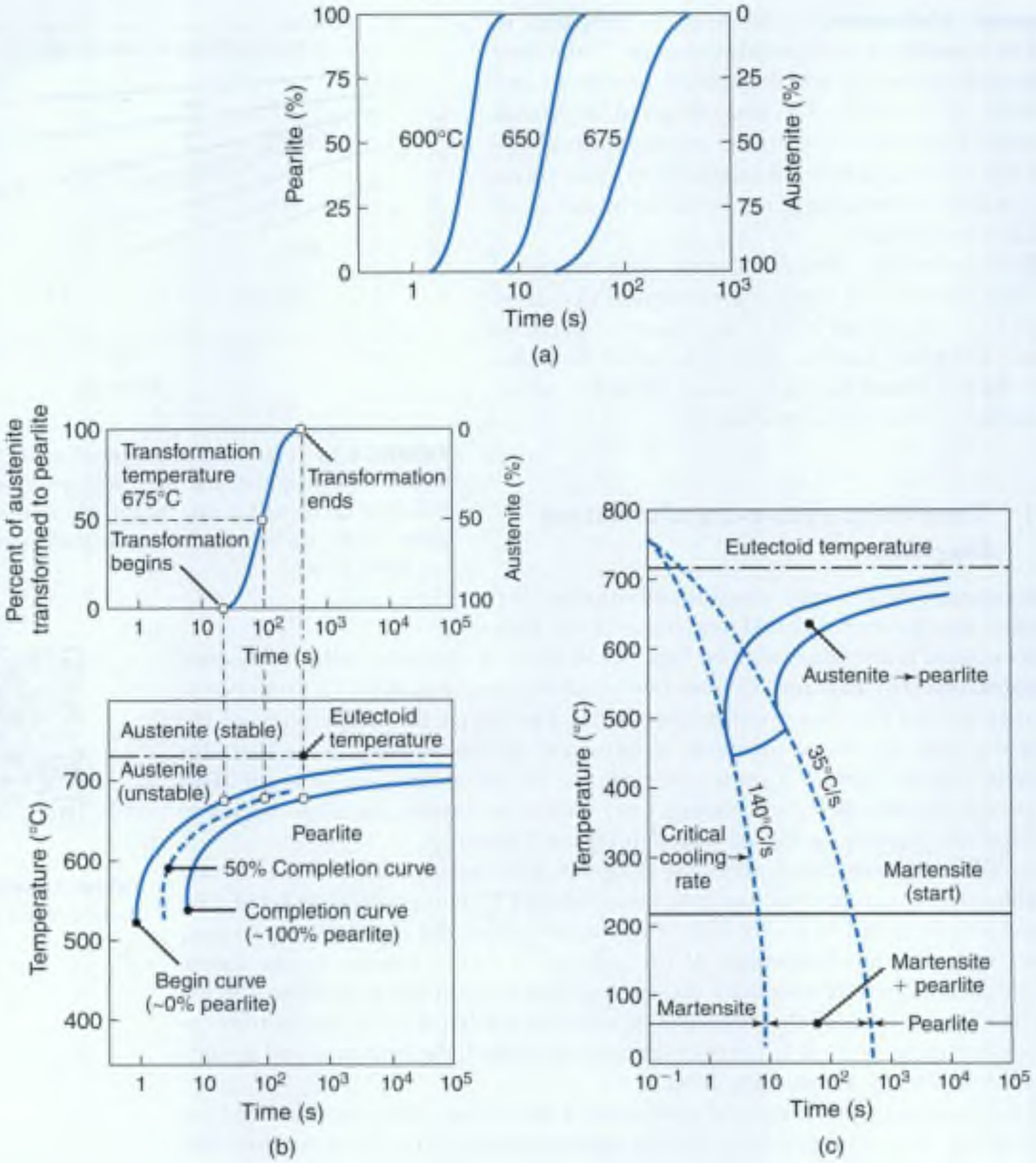


FIGURE 4.15 (a) Austenite-to-pearlite transformation of iron–carbon alloy as a function of time and temperature. (b) Isothermal transformation diagram obtained from (a) for a transformation temperature of 675°C. (c) Microstructures obtained for a eutectoid iron–carbon alloy as a function of cooling rate.

4.8.1 The End-quench Hardenability Test

In this commonly used **Jominy test** (after the American metallurgist W.E. Jominy, 1893–1976), a round test bar 100 mm long, made from a particular alloy, is **austenitized**—that is, heated to the proper temperature to form 100% austenite. It is then quenched directly at one end (Fig. 4.18a) with a stream of water at 24°C. The cooling rate thus varies throughout the length of the bar, the rate being

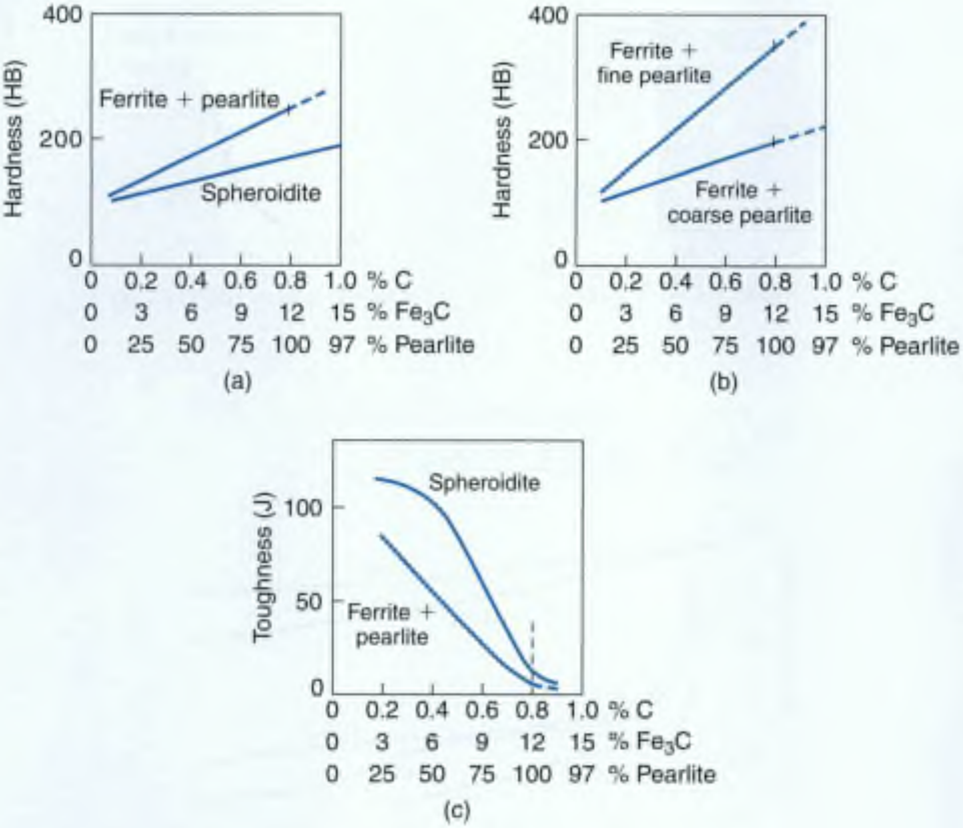


FIGURE 4.16 (a) and (b) Hardness and (c) toughness for annealed plain-carbon steels as a function of carbide shape. Carbides in the pearlite are lamellar. Fine pearlite is obtained by increasing the cooling rate. The spheroidite structure has sphere-like carbide particles.

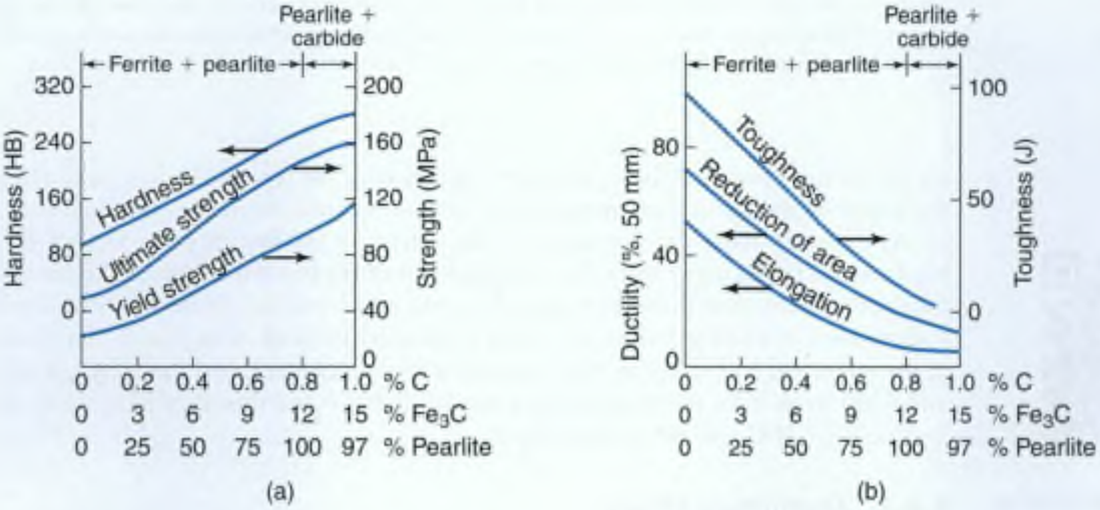


FIGURE 4.17 Mechanical properties of annealed steels as a function of composition and microstructure. Note in (a) the increase in hardness and strength, and in (b), the decrease in ductility and toughness, with increasing amounts of pearlite and iron carbide.

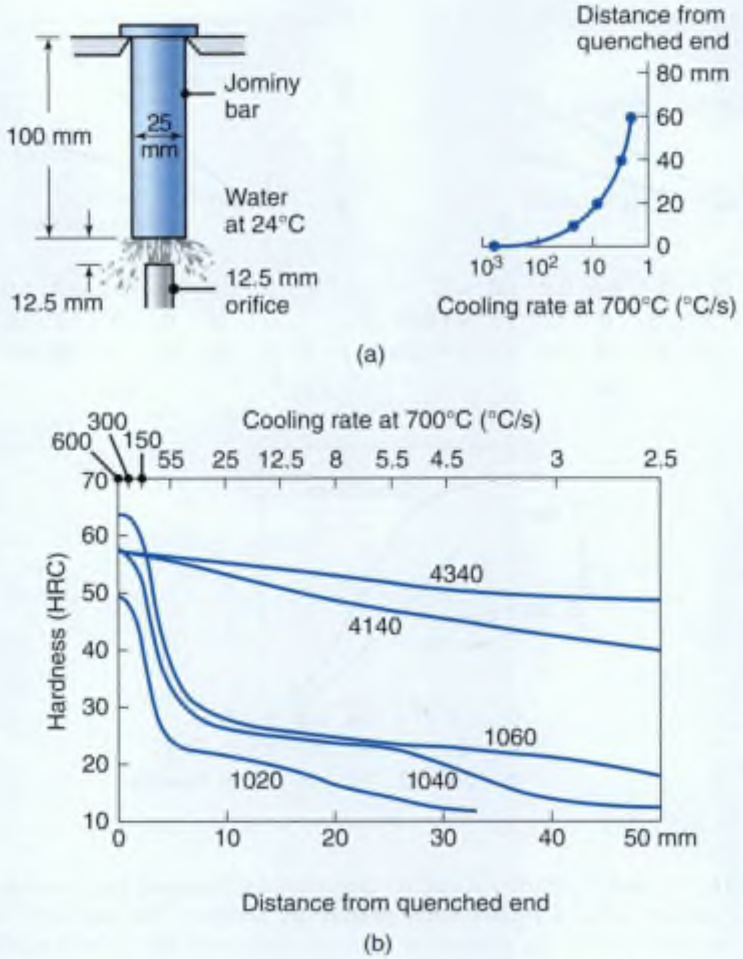


FIGURE 4.18 (a) End-quench test and cooling rate. (b) Hardenability curves for five different steels, as obtained from the end-quench test. Small variations in composition can change the shape of these curves. Each curve is actually a band, and its exact determination is important in the heat treatment of metals, for better control of properties.

highest at the lower end, being in direct contact with the water. The hardness along the length of the bar is then measured at various distances from the quenched end.

As expected from the discussion of the effects of cooling rates in Section 4.7, hardness decreases away from the quenched end of the bar (Fig. 4.18b). The greater the depth to which hardness increases, the greater the hardenability of the alloy. Each composition of an alloy has its particular **hardenability band**. Note that the hardness at the quenched end increases with increasing carbon content, and that 1040, 4140, and 4340 steels have the same carbon content (0.40%) and thus they have the same hardness (57 HRC) at the quenched end.

QR Code 4.2 Hardening and quenching balls with induction heating. (*Source:* Courtesy of GH Induction Atmospheres)

4.8.2 Quenching Media

The fluid used for quenching the heated specimen also has an effect on hardenability. Quenching may be carried out in water, brine (salt water), oil, molten salt, or air; caustic solutions, and polymer solutions; gases may also be used. Because of the differences in thermal conductivity, specific heat, and heat of vaporization of these media, the rate of cooling of the specimen (**severity of quench**) is also different. In relative terms and in decreasing order, the cooling capacities of several quenching media are: agitated brine, 5; still water, 1; still oil, 0.3; cold gas, 0.1; and still air, 0.02.

Agitation also is a significant factor in the rate of cooling; the more vigorous the agitation, the higher is the rate of cooling. In tool steels, the quenching medium is specified by a letter (see Table 5.7), such as W for water hardening, O for oil hardening, and A for air hardening. The cooling rate also depends on the surface-area-to-thickness or surface-area-to-volume ratio of the part to be quenched; the higher this ratio, the higher is the cooling rate. For example, a thick plate cools more slowly than a thin plate with the same surface area. These considerations are also significant in the cooling of metals and of plastics in casting and in molding processes (Sections 10.5.1 and 19.3).

Water is a common medium for rapid cooling. However, the heated specimen may form a **vapor blanket** along its surfaces due to the water-vapor bubbles that form when water boils at the metal–water interface. This blanket creates a barrier to heat conduction, because of the lower thermal conductivity of the vapor. Agitating the fluid or the part helps to reduce or eliminate the blanket; also, water may be sprayed onto the part under high pressure. Brine is an effective quenching medium, because salt helps to nucleate bubbles at the interfaces, which improves agitation; note, however, that brine can corrode the part.

Polymer quenchants can be used for ferrous as well as for nonferrous alloys; they have cooling characteristics that generally are between those of water and petroleum oils. Typical polymer quenchants are polyvinyl alcohol, polyalkaline oxide, polyvinyl pyrrolidone, and polyethyl oxazoline. These quenchants have such advantages as better control of hardness, elimination of fumes and fire (as may occur when oils are used as a quenchant), and reduction of corrosion (as may occur when water is used).

4.9 Heat Treatment of Nonferrous Alloys and Stainless Steels

Nonferrous alloys and some stainless steels cannot be heat treated by the techniques described for ferrous alloys. The reason is that nonferrous alloys do not undergo phase transformations like those in steels; the hardening and strengthening mechanisms for these alloys are fundamentally different. Heat-treatable aluminum alloys, copper alloys, and martensitic and some other stainless steels are hardened and strengthened by a process called **precipitation hardening**. In this process, small particles of a different phase, called **precipitates**, are uniformly dispersed in the matrix of the original phase (Fig. 4.3a). Precipitates form because the solid solubility of one element (one component of the alloy) in the other is exceeded.

Three stages are involved in precipitation hardening, which can best be described by reference to the phase diagram for the aluminum–copper system (Fig. 4.19a). For a composition of 95.5% Al–4.5% Cu, a single-phase (kappa phase) substitutional solid solution of copper (solute) in aluminum (solvent) exists between 500°C and 570°C. This *kappa phase* is aluminum rich, has an fcc structure, and is ductile. Below the lower temperature (that is, below the lower solubility curve) there are two phases: *kappa* (κ) and *theta* (θ) which is a hard intermetallic compound of $CuAl_2$. This alloy can be heat treated and its properties modified by two different methods: *solution treatment* and *precipitation hardening*.

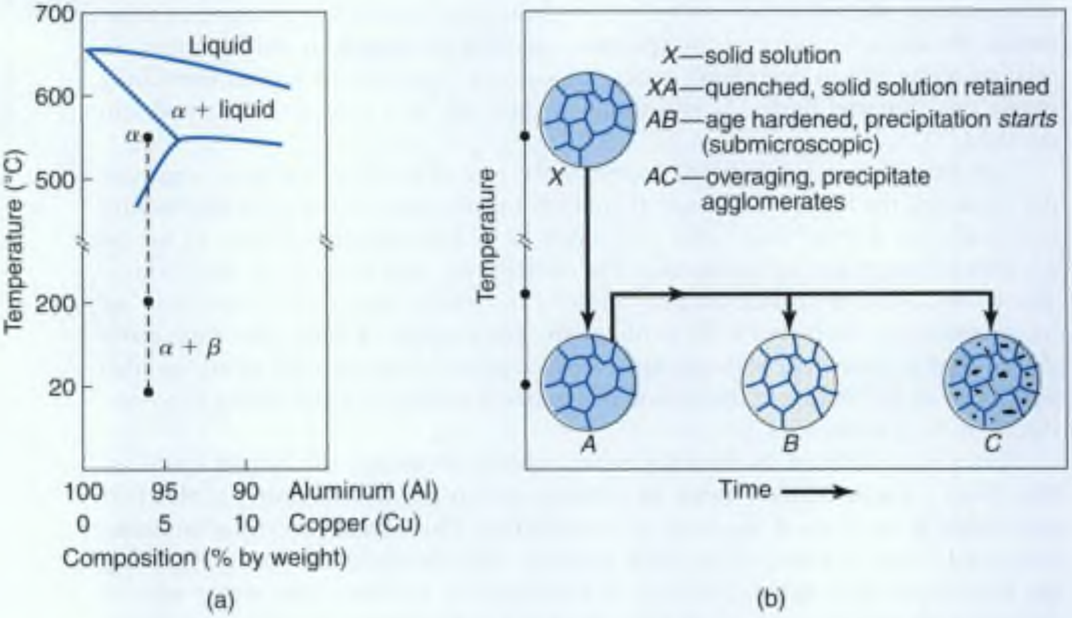


FIGURE 4.19 (a) Phase diagram for the aluminum–copper alloy system. (b) Various microstructures obtained during the age-hardening process.

4.9.1 Solution Treatment

In *solution treatment*, the alloy is heated to within the solid-solution kappa phase (say, 540°C) and then cooled rapidly, such as by quenching it in water. The structure obtained soon after quenching (*A* in Fig. 4.19b) consists only of the single phase kappa. This alloy has moderate strength and considerable ductility.

4.9.2 Precipitation Hardening

The structure obtained in *A* in Fig. 4.19b can be made stronger by *precipitation hardening*. In this process, the alloy is first reheated to an intermediate temperature and then held there for a period of time, during which precipitation takes place. The copper atoms diffuse to nucleation sites and combine with aluminum atoms. This process produces the theta phase, which forms as submicroscopic precipitates (shown in *B* by the small dots within the grains of the kappa phase). The resulting structure is stronger than that in *A*, although it is less ductile. The increase in strength is due to increased resistance to dislocation movement in the region of the precipitates.

Aging. Because the precipitation process is one of time and temperature, it is also called aging, and the property improvement is known as **age hardening**. If carried out above room temperature, the process is called **artificial aging**. Several aluminum alloys harden and become stronger over a period of time at room temperature; this process is then called **natural aging**. Such alloys are first quenched and then, if desired, they are shaped by plastic deformation at room temperature. Finally, they are allowed to develop strength and hardness by aging naturally. The rate of natural aging can be slowed by refrigerating the quenched alloy (**cryogenic treatment**).

In the precipitation process, if the reheated alloy is held at the elevated temperature for an extended period of time, the precipitates begin to coalesce and grow. They become larger but fewer in number, as is shown by the larger dots in C in Fig. 4.19b. This process is called **over-aging**, and the resulting alloy is softer and weaker.

There is an optimal time–temperature relationship in the aging process that must be followed in order to obtain the desired properties (Fig. 4.20). It is apparent that an aged alloy can be used only up to a certain maximum temperature in service, otherwise it will over-age and lose its strength and hardness. Although weaker, an over-aged part has better dimensional stability.

Maraging. This is a precipitation-hardening treatment for a spe cial group of high-strength iron-base alloys. The word *maraging* is derived from *martensite age hardening*, a process in which one or more intermetallic compounds are precipitated in a matrix of lowcarbon martensite. A typical maraging steel may contain 18% Ni, in addition to other elements, and aging takes place at 480°C. Because hardening by maraging does not depend on the cooling rate, uniform and full hardness can be obtained throughout large parts and with minimal distortion. Typical uses of maraging steels are in dies and tooling for casting, molding, forging, and extrusion (Parts II and III).

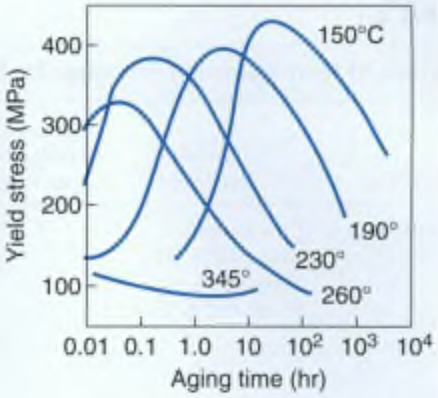


FIGURE 4.20 The effect of aging time and temperature on the yield stress of 2014-T4 aluminum alloy; note that, for each temperature, there is an optimal aging time for maximum strength.

4.10 Case Hardening

The heat-treatment processes described thus far involve microstructural alterations and property changes in the bulk of the component by means of *through hardening*. It is not always desirable to through harden parts, because a hard part lacks the required toughness for some applications. For example, a small surface crack could propagate rapidly through a part and cause sudden and total failure. In many cases, modification of only the *surface properties* of a part (hence, the term *surface* or *case hardening*) is desirable. This widely used method is particularly useful for improving resistance to surface indentation, fatigue, and wear. Typical applications for case hardening are gear teeth, cams, shafts, bearings, fasteners, pins, automotive clutch plates, tools, and dies.

Several case-hardening processes are available (Table 4.1):

1. **Carburizing** (gas, liquid, and pack carburizing)
2. **Carbonitriding**
3. **Cyaniding**
4. **Nitriding**
5. **Boronizing**
6. **Flame hardening**
7. **Induction hardening**
8. **Laser-beam hardening**

Basically, these are operations where the component is heated in an atmosphere containing elements (such as carbon, nitrogen, or boron) that alter the composition, microstructure, and properties of surface layers. For steels with sufficiently high carbon content, surface hardening takes place without using any of these additional elements; only the heat-treatment processes described in Section 4.7 are needed to alter the microstructures, usually by either flame hardening or induction hardening, as outlined in Table 4.1.

TABLE 4.1

Outline of Heat-treatment Processes for Surface Hardening

Process	Metals hardened	Element added to surface	Procedure	General characteristics	Typical applications
Carburizing	Low-carbon steel (0.2% C), alloy steels (0.08–0.2% C)	C	Heat steel at 870°C–950°C in an atmosphere of carbonaceous gases (gas carburizing) or carbon-containing solids (pack carburizing); then quench.	A hard, high-carbon surface is produced. Hardness = 55–65 HRC. Case depth = <0.5–1.5 mm. Some distortion of part during heat treatment.	Gears, cams, shafts, bearings, piston pins, sprockets, clutch plates
Carbonitriding	Low-carbon steel	C and N	Heat steel at 700°C–800°C in an atmosphere of carbonaceous gas and ammonia; then quench in oil.	Surface hardness = 55–62 HRC. Case depth = 0.07–0.5 mm. Less distortion than in carburizing.	Bolts, nuts, gears
Cyaniding	Low-carbon steel (0.2% C), alloy steels (0.08–0.2% C)	C and N	Heat steel at 760°C–845°C in a molten bath of solutions of cyanide (e.g., 30% sodium cyanide) and other salts.	Surface hardness up to 65 HRC. Case depth = 0.025–0.25 mm. Some distortion.	Bolts, nuts, screws, small gears
Nitriding	Steels (1% Al, 1.5% Cr, 0.3% Mo), alloy steels (Cr, Mo), stainless steels, high-speed tool steels	N	Heat steel at 500°C–600°C in an atmosphere of ammonia gas or mixtures of molten cyanide salts; no further treatment.	Surface hardness up to 1100 HV. Case depth = 0.1–0.6 mm and 0.02–0.07 mm for high-speed steel.	Gears, shafts, sprockets, valves, cutters, boring bars, fuel-injection pump parts
Boronizing	Steels	B	Part is heated using boron-containing gas or solid in contact with part.	Extremely hard and wear-resistant surface. Case depth = 0.025–0.075 mm.	Tool and die steels
Flame hardening	Medium-carbon steels, cast irons	None	Surface is heated with an oxyacetylene torch, then quenched with water spray or other quenching methods.	Surface hardness = 50–60 HRC. Case depth = 0.7–6 mm. Little distortion.	Gear and sprocket teeth, axles, crankshafts, piston rods, lathe beds and centers
Induction hardening	Same as above	None	Metal part is placed in copper induction coils and is heated by high frequency current; then quenched.	Same as above	Same as above

Laser beams and **electron beams** (Sections 27.6 and 27.7) are used effectively to harden small as well as large surfaces, such as gears, valves, punches, and engine cylinders. The depth of the case-hardened layer is usually less than 2.5 mm. These methods are also used for through hardening of relatively small parts. The main advantages of laser surface hardening are close control of power input, low part distortion, and the ability to reach areas that may be inaccessible by other means.

Because case hardening involves a localized layer, case-hardened parts have a *hardness gradient*. Typically, the hardness is maximum at the surface and decreases inward, the rate of decrease depending on the composition and physical properties of the metal and processing variables. Surface-hardening techniques can also be used for *tempering* (Section 4.11) and for modifying the properties of surfaces that have been subjected to heat treatment. Several other processes and techniques for surface hardening, such as shot peening and surface rolling, to improve wear resistance and other characteristics, are described in Section 34.2.

Decarburization is the phenomenon in which alloys lose carbon from their surfaces as a result of heat treatment or of hot working in a medium, usually oxygen, that reacts with the carbon. Decarburization is undesirable because it affects the hardenability of the surfaces of a part, by lowering its carbon content; it also adversely affects the hardness, strength, and fatigue life of steels, significantly lowering their endurance limit.

4.11 Annealing

Annealing is a general term used to describe the restoration of a cold-worked or heat-treated alloy to its original properties—for instance, to increase ductility (and hence formability) and to reduce hardness and strength, or to modify the microstructure of the alloy. The annealing process is also used to relieve residual stresses in a part, as well as to improve machinability and dimensional stability. The term "annealing" also applies to the thermal treatment of glass and similar products (Section 18.4), castings, and weldments.

The annealing process consists of the following steps:

1. Heating the workpiece to a specific temperature in a furnace
2. Holding it at that temperature for a period of time (soaking)
3. Cooling the workpiece, in air or in a furnace

The annealing process may be carried out in an inert or a controlled atmosphere, or it may be performed at lower temperatures to minimize or prevent surface oxidation.

The *annealing temperature* may be higher than the material's recrystallization temperature, depending on the degree of cold work. For example, the recrystallization temperature for copper ranges between 200° and 300°C, whereas the annealing temperature required to fully recover the original properties ranges from 260° to 650°C, depending on the degree of prior cold work (see also Section 1.7).

Full annealing is a term applied to ferrous alloys. The steel is heated to above A_1 or A_3 (Fig. 4.21) and the cooling takes place slowly [typically at 10°C per hour], in a furnace, after which it is turned off. The structure obtained through full annealing is coarse pearlite, which is soft and ductile and has small, uniform grains.

To avoid excessive softness from annealing of steels, the cooling cycle may be done completely in still air. This process is called **normalizing**, to indicate that

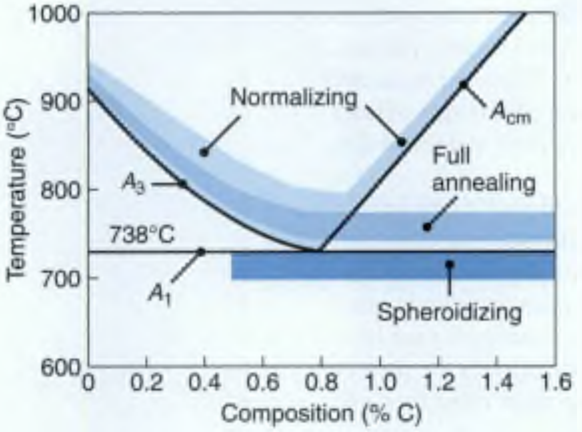


FIGURE 4.21 Heat-treating temperature ranges for plain-carbon steels, as indicated on the iron–iron carbide phase diagram.

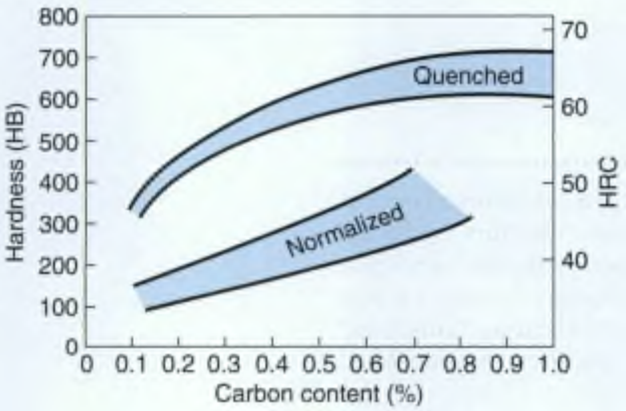


FIGURE 4.22 Hardness of steels in the quenched and normalized conditions as a function of carbon content.

the part is heated to a temperature above A_3 or A_{cm} in order to transform the structure to austenite. Normalizing results in somewhat higher strength and hardness, and lower ductility, than does full annealing (Fig. 4.22). The structure obtained is fine pearlite, with small, uniform grains. Normalizing is generally carried out to refine the grain structure, obtain uniform structure (homogenization), decrease residual stresses, and improve machinability.

The structure of spheroidites and the procedure for obtaining it are described in Section 4.7 and shown in Figs. 4.12 and 4.21. *Spheroidizing annealing* improves the cold workability (Section 14.5) and the machinability of steels (Section 21.7).

Stress-relief Annealing. To reduce or eliminate residual stresses, a workpiece is generally subjected to *stress-relief annealing*, or **stress relieving**. The temperature and time required for this process depend on the material and on the magnitude of the residual stresses present. The residual stresses may have been induced during forming, machining, or caused by volume changes during phase transformations.

Tempering. If steels are hardened by heat treatment, *tempering* (also called **drawing**) is used in order to reduce brittleness, increase ductility and toughness, and reduce residual stresses. The term "tempering" is also used for glasses (Section 8). In tempering, the steel is heated to a specific temperature, depending on its composition, and then cooled at a prescribed rate. The results of tempering for an oil-quenched AISI 4340 steel are shown in Fig. 4.23.

Alloy steels may undergo **temper embrittlement**, which is caused by the segregation of impurities along the grain boundaries, at temperatures between 480°C and 590°C.

Austempering. In *austempering*, the heated steel is quenched from the austenitizing temperature rapidly, to avoid formation of ferrite or pearlite. It is held at a certain temperature until isothermal transformation from austenite to bainite is complete. It is then cooled to room temperature, usually in still air and at a moderate rate in order to avoid thermal gradients within the part. The quenching medium most commonly used is molten salt, at temperatures ranging from 160°C to 750°C.

Austempering is often substituted for conventional quenching and tempering, either to reduce the tendency for cracking and distortion during quenching or to improve ductility and toughness while maintaining hardness. Because of the shorter cycle time involved, this process is also economical.

Martempering (Marquenching). In *martempering*, steel or cast iron is first quenched from the austenitizing temperature in a hot fluid medium, such as hot oil or molten salt. Next, it is held at that temperature until the temperature is uniform throughout the part. It is cooled at a moderate rate, such as in air, in order to avoid excessive temperature gradients within the part. Usually, the part is subsequently tempered, because the structure obtained is otherwise primarily untempered martensite, and thus not suitable for most applications.

Martempered steels have lower tendency to crack, distort, or develop residual stresses during heat treatment. In **modified martempering**, the quenching temperature is lower, and thus the cooling rate is higher. The process is suitable for steels with lower hardenability.

Ausforming. In *ausforming*, also called **thermomechanical processing**, the steel is formed into desired shapes, within controlled ranges of temperature and time to avoid formation of nonmartensitic transformation products. The part is then cooled at various rates to obtain the desired microstructures.

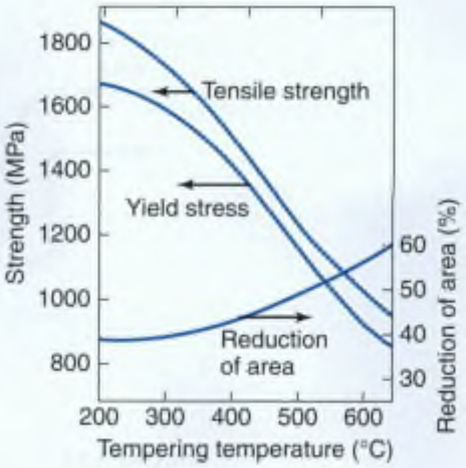


FIGURE 4.23 Mechanical properties of oil-quenched 4340 steel as a function of tempering temperature.

4.12 Heat-treating Furnaces and Equipment

Two basic types of furnaces are used for heat treating: batch furnaces and continuous furnaces. Because they consume much energy, their insulation and efficiency are important design considerations, as are their initial cost, the personnel needed for their operation and maintenance, and their safe use.

Uniform temperature and accurate control of temperature–time cycles are important. Modern furnaces are equipped with various electronic controls, including computer-controlled systems, programmed to run through a complete heat-treating cycle repeatably and with reproducible accuracy. The fuels used are usually natural gas, oil, or electricity (for resistance or induction heating); the type of fuel affects the furnace's atmosphere. Unlike electric heating, gas or oil introduces combustion products into the furnace. Electrical heating, however, has a slower start-up time and is more difficult to adjust and control.

Batch Furnaces. In a *batch furnace*, the parts to be heat treated are loaded into and unloaded from the furnace in individual batches. The furnace basically consists of an insulated chamber, a heating system, and an access door or doors. Batch furnaces are of the following basic types:

1. A **box furnace** is a horizontal rectangular chamber, with one or two access doors through which parts are loaded.
2. A **pit furnace** is a vertical pit below ground level into which the parts are lowered.
3. A **bell furnace** is a round or rectangular box furnace without a bottom, and is lowered over stacked parts that are to be heat treated; this type of furnace is particularly suitable for coils of wire, rods, and sheet metal.
4. In an **elevator furnace**, the parts to be heat treated are loaded onto a car platform, rolled into position, and then raised into the furnace.

Continuous Furnaces. In this type of furnace, the parts to be heat treated move continuously through the furnace on conveyors of various designs.

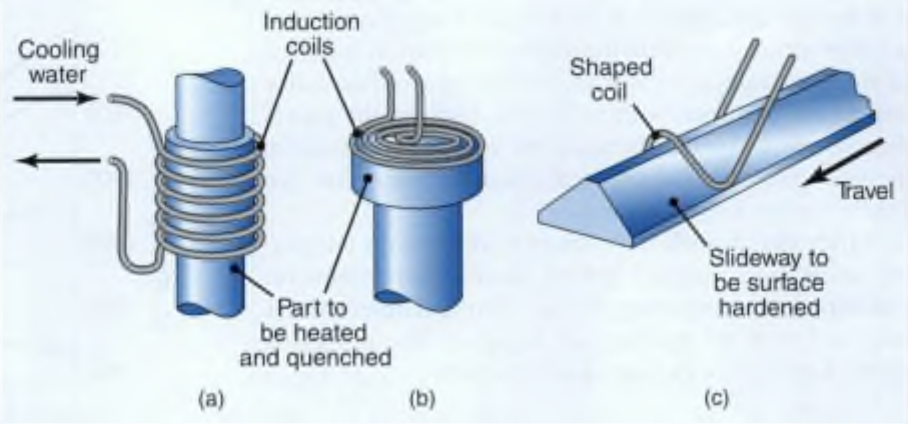


FIGURE 4.24 Types of coils used in induction heating of various surfaces of parts.

Salt-bath Furnaces. Because of their high heating rates and better control of uniformity of temperature, *salt baths* are commonly used in various heat-treating operations, particularly for nonferrous strip and wire. Heating rates are high because of the higher thermal conductivity of liquid salts as compared with that of air or gases.

Fluidized Beds. Dry, fine, and loose solid particles, usually aluminum oxide, are heated and suspended in a chamber by an upward flow of hot gas at various speeds. The parts to be heat treated are then placed within the floating particles, hence the term *fluidized bed*.

Induction Heating. In this method, the part is heated rapidly by the electromagnetic field generated by an *induction coil* carrying alternating current, which induces eddy currents in the part. The coil, which can be shaped to fit the contour of the part to be heat treated (Fig. 4.24), is made of copper or of a copper-base alloy. The coil, which is usually water cooled, may be designed to quench the part as well.

Furnace Atmospheres. The atmospheres in furnaces can be controlled so as to avoid oxidation, tarnishing, and decarburization of ferrous alloys heated to elevated temperatures. Oxygen causes corrosion, rusting, and scaling. Carbon dioxide, which has various effects, may be neutral or decarburizing, depending on its concentration in the furnace atmosphere. Nitrogen is a common neutral atmosphere, and a vacuum provides a completely neutral atmosphere. Water vapor in the furnace causes oxidation of steels, resulting in a blue color. The term **bluing** is used to describe formation of a thin, blue film of oxide on finished parts to improve their appearance and their resistance to oxidation.

4.13 Design Considerations for Heat Treating

In addition to metallurgical factors, successful heat treating involves design considerations for avoiding such problems as cracking, distortion, and nonuniformity of properties throughout and among heat-treated parts. The rate of cooling during quenching may not be uniform, particularly in complex shapes having varying cross-sections and thicknesses, producing severe temperature gradients in the part.

QR Code 4.3 Demonstration of induction heating. (*Source:* Courtesy of GH Induction Atmospheres)

Nonuniformity can lead to variations in contraction, resulting in thermal stresses that may cause warping or cracking of the part. Nonuniform cooling also causes residual stresses in the part, which then can lead to stress-corrosion cracking. The quenching method selected, the care taken during the operation, and the selection of a proper quenching medium and temperature also are important considerations.

As a general guideline for part design for heat treating.

- Sharp internal or external corners should be avoided, as otherwise stress concentrations at these corners may raise the level of stresses high enough to cause cracking.
- The part should have its thicknesses as nearly uniform as possible.
- The transition between regions of different thicknesses should be made smooth.
- Parts with holes, grooves, keyways, splines, and asymmetrical shapes may be difficult to heat treat, because they may crack during quenching.
- Large surfaces with thin cross-sections are likely to warp.
- Hot forgings and hot steel-mill products may have a *decarburized skin* which may not respond successfully to heat treatment.

SUMMARY

- Commercially pure metals generally do not have sufficient strength for most engineering applications; consequently, they must be alloyed with various elements which alter their structures and properties. Important concepts in alloying are the solubility of alloying elements in a host metal and the phases present at various ranges of temperature and composition.
- Alloys basically have two forms: solid solutions and intermetallic compounds. Solid solutions may be substitutional or interstitial. There are certain conditions pertaining to the crystal structure and atomic radii that have to be met in order to develop these structures.
- Phase diagrams show the relationships among the temperature, composition, and phases present in a particular alloy system. As temperature is decreased at various rates, correspondingly various transformations take place, resulting in microstructures that have widely different characteristics and properties.
- Among binary systems, the most important is the iron–carbon system, which includes a wide range of steels and cast irons. Important components in this system are ferrite, austenite, and cementite. The basic types of cast irons are gray iron, ductile (nodular) iron, white iron, malleable iron, and compacted-graphite iron.
- The mechanisms for hardening and strengthening metal alloys basically involve heating the alloy and subsequently quenching it at varying cooling rates. Important phase transformations then take place, producing structures such as pearlite (fine or coarse), spheroidite, bainite, and martensite. Heat treating of nonferrous alloys and stainless steels involves solution treatment and precipitation hardening.
- The furnace atmosphere, the quenchants used, the control and characteristics of the equipment, and the shape of the parts to be heat treated are important heat-treatment considerations
- Hardenability is the capability of an alloy to be hardened by heat treatment. The Jominy end-quench hardenability test is a method commonly used to determine hardenability bands for alloys.

- Case hardening is an important process for improving the wear and fatigue resistance of parts. Several methods are available, such as carburizing, nitriding, induction hardening, and laser hardening.
- Annealing includes normalizing, process annealing, stress relieving, tempering, austempering, and martempering, each with the purpose of enhancing the ductility and toughness of heat-treated parts.

KEY TERMS

Age hardening
Aging
Alloy
Annealing
Austempering
Austenite
Bainite
Case hardening
Cast iron
Cementite
Curie temperature
Decarburization
Distortion
End-quench test
Equilibrium diagram
Eutectic point
Eutectoid reaction
Ferrite
Furnaces
Hardenability
Heat treatment
Intermetallic compounds
Iron–carbon system
Jominy test
Maraging
Martempering
Martensite
Normalizing
Over-aging
Pearlite
Phase diagram
Phase transformations
Precipitation hardening
Pure metals
Retained austenite
Solid solution
Solute
Solution treatment
Solvent
Spheroidite
Stress relieving
Tempered martensite
Tempering
Time–temperature–transformation diagrams
Two-phase systems

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REVIEW QUESTIONS

4.1 Describe the difference between a solute and a solvent.

4.2 What is a solid solution?

4.3 What are the conditions for obtaining (a) substitutional and (b) interstitial solid solutions?

4.4 Describe the difference between a single-phase and a two-phase system.

4.5 What is an induction heater? What kind of part shapes can be heated by induction heating?

4.6 Describe the major features of a phase diagram.

4.7 What do the terms "equilibrium" and "constitutional," as applied to phase diagrams, indicate?

4.8 What is the difference between "eutectic" and "eutectoid"?

4.9 What is tempering? Why is it performed?

4.10 Explain what is meant by "severity of quenching."

4.11 What are precipitates? Why are they significant in precipitation hardening?

4.12 What is the difference between natural and artificial aging?

4.13 Describe the characteristics of ferrite, austenite, and cementite.

4.14 What is the purpose of annealing?

4.15 What is a time–temperature–transformation diagram? How is it used?

QUALITATIVE PROBLEMS

4.16 You may have seen some technical literature on products stating that certain parts in those products are "heat treated." Describe briefly your understanding of this term and why the manufacturer includes it.

4.17 Describe the engineering significance of the existence of a eutectic point in phase diagrams.

4.18 What is the difference between hardness and hardenability?

4.19 Referring to Table 4.1, explain why the items listed under typical applications are suitable for surface hardening.

4.20 It generally is not desirable to use steels in their as-quenched condition. Explain why.

4.21 Describe the differences between case hardening and through hardening, insofar as engineering applications of metals are concerned.

4.22 Describe the characteristics of (a) an alloy, (b) pearlite, (c) austenite, (d) martensite, and (e) cementite.

4.23 Explain why carbon, among all elements, is so effective in imparting strength to iron in the form of steel.

4.24 How does the shape of graphite in cast iron affect its properties?

4.25 In Section 4.8.2, several fluids are listed in terms of their cooling capacity in quenching. Which physical properties of these fluids influence their cooling capacity?

4.26 Why is it important to know the characteristics of heat-treating furnaces? Explain.

4.27 Explain why, in the abscissa of Fig. 4.16c, the percentage of pearlite begins to decrease after 0.8% carbon content is reached.

4.28 What is the significance of decarburization? Give some examples.

4.29 Explain your understanding of size distortion and shape distortion in heat-treated parts, and describe their causes.

4.30 Comment on your observations regarding Fig. 4.18b.

QUANTITATIVE PROBLEMS

4.31 Design a heat-treating cycle for carbon steel, including temperature and exposure times, to produce (a) pearlite–martensite steels and (b) bainite–martensite steels.

4.32 Using Fig. 4.4, estimate the following quantities for a 75% Cu–25% Ni alloy: (a) the liquidus temperature, (b) the solidus temperature, (c) the percentage of nickel in the liquid at 1150°C, (d) the major phase at 1150°C, and (e) the ratio of solid to liquid at 1150°C.

4.33 Extrapolating the curves in Fig. 4.14, estimate the time that it would take for 1080 steel to soften to 40 HRC at (a) 300°C and (b) 400°C.

4.34 A typical steel for tubing is AISI 1040, and one for music wire is 1085. Considering their applications, explain the reason for the difference in carbon content.

SYNTHESIS, DESIGN, AND PROJECTS

4.35 It was stated in this chapter that, in parts design, sharp corners should be avoided in order to reduce the tendency toward cracking during heat treatment. If it is essential for a part to have sharp corners for functional purposes, and it still requires heat treatment, what method would you recommend for manufacturing this part?

4.36 The heat-treatment processes for surface hardening are summarized in Table 4.1. Each of these processes involves different equipment, procedures, and cycle times; as a result, each incurs different costs. Review the available literature, contact various companies, and then make a similar table outlining the costs involved in each process.

4.37 It can be seen that, as a result of heat treatment, parts can undergo size distortion and shape distortion to various degrees. By referring to the Bibliography at the end of this chapter, make a survey of the technical literature and report quantitative data regarding the distortions of parts having different shapes.

4.38 Figure 4.18b shows hardness distributions in end-quench tests, as measured along the length of the round bar. Make a simple qualitative sketch showing the hardness distribution across the diameter of the bar. Would the shape of the curve depend on the bar's carbon content? Explain.

4.39 Throughout this chapter, you have seen specific examples of the importance and the benefits of heat-treating parts or certain regions of parts. Refer to the Bibliography at the end of this chapter, make a survey of the heat-treating literature, and then compile several examples and illustrations of parts that have been heat treated.

4.40 Refer to Fig. 4.24, and think of a variety of other part shapes to be heat treated, and design coils that are appropriate for these shapes. Describe how different your designs would be if the parts have varying shapes along their length (such as from a square at one end to a round shape at the other end).

4.41 Inspect various parts in your car or home, and identify those that are likely to have been case hardened. Explain your reasons.

CHAPTER 5

Ferrous Metals and Alloys: Production, General Properties, and Applications

CASE STUDIES:

- Ferrous metals and alloys are the most widely used structural materials, generally because of their properties and performance, ease of manufacturing, and low cost.
- The chapter opens with a brief outline of iron and steel production from ore, including descriptions of furnaces and foundry operations.
- The casting of ingots is described, followed by continuous casting operations, which are now into wide use for producing high-quality metals in large volumes.
- The chapter then discusses in detail the properties and applications of ferrous metals, including cast irons, carbon and alloy steels, stainless steels, and tool and die steels.

5.1 Introduction

By virtue of their relatively low cost and wide range of mechanical, physical, and chemical properties, **ferrous metals and alloys** are among the most useful of all metals. They contain iron as their base metal and are generally classified as *carbon and alloy steels*, *stainless steels*, *tool and die steels*, *cast irons*, and *cast steels*. **Steel** refers to a ferrous alloy, which can be as simple as an alloy of iron and carbon, but also often containing a number of alloying elements to impart various properties. Ferrous alloys are produced as

- Sheet steel, for automobiles, appliances, and containers
- Plates, for boilers, ships, and bridges
- Structural members, such as I-beams, bar products, axles, crankshafts, and railroad rails
- Tools, dies, and molds
- Rods and wire, for fasteners such as bolts, rivets, nuts, and staples

Carbon steels are the least expensive of all structural metals. As an example of their widespread use, ferrous metals make up 70–85% by weight of structural members and mechanical components. The average U.S. passenger vehicle (including trucks and sport utility vehicles) contains about 1200 kg of steel, accounting for about 60% of its total weight.

The use of iron and steel as structural materials has been one of the most important technological developments. Primitive ferrous tools, which first appeared about 4000 to 3000 B.C., were made from meteoritic iron, obtained from meteorites that had struck the earth. True ironworking began in Asia Minor in about 1100 B.C. and signaled the advent of the *Iron Age*. Invention of the blast furnace in about 1340 A.D. made possible the production of large quantities of high-quality iron and steel. (See Table I.2.)

5.2 Production of Iron and Steel

5.2.1 Raw Materials

The three basic materials used in iron- and steelmaking are **iron ore, limestone**, and **coke**. Although it does not occur in a free state in nature, *iron* is one of the most abundant elements (in the form of various ores) in the world, making up about 5% of the earth's crust. The principal iron ores are (a) *taconite* (a black flintlike rock), (b) *hematite* (an iron-oxide mineral), and (c) *limonite* (an iron oxide containing water). After it is mined, the ore is crushed into fine particles, the impurities are removed (by various means such as magnetic separation), and the ore is formed into pellets, balls, or briquettes, using water and various binders. Typically, pellets are about 65% pure iron and about 25 mm in diameter. The concentrated iron ore is referred to as *beneficiated* (as are other concentrated ores). Some iron-rich ores are used directly, without pelletizing.

Coke is obtained from special grades of bituminous coal (a soft coal rich in volatile hydrocarbons and tars) that are heated in vertical ovens to temperatures of up to 1150°C, and then cooled with water in quenching towers. Coke has several functions in steelmaking, including (a) generating the high level of heat required for the chemical reactions in ironmaking to take place and (b) producing carbon monoxide (a reducing gas, meaning that it removes oxygen), to reduce iron oxide to iron. The chemical by-products of coke are used in the synthesis of plastics and of chemical compounds; the gases evolved during the conversion of coal to coke are used as fuel for plant operations.

The function of *limestone* (calcium carbonate) is to remove impurities from the molten iron. The limestone reacts chemically with impurities, acting like a **flux** (meaning to flow as a fluid) that causes the impurities to melt at a low temperature. The limestone combines with the impurities and forms a **slag** (which, being light, floats over the molten metal and subsequently is removed). *Dolomite* (an ore of calcium magnesium carbonate) also is used as a flux. The slag is later used in making cement, fertilizers, glass, building materials, rock-wool insulation, and road ballast.

5.2.2 Ironmaking

The three raw materials described above are dumped into the top of a **blast furnace** (Fig. 5.1), an operation called *charging the furnace*. A blast furnace is basically a large steel cylinder lined with refractory (heat-resistant) brick; it has the height of about a 10-story building. The charge mixture is melted in a reaction at 1650°C, with air preheated to about 1100°C and *blasted* into the furnace (hence the term "blast furnace"), through nozzles called *tuyeres*. Although a number of other reactions may take place, the basic reaction is that of oxygen combining with carbon to produce carbon monoxide, which, in turn, reacts with the iron oxide, reducing it to **iron**. Preheating the incoming air is necessary because the burning coke alone does not produce sufficiently high temperatures for these reactions to occur.

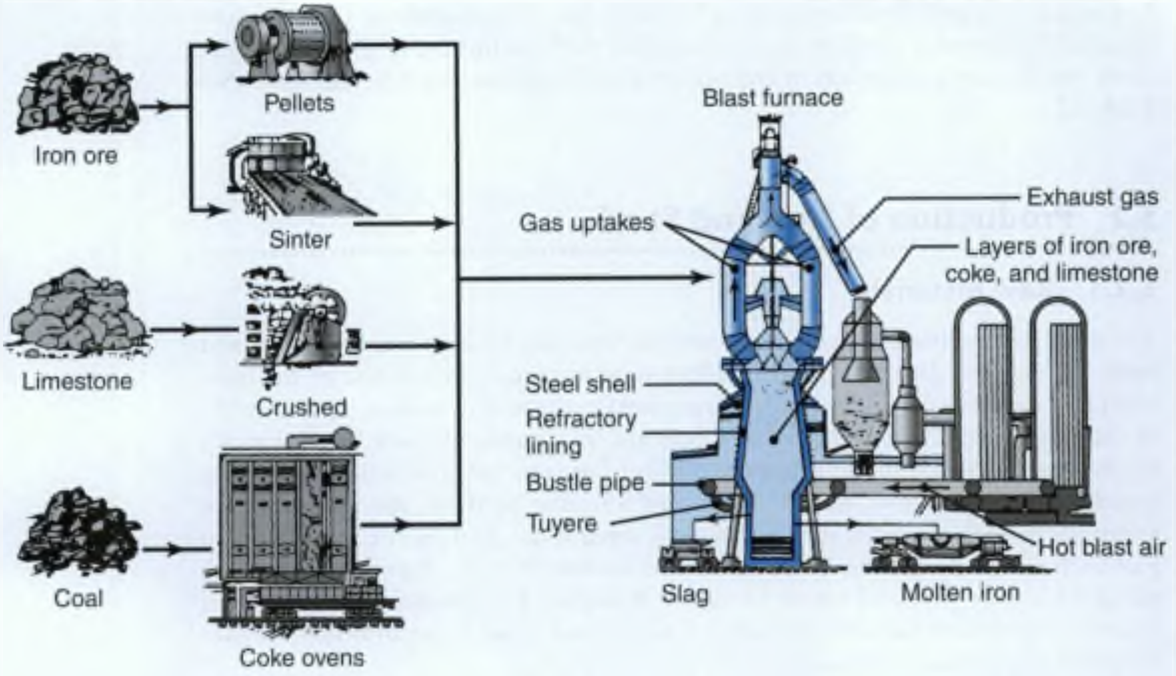

FIGURE 5.1 Schematic illustration of a blast furnace.

The molten metal accumulates at the bottom of the blast furnace, while the impurities float to the top. At intervals of four to five hours, the molten metal is drawn off (*tapped*) into ladle cars, each holding as much as 145 metric tons of molten iron. The molten metal at this stage is called **pig iron**, or simply **hot metal**, and has a typical composition of 4% C, 1.5% Si, 1% Mn, 0.04% S, 0.4% P, with the rest being iron. The word **pig** comes from the early practice of pouring the molten iron into small sand molds arranged around a main channel, reminding early ironworkers of a litter of small pigs crowding against their mother sow. The solidified metal is then used in making iron and steels.

5.2.3 Steelmaking

Steel was first produced in China and Japan about 600 to 800 A.D. The steelmaking process is essentially one of **refining** the pig iron by (a) reducing the percentages of manganese, silicon, carbon, and other elements and (b) controlling the composition of the output through the addition of various elements. The molten metal from the blast furnace is transported into one of four types of furnaces: **open-hearth**, **electric**, **vacuum**, or **basic-oxygen**. The name "open-hearth" derives from the shallow hearth shape that is open directly to the flames that melt the metal. Developed in the 1860s, the open-hearth furnace essentially has been replaced by electric furnaces and by the basic-oxygen process, because the latter two are more efficient and produce steels of better quality.

Electric Furnace. The source of heat in this type of furnace is a continuous electric arc that is formed between the electrodes and the charged metal (Figs. 5.2a and b); temperatures as high as 1925°C are generated. There are usually three

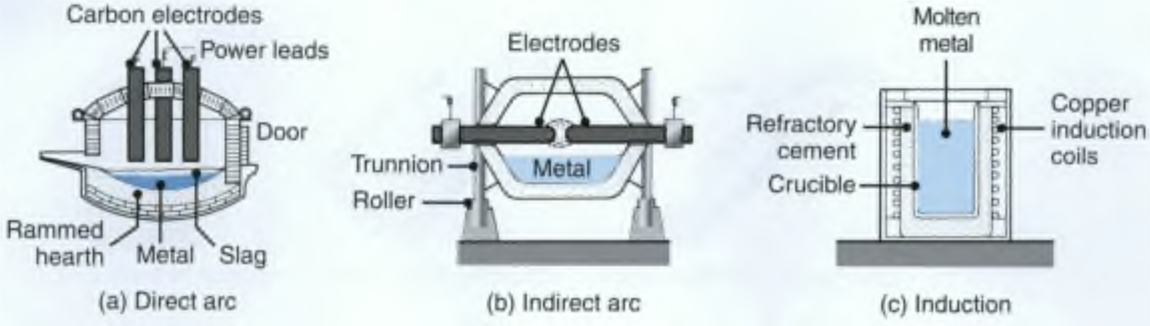

FIGURE 5.2 Schematic illustration of types of electric furnaces.

graphite electrodes, and they can be as large as 750 mm in diameter and 1.5–2.5 m in length. Their height in the furnace can be adjusted in response to the amount of metal present and the amount of wear of the electrodes.

Steel scrap and a small amount of carbon and limestone are first dropped into the electric furnace through the open roof. The roof is then closed and the electrodes are lowered. The power is turned on, and within a period of about two hours, temperatures increase sufficiently to melt the metal. The current is then shut off, the electrodes are raised, the furnace is tilted, and the molten metal is poured into a *ladle* (a receptacle used for transferring and pouring molten metal). Electric-furnace capacities range from 55 to 82 metric tons of steel per day, and the quality of steel produced is better than that from either the open-hearth or the basic-oxygen process (see below).

For smaller quantities, electric furnaces can be of the **induction** type (Fig. 5.2c). The metal is placed in a **crucible**, a large pot made of refractory material and surrounded with a copper coil through which alternating current is passed. The induced current in the charge generates heat and melts the metal.

Basic-oxygen Furnace. The basic-oxygen furnace (BOF) is the fastest and by far the most common steelmaking furnace. Typically, 181 metric tons of molten pig iron and 82 metric tons of scrap are charged into a vessel (Fig. 5.3a); some units can hold as much as 317 metric tons. Pure oxygen is then blown into the furnace, for about 20 min, through a water-cooled *lance* (a long tube) and under a pressure of about 1250 kPa, as shown in Fig. 5.3b. Fluxing agents (such as calcium or magnesium oxide) are added through a chute. The process is known as *basic* because of the pH of these fluxing agents.

The vigorous agitation of the oxygen refines the molten metal by an oxidation process, in which iron oxide is produced. The oxide reacts with the carbon in the molten metal, producing carbon monoxide and carbon dioxide. The lance is then retracted, and the furnace is tapped by tilting it (note the opening in Fig. 5.3c for the molten metal); then the slag is removed by tilting the furnace in the opposite direction. The BOF process is capable of refining 227 metric tons of steel in 35–50 min. Most BOF steels, which have low impurity levels and are of better quality than openhearth furnace steels, are processed into plates, sheets, and various structural shapes, such as I-beams and channels (see Fig. 13.1).

Vacuum Furnace. Steel may also be melted in induction furnaces from which the air has been removed, similar to the one shown in Fig. 5.2c. Cooling is accomplished by injecting an inert gas (typically argon) at high pressure into the furnace. Because the operation removes gaseous impurities from the molten metal and prevents oxidation,

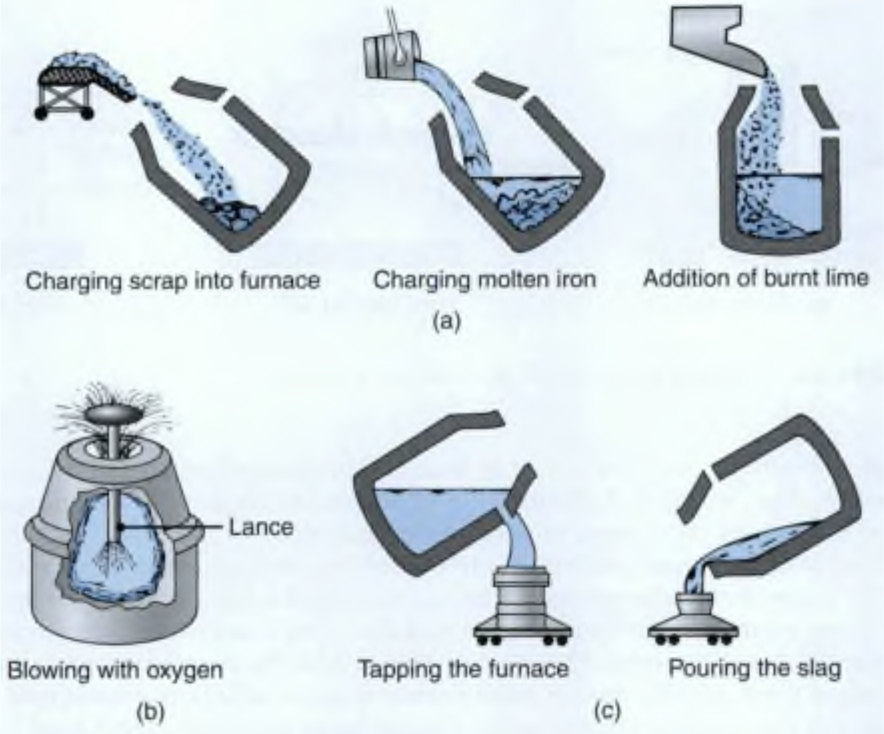

FIGURE 5.3 Schematic illustrations showing charging, melting, and pouring of molten iron in a basic-oxygen process.

vacuum furnaces produce high-quality steels. They are also commonly used for heat treating (Section 4.7) and brazing (Section 32.2).

5.3 Casting of Ingots

QR Code 5.1 Animation of ingot casting. (*Source:* Courtesy of Sandvik Coromant)

Traditionally, the steelmaking process involves the shaping of the molten steel into a solid form (**ingot**), for such further processing as rolling it into shapes, casting into semifinished forms, or forging. The molten metal is poured (*teemed*) from the ladle into ingot molds, in which the metal solidifies. Molds usually are made of cupola iron or blast-furnace iron with 3.5% carbon, and are tapered in order to facilitate the removal of the solidified metal. The bottoms of the molds may be closed or open; if they are open, the molds are placed on a flat surface. The cooled ingots are then stripped from the molds and lowered into **soaking pits**, where they are reheated to a uniform temperature of about 1200°C prior to subsequent processing.

Certain reactions take place during the solidification of an ingot that have an important influence on the quality of the steel produced. For example, significant amounts of oxygen and other gases can dissolve in the molten metal during steelmaking. Most of these gases are rejected during the solidification of the metal, because the solubility limit of the gases in the metal decreases sharply as its temperature decreases (see Fig. 10.15). The rejected oxygen combines with carbon to form carbon monoxide, which causes porosity in the solidified ingot.

Depending on the amount of gas evolved during solidification, three types of steel ingots can be produced: killed, semi-killed, and rimmed.

1. **Killed Steel.** The term *killed* comes from the fact that the steel lies quietly after being poured into the mold. **Killed steel** is a fully deoxidized steel; that is, oxygen is removed and the associated porosity is thus eliminated. In the deoxidation process, the oxygen dissolved in the molten metal is made to react with elements such as aluminum, silicon, manganese, and vanadium that have been added to the melt. These elements have an affinity for oxygen and form metallic oxides. If aluminum is used, the product is called *aluminum-killed steel* (see Table 16.4).

   If they are sufficiently large, the oxide inclusions in the molten bath float out and adhere to, or are dissolved in, the slag. A fully killed steel thus is free of any porosity caused by gases; it also is free of any **blowholes** (large spherical holes near the surfaces of the ingot). Consequently, the chemical and mechanical properties of a killed-steel ingot are relatively uniform throughout. Because of shrinkage during solidification, however, an ingot of this type develops a **pipe** at the top (also called a **shrinkage cavity**); it has the appearance of a funnel-like shape. This pipe can take up a substantial volume of the ingot, and it has to be cut off and scrapped.
2. **Semi-killed Steel. Semi-killed steel** is a *partially deoxidized steel*. It contains some porosity (generally in the upper central section of the ingot), but it has little or no pipe. Although the piping in semi-killed steels is less, this advantage is offset by the presence of porosity in that region. Semi-killed steels are economical to produce.
3. **Rimmed Steel.** In a **rimmed steel**, which generally has a carbon content of less than 0.15%, the evolved gases are only partially killed (or controlled) by the addition of other elements, such as aluminum. The gases produce blowholes along the outer rim of the ingot—hence the term *rimmed*. These steels have little or no piping, and they have a ductile skin with good surface finish; however, if not controlled properly, blowholes may break through the skin. Furthermore, impurities and inclusions tend to segregate toward the center of the ingot. Products made from this steel may thus be defective, hence thorough inspection is essential.

Refining. The properties and manufacturing characteristics of ferrous alloys are affected adversely by the amount of impurities, inclusions, and other elements present (see Section 2.10). The removal of impurities is known as *refining*. Most refining is done in melting furnaces or in ladles, by the addition of various elements.

Refining is particularly important in producing high-grade steels and alloys for high-performance and critical applications, such as aircraft components, automobile structural elements, medical devices, and cutlery. Moreover, warranty periods on shafts, camshafts, crankshafts, and similar parts can be increased significantly by using higher quality steels. Such steels are subjected to **secondary refining** in ladles (**ladle metallurgy**) and ladle refining (**injection refining**), which generally consists of melting and processing the steel in a vacuum. Several processes using controlled atmospheres have been developed, such as electron-beam melting, vacuum-arc remelting, argon–oxygen decarburization, and vacuum-arc double-electrode remelting.

5.4 Continuous Casting

Conceived in the 1860s, **continuous** or **strand casting** was first developed for casting nonferrous metal strips. The process is now used widely for steel production, with major productivity improvements and cost reductions. One system for continuous casting is shown schematically in Fig. 5.4a. The molten metal in the ladle is cleaned,

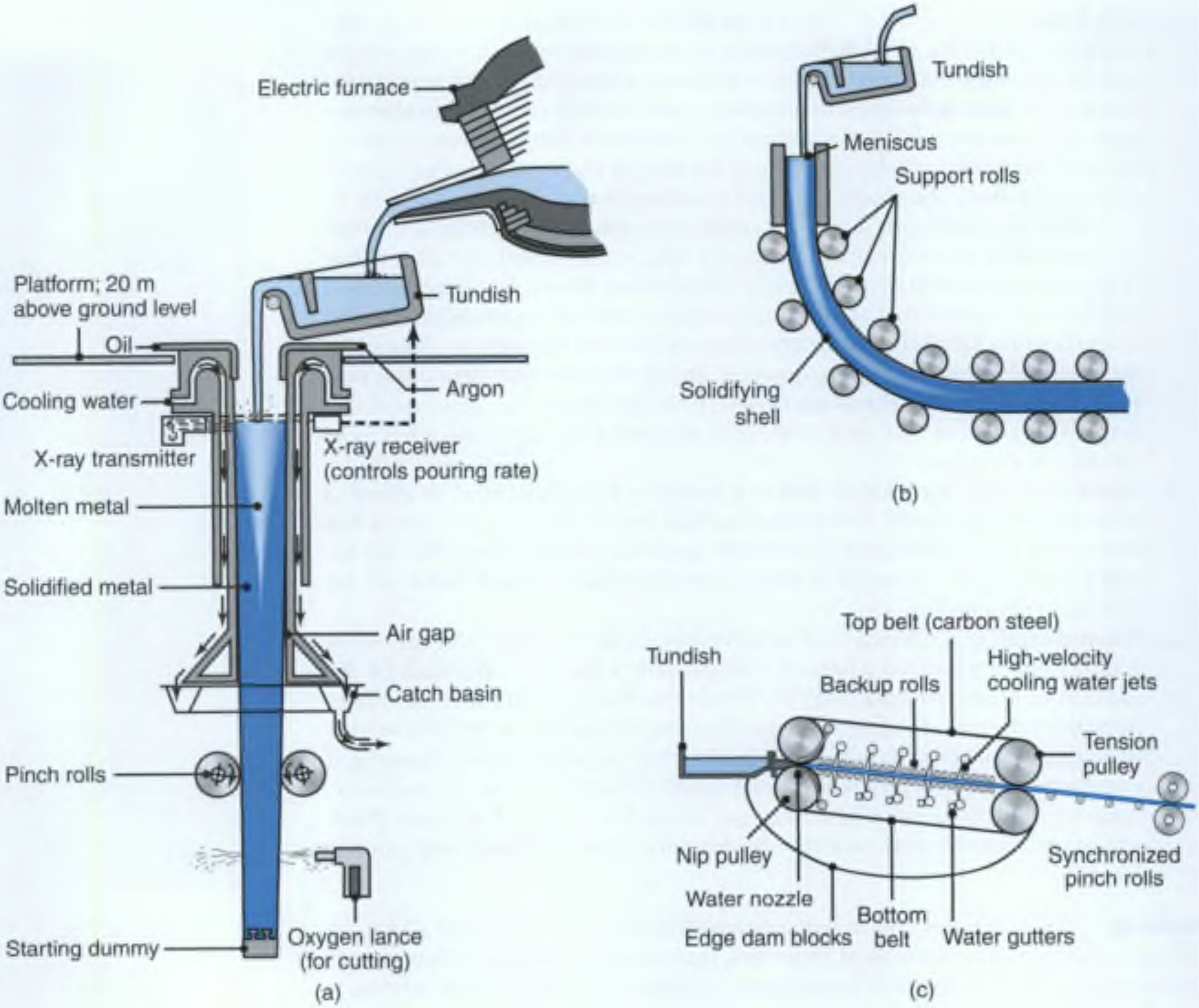

FIGURE 5.4 (a) The continuous-casting process for steel. Typically, the solidified metal descends at a speed of 25 mm/s. Note that the platform is about 20 m above ground level. *Source:* Figure adapted from *Metalcaster's Reference and Guide* (c. 1989, p. 41), American Foundrymen's Society. (b) Continuous casting using support or guide rollers to allow transition from a vertical pour zone to horizontal conveyors. (c) Continuous strip casting of nonferrous metal strip. *Source:* Courtesy of Hazelett Corporation.

QR Code 5.2 Animation of continuous casting. (*Source:* Courtesy of Sandvik Coromant)

then it is equalized in temperature by blowing nitrogen gas through it for 5–10 min. The metal is then poured into a refractory-lined intermediate pouring vessel (**tundish**), where impurities are skimmed off. The tundish holds as much as 2.7 metric tons of metal. The molten metal is then tapped from the tundish, travels downward through water-cooled copper molds, and begins to solidify as it is drawn through the molds at a constant velocity by rollers (called *pinch rolls*).

Before starting the casting operation, a solid *starter bar* (*dummy bar*) is inserted into the bottom of the mold. When the molten metal is first poured, it solidifies onto the dummy bar. The bar is withdrawn at the same rate at which the metal is poured. The cooling rate is such that the metal develops a solidified skin (*shell*), so as to support itself during its travel downward, typically at speeds of about 25 mm/s. The shell thickness at the exit end of the mold is about 12–18 mm. Additional cooling is provided by water sprays along the travel path of the solidifying metal. The molds generally are coated with graphite or similar solid lubricants, in order to reduce both friction and adhesion at the mold–metal interfaces; also, the molds are vibrated in order to reduce friction and sticking.

The continuously cast metal may be cut into desired lengths by shearing or computer-controlled torch cutting, or it may be fed directly into a rolling mill for further reduction in thickness and for the shaping of products, such as channels and I-beams. In addition to lower cost, continuously cast metals have more uniform compositions and properties than those obtained by ingot casting.

Modern facilities include computer-controlled operations on continuously cast strands, with final sheet thicknesses on the order of 2–6 mm for carbon and stainless steels. They have capabilities for a rapid switchover from one type of steel to another. Steel plates or other shapes undergo one or more further processing, such as (a) cleaning and pickling by chemicals, to remove surface oxides, (b) cold rolling, to improve strength and surface finish, (c) annealing, and (d) galvanizing or aluminizing, to improve resistance to corrosion.

In **strip casting**, thin slabs, or strips, are produced from molten metal. The metal solidifies in similar manner to strand casting, but the hot solid is then rolled to produce the final shape (Fig. 5.4b). The compressive stresses in rolling (see Section 13.2) serve to reduce porosity and to provide better material properties. In effect, strip casting eliminates a hot-rolling operation in the production of metal strips or slabs.

5.5 Carbon and Alloy Steels

Steel is an alloy that consists primarily of iron, and has a carbon content between 0.2 and 2.1%, by weight. Alloys with higher than 2.1% carbon are known as cast irons (discussed in Section 12.3.2), and have a lower melting point than other steels and good castability. Carbon and alloy steels are among the most commonly used metals and have a wide variety of compositions, processing options, and applications (Table 5.1). These steels are available in a variety of basic product shapes: plate, sheet, strip, bar, wire, tube, castings, and forgings.

TABLE 5.1

Applications for Selected Carbon and Alloy Steels

Product	Steel
Aircraft forgings, tubing, fittings	4140, 8740
Automobile bodies	1010
Axles	1040, 4140
Ball bearings and races	52100
Bolts	1035, 4042, 4815
Camshafts	1020, 1040
Chains (transmission)	3135, 3140
Coil springs	4063
Connecting rods	1040, 3141, 4340
Crankshafts (forged)	1045, 1145, 3135, 3140
Differential gears	4023
Gears (car and truck)	4027, 4032
Landing gear	4140, 4340, 8740
Lock washers	1060
Nuts	3130
Railroad rails and wheels	1080
Springs (coil)	1095, 4063, 6150
Springs (leaf)	1085, 4063, 9260, 6150
Tubing	1040
Wire	1045, 1055
Wire (music)	1085

5.5.1 Effects of Various Elements in Steels

Various elements are added to steels in order to impart specific properties, such as hardenability, strength, hardness, toughness, wear resistance, workability, weldability, and machinability. These elements are listed in Table 5.2, with summaries of their beneficial and detrimental effects. Generally, the higher the percentages of these elements in steels, the greater are

TABLE 5.2

Effect of Various Elements in Steels

Element	Effect
Aluminum	Deoxidizes nitriding steels, limits austenite grain growth, increases hardness of nitriding steels
Bismuth	Improves machinability
Boron	Improves hardness without loss of (and perhaps some improvement in) machinability and formability
Calcium	Deoxidizes steel; improves toughness; may improve formability and machinability
Carbon	Improves hardenability, strength, hardness, and wear resistance; reduces ductility, weldability, and toughness
Cerium, magnesium, zirconium	Deoxidizes steel, improves toughness in HSLA steels; controls shape of inclusions
Chromium	Improves toughness, hardenability, wear and corrosion resistance, and high-temperature strength; promotes carburization and depth of hardening in heat treatment
Cobalt	Improves strength and hardness at elevated temperatures
Copper	Improves resistance to atmospheric corrosion; can increase strength without loss in ductility; adversely affects hot workability and surface quality
Lead	Improves machinability; can cause liquid metal embrittlement
Manganese	Deoxidizes steel; improves hardenability, strength, abrasion resistance, and machinability; reduces hot shortness; decreases weldability
Molybdenum	Improves hardenability, wear resistance, toughness, elevated-temperature strength, creep resistance, and hardness; minimizes temper embrittlement
Nickel	Improves strength, toughness, corrosion resistance, and hardenability
Niobium, tantalum	Improves strength and impact toughness; lowers transition temperature; may decrease hardenability
Phosphorus	Improves strength, hardenability, corrosion resistance, and machinability; severely reduces ductility and toughness
Selenium	Improves machinability
Silicon	Improves strength, hardness, corrosion resistance, and electrical conductivity; decreases machinability and cold formability
Sulfur	Improves machinability when combined with manganese; decreases impact strength, ductility, and weldability
Tellurium	Improves machinability, formability, and toughness
Titanium	Deoxidizes steel; improves hardenability
Tungsten	Improves hardness, especially at elevated temperature
Vanadium	Improves strength, toughness, abrasion resistance, and hardness at elevated temperatures; inhibits grain growth during heat treatment

the particular properties that they impart. For example, the higher the carbon content, the greater the hardenability of the steel and the higher its strength, hardness, and wear resistance. On the other hand, ductility, weldability, and toughness are reduced with increasing carbon content.

Some *residual elements*, called **trace elements**, may remain after production, refining, and processing of steels. Although the elements in Table 5.2 may also be considered as residuals, the following generally are considered unwanted residual elements:

Antimony and **arsenic** cause temper embrittlement.

Hydrogen severely embrittles steels; however, heating during processing drives out most of the hydrogen.

Nitrogen improves strength, hardness, and machinability; in aluminum-deoxidized steels, it controls the size of inclusions. Nitrogen can increase or decrease strength, ductility, and toughness, depending on the presence of other elements.

Oxygen slightly increases the strength of rimmed steels; it severely reduces toughness.

Tin causes hot shortness and temper embrittlement.

5.5.2 Designations for Steels

Traditionally, the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE) have designated carbon and alloy steels by four digits. The first two digits indicate the alloying elements and their percentages, and the last two digits indicate the carbon content by weight.

The American Society for Testing and Materials (ASTM) has a designation system, which incorporates the AISI and SAE designations and includes standard specifications for steel products. For ferrous metals, the designation consists of the letter "A" followed by a few numbers (generally three). The current standard numbering system is known as the *Unified Numbering System* (UNS), and has been widely adopted by both ferrous and nonferrous industries. It consists of a letter, indicating the general class of the alloy, followed by five digits, designating its chemical composition. Typical letter designations are:

G — AISI and SAE carbon and alloy steels
J — Cast steels
K — Miscellaneous steels and ferrous alloys
S — Stainless steels and superalloys
T — Tool steels

Two examples are: G41300 for AISI 4130 alloy steel, and T30108 for AISI A-8 tool steel.

5.5.3 Carbon Steels

Carbon steels generally are classified by their proportion, by weight, of carbon content. The general mechanical properties of carbon and alloy steels are given in Table 5.3, and the effect of carbon on the properties of steel is shown in Fig. 5.5, and summarized as:

- **Low-carbon steel**, also called **mild steel**, has less than 0.30% C. It often is used for common industrial products (such as bolts, nuts, sheets, plates, and tubes) and for machine components that do not require high strength.
- **Medium-carbon steel** has 0.30–0.60% C. It generally is used in applications requiring higher strength than is available in low-carbon steels, such as in machinery, automotive and agricultural parts (gears, axles, connecting rods, and crankshafts), railroad equipment, and parts for metalworking machinery.
- **High-carbon steel** has more than 0.60% C. Generally, high-carbon steel is used for applications requiring strength, hardness, and wear resistance, such as cutting tools, cables, music wire, springs, and cutlery. After being manufactured into shapes, the parts usually are heat treated and tempered. The higher

TABLE 5.3

Typical Mechanical Properties of Selected Carbon and Alloy Steels

AISI	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Reduction of area (%)	Typical hardness (HB)
1020	As-rolled	448	346	36	59	143
	Normalized	441	330	35	67	131
	Annealed	393	294	36	66	111
1080	As-rolled	1010	586	12	17	293
	Normalized	965	524	11	20	293
	Annealed	615	375	24	45	174
3140	Normalized	891	599	19	57	262
	Annealed	689	422	24	50	197
4340	Normalized	1279	861	12	36	363
	Annealed	744	472	22	49	217
8620	Normalized	632	385	26	59	183
	Annealed	536	357	31	62	149

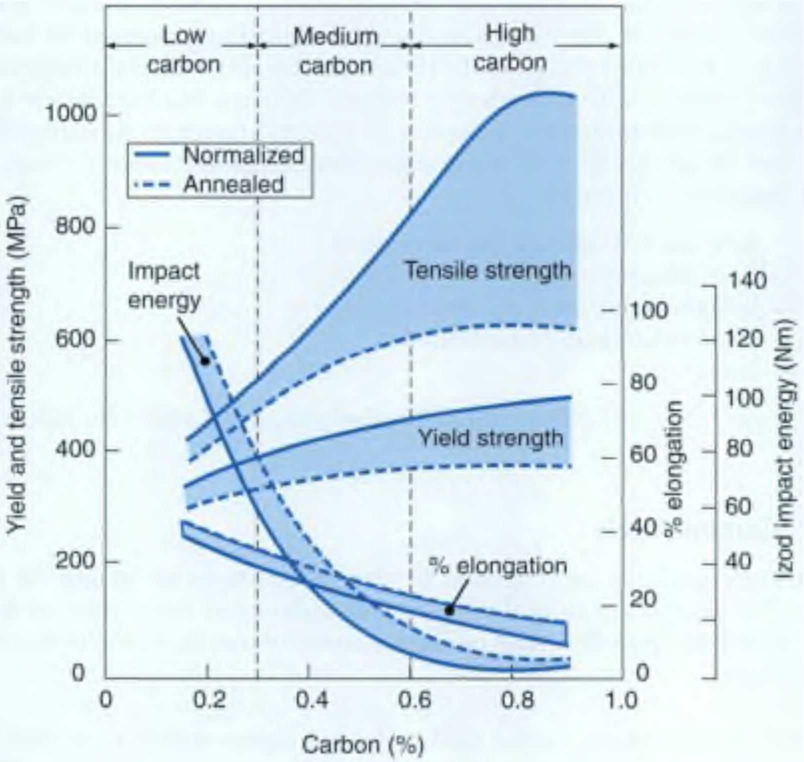

FIGURE 5.5 Effect of carbon content on the mechanical properties of carbon steel.

the carbon content of the steel, the higher is its hardness, strength, and wear resistance after heat treatment.

- Carbon steels containing sulfur and phosphorus are known as **resulfurized** carbon steels (11xx series) and **rephosphorized and resulfurized** carbon steels (12xx series). For example, 1112 steel is a resulfurized steel with a carbon content of 0.12%. These steels have improved machinability, as described in Section 21.7.

5.5.4 Alloy Steels

Steels containing significant amounts of alloying elements are called **alloy steels. Structural-grade alloy steels** are used mainly in the construction and transportation industries, because of their high strength. Other types of alloy steels are used in applications where strength, hardness, creep and fatigue resistance, and toughness are required; they can be heat treated to obtain specific desired properties.

5.5.5 High-strength Low-alloy Steels

In order to improve the strength-to-weight ratio of steels, a number of **high-strength, low-alloy steels** (HSLA) have been developed. These steels have a low carbon content (usually less than 0.30%) and are characterized by a microstructure consisting of fine-grain ferrite as one phase and a hard second phase of martensite and austenite. Mechanical properties for selected HSLA steels are given in Table 5.4. The steels have high strength and energy-absorption capabilities as compared to conventional steels. The ductility, formability, and weldability of HSLA steels are, however, generally inferior to those of conventional low-alloy steels (see Fig. 5.6). To improve these properties, several ultra-high-strength steels have been developed, as described in Section 5.5.6.

Sheet products of HSLA steels typically are used for parts of automobile bodies and other transportation equipment (in order to reduce weight and, hence, fuel consumption) and in mining, agricultural, and various other industrial applications. Plates are used in ships, bridges, building construction, and for such shapes as I-beams, channels, and angles used in buildings and in various structures.

Designations. Three categories compose the system of AISI designations for high-strength sheet steel (Table 5.5): (a) *Structural quality* (S) includes the elements C, Mn, P, and N; (b) *low alloys* (X) contain Nb, Cr, Cu, Mo, Ni, Si, Ti, V, and Zr, either singly or in combination; (c) *weathering steels* (W) have environmental-corrosion resistance that is approximately four times higher than that of conventional low-carbon steels

TABLE 5.4

Mechanical Properties of Selected Advanced High-strength Steels

Steel	Minimum ultimate strength (MPa)	Minimum yield strength (MPa)	Elongation in 50 mm (%)	Strain-hardening exponent, n
BH 210/340	340	210	36	0.18
BH 260/370	370	260	32	0.13
HSLA 350/450	450	450	25	0.14
DP 350/600	600	600	27	0.14
DP 500/800	800	800	17	0.14
DP 700/1000	1,000	1,000	15	0.13
TRIP 450/800	800	450	29	0.24
TRIP 400/600	600	400	30	0.23
CP 700/800	800	700	12	0.13
MART 950/1200	1200	950	6	0.07
MART 1250/1520	1520	1250	5	0.065
27MnCrB5, as rolled	967	478	12	0.06
27MnCrB5, hot stamped	1350	1097	5	0.06
37MnB4, as rolled	810	580	12	0.06
37MnB4, hot stamped	2040	1378	4	0.06

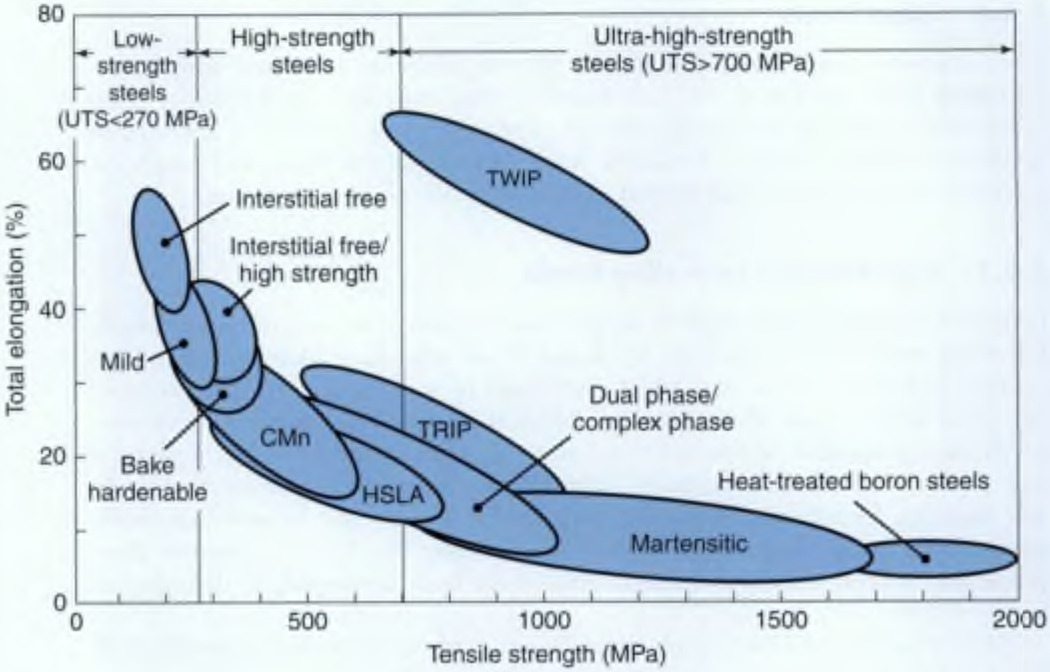

FIGURE 5.6 Comparison of advanced high-strength steels.

TABLE 5.5

AISI Designations for High-strength Sheet Steel

Yield strength			
psi x 10^3	MPa	Chemical composition	Deoxidation practice
35	240	S = structural quality	F = killed plus sulfide inclusion control
40	275	X = low alloy	K = killed
45	310	W = weathering	O = nonkilled
50	350	D = dual-phase	
60	415		
70	485		
80	550		
100	690		
120	830		
140	970		
Example: 50XF			
50×10^3 psi (350 MPa) min yield strength		Low alloy	Killed plus sulfide inclusion control

and contain Si, P, Cu, Ni, and Cr in various combinations. In addition, the formability of these sheet steels is graded by the letters F (excellent), K (good), and O (fair).

Another designation scheme in wide use is that defined by the Ultralight Steel Auto Body Consortium (ULSAB). The ULSAB practice is to define both the type of a steel and its yield and tensile strengths, in a compact designation, in the form XX aaa/bbb, where XX is the type of steel, aaa is the yield strength in MPa, and bbb is the ultimate tensile strength, in MPa. The types of steel are:

BH — Bake-hardenable
HSLA — High-strength low-alloy
DP — Dual-phase
TRIP — Transformation-induced plasticity
TWIP — Twinning-induced plasticity
MART — Martensitic
CP — Complex phase

Thus, for example; HSLA 350/450 would be a high-strength low-alloy steel with a minimum yield strength of 350 MPa and a minimum ultimate tensile strength of 450 MPa.

Microalloyed Steels. These steels provide superior properties and can eliminate the need for heat treatment. They have a ferrite–pearlite microstructure, with fine dispersed particles of carbonitride. When subjected to carefully controlled cooling (usually in air), these steels develop improved and uniform strength. Compared to medium-carbon steels, **microalloyed steels** also can provide cost savings of as much as 10%, since the steps of quenching, tempering, and stress relieving are not required.

Nanoalloyed Steels. These steels have extremely small grain sizes (10–100 nm), and are produced using metallic glasses (Section 6.14) as a precursor. The metallic glass is subjected to a carefully controlled vitrification (crystallization) process at a high nucleation rate, resulting in fine nanoscale phases. (See also Section 8.8.)

5.5.6 Ultra-high-strength Steels

Ultra-high-strength steels are defined by AISI as those with an ultimate tensile strength higher than 700 MPa. There are five important types of ultra-high-strength steel: dual-phase, TRIP, TWIP, complex phase, and martensitic. The main application of these steels is for crashworthy design of automobiles. The use of stronger steels allows for smaller cross-sections in structural components, thus resulting in weight savings and increases in fuel economy without compromising safety. The significant drawbacks of all these steels are higher springback, tool and die wear, and forming loads.

Dual-phase steels are processed specially to have a mixed ferrite and martensite structure. They have a high work-hardening exponent, n, in Eq. (2.8), which improves their ductility and formability.

TRIP steels consist of a ferrite–bainite matrix and 5–20% retained austenite. During forming, the austenite progressively transforms into martensite. TRIP steels have both excellent ductility (because of the austenite) and high strength after forming. As a result, these steels can be used to produce more complex parts than other high-strength steels.

TWIP steels (from *TW*inning-*I*nduced *P*lasticity) are austenitic and have high manganese content (17–20%). These steels derive their properties from the generation of twins during deformation (see Section 1.4) without a phase change, resulting in very high strain hardening and avoiding thinning during processing. As shown in Fig. 5.5, TWIP steels combine high strength with high formability.

Complex-phase grades (CP grades) are very-fine-grained microstructures of ferrite and a high volume fraction of hard phases (martensite and bainite). These steels have ultimate tensile strengths as high as 800 MPa, and are therefore of interest for automotive crash applications, such as bumpers and roof supports. *Martensitic grades* also are available, consisting of high fractions of martensite to attain tensile strengths as high as 1500 MPa.

CASE STUDY 5.1 Advanced High-strength Steels in Automobiles

Increasing fuel economy in automobiles has received considerable attention in recent years, for both environmental and economic reasons. Regulatory requirements call for automobile manufacturers to achieve *corporate average fuel economy* (CAFE) standards. To achieve higher fuel economy without compromising performance or safety, manufacturers have increasingly applied advanced high-strength steels in structural elements of automobiles; for example, the application of steel in the Ford 500 automobile shown in Fig. 5.7. Note that although 60% of the steel in this automobile is mild steel, and is associated with body panels and transmission and engine components, structural components are exploiting the higher strength-to-weight ratios of advanced high-strength steels.

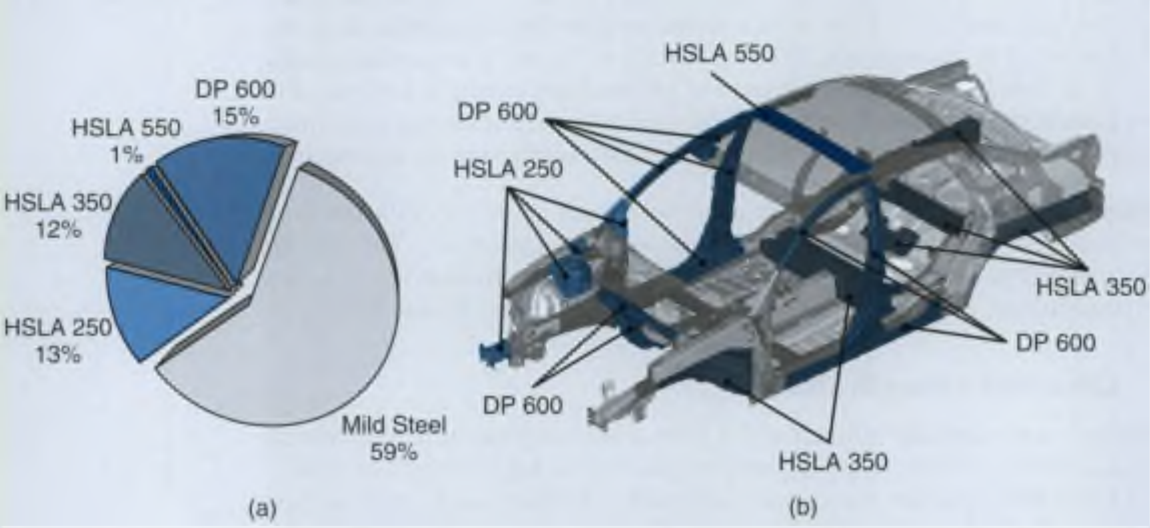

FIGURE 5.7 Advanced high-strength steel applications in the Ford 500 automobile. (a) Use of advanced high-strength steels by weight percent; (b) structural components and alloys used. *Source:* Courtesy of American Iron and Steel Institute.

5.6 Stainless Steels

Stainless steels are characterized primarily by their corrosion resistance, high strength, and ductility. They are called *stainless* because, in the presence of oxygen (air), they develop a thin, hard, and adherent film of chromium oxide that protects the metal from corrosion (*passivation*; see Section 3.8); this protective film builds up again in the event that the surface is scratched. For passivation to occur, the minimum chromium content should be 10–12% by weight. In addition to chromium and carbon, other alloying elements in stainless steels typically are nickel, molybdenum, copper, titanium, silicon, manganese, columbium, aluminum, nitrogen, and sulfur.

The higher the carbon content, the lower is the corrosion resistance of stainless steels. The reason is that the carbon combines with the chromium in the steel and forms chromium carbide; the reduced presence of chromium lowers the passivity of the steel. In addition, the chromium carbide introduces a second phase and thereby promotes galvanic corrosion.

Developed in the early 1900s, stainless steels are produced in electric furnaces or by the basic-oxygen process, and using techniques similar to those used in other types of steelmaking. The level of purity is controlled through various refining techniques. Stainless steels are available in a wide variety of shapes. Typical applications include cutlery, kitchen equipment, health care and surgical equipment, and applications in the chemical, food-processing, and petroleum industries.

Stainless steels generally are divided into five types (see also Table 5.6).

Austenitic (200 and 300 series). These steels generally are composed of chromium, nickel, and manganese in iron. They are nonmagnetic and have excellent corrosion resistance, but are susceptible to stress-corrosion cracking (Section 3.8). Austenitic stainless steels, which are hardened by cold working, are the most ductile of all stainless steels and can be formed easily. They are used in a wide variety of applications, such as kitchenware, fittings, welded construction, lightweight transportation equipment, furnace and heat-exchanger parts, and components for severe chemical environments.

Ferritic (400 series). These steels have a high chromium content. They are magnetic and have good corrosion resistance, but have lower ductility than austenitic stainless steels. Ferritic stainless steels are hardened by cold working. They generally are used for nonstructural applications, such as kitchen equipment and automotive trim.

Martensitic (400 and 500 series). Most martensitic stainless steels do not contain nickel and are hardenable by heat treatment. These steels are magnetic and have high strength, hardness, and fatigue resistance, good ductility, and moderate corrosion resistance. Martensitic stainless steels typically are used for cutlery, surgical tools, instruments, valves, and springs.

Precipitation-hardening (PH). These stainless steels contain chromium and nickel, along with copper, aluminum, titanium, or molybdenum. They have good corrosion

TABLE 5.6

Mechanical Properties and Typical Applications of Selected Annealed Stainless Steels at Room Temperature

AISI (UNS) designation	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Characteristics and typical applications
303 (S30300)	550–620	240–260	53–50	Screw machine products (shafts, valves, bolts, bushings, and nuts) and aircraft fittings (bolts, nuts, rivets, screws, and studs)
304 (S30400)	5–620	240–290	60–55	Chemical and food-processing equipment, brewing equipment, cryogenic vessels, gutters, downspouts, and flashings
316 (S31600)	50–590	210–290	60–55	High corrosion resistance and high creep strength, chemical- and pulp-handling equipment, photographic equipment, brandy vats, fertilizer parts, ketchup-cooking kettles, and yeast tubs
410 (S41000)	480–520	240–310	35–25	Machine parts, pump shafts, bolts, bushings, coal chutes, cutlery, tackle, hardware, jet engine parts, mining machinery, rifle barrels, screws, and valves
416 (S41600)	480–520	275	30–20	Aircraft fittings, bolts, nuts, fire extinguisher inserts, rivets, and screws

resistance and ductility, and have high strength at elevated temperatures. Their main application is in aircraft and aerospace structural components.

Duplex Structure. These stainless steels have a mixture of austenite and ferrite. They have good strength and higher resistance to both corrosion (in most environments) and stress-corrosion cracking than do the 300 series of austenitic steels. Typical applications are in water-treatment plants and in heat-exchanger components.

CASE STUDY 5.2 Stainless Steels in Automobiles

The types of stainless steel usually selected by materials engineers for use in automobile parts are 301, 409, 430, and 434. Because of its good corrosion resistance and mechanical properties, type 301 is used for wheel covers; cold working during the forming process increases its yield strength and gives the wheel cover a springlike action.

Type 409 is used extensively for catalytic converters. Type 430 had been used for automotive trim, but it is not as resistant as type 434 is to the road deicing salts used in colder climates in winter; as a result, its use is now limited. In addition to being more corrosion resistant, type 434 closely resembles the color of chromium plating, thus becoming an attractive alternative to 430.

Stainless steels also are well suited for use in other automobile components. Examples include: exhaust manifolds (replacing cast-iron manifolds, to reduce weight, increase durability, provide higher thermal conductivity, and reduce emissions), mufflers and tailpipes (for better corrosion protection in harsh environments), and brake tubing.

5.7 Tool and Die Steels

Tool and die steels are specially alloyed steels (Tables 5.7 and 5.8), designed for tool and die requirements, such as high strength, impact toughness, and wear resistance at room and elevated temperatures. They commonly are used in forming and machining of metals (Parts III and IV).

TABLE 5.7

Basic Types of Tool and Die Steels

Type	AISI
High speed	M (molybdenum base) T (tungsten base)
Hot work	H1 to H19 (chromium base) H20 to H39 (tungsten base) H40 to H59 (molybdenum base)
Cold work	D (high carbon, high chromium) A (medium alloy, air hardening) O (oil hardening)
Shock resisting	S
Mold steels	P1 to P19 (low carbon) P20 to P39 (others)
Special purpose	L (low alloy) F (carbon–tungsten)
Water hardening	W

5.7.1 High-speed Steels

High-speed steels (HSS) are the most highly alloyed tool and die steels. First developed in the early 1900s, they maintain their hardness and strength at elevated operating temperatures. There are two basic types of high-speed steels: the **molybdenum type** (M-series) and the **tungsten type** (T-series).

The **M-series** steels contain up to about 10% molybdenum, with chromium, vanadium, tungsten, and cobalt as other alloying elements. The **T-series** steels contain 12–18% tungsten, with chromium, vanadium, and cobalt as other alloying elements. The M-series steels generally have higher abrasion resistance than T-series steels, undergo less distortion in heat treatment, and are less expensive. The M-series constitutes about 95% of all the high-speed steels produced in the United States. High-speed steel tools can be coated with titanium nitride and titanium carbide for improved wear resistance.

TABLE 5.8

Processing and Service Characteristics of Common Tool and Die Steels

AISI designation	Resistance to decarburization	Resistance to cracking	Approximate hardness (HRC)	Machinability	Toughness	Resistance to softening	Resistance to wear
M2	Medium	Medium	60–65	Medium	Low	Very high	Very high
H11, 12, 13	Medium	Highest	38–55	Medium to high	Very high	High	Medium
A2	Medium	Highest	57–62	Medium	Medium	High	High
A9	Medium	Highest	35–56	Medium	High	High	Medium to high
D2	Medium	Highest	54–61	Low	Low	High	High to very high
D3	Medium	High	54–61	Low	Low	High	Very high
H21	Medium	High	36–54	Medium	High	High	Medium to high
P20	High	High	28–37	Medium to high	High	Low	Low to medium
P21	High	Highest	30–40	Medium	Medium	Medium	Medium
W1, W2	Highest	Medium	50–64	Highest	High	Low	Low to medium

5.7.2 Die Steels

Hot-work steels (H-series) are designed for use at elevated temperatures. They have high toughness, as well as high resistance to wear and cracking. The alloying elements generally are tungsten, molybdenum, chromium, and vanadium. **Cold-work steels** (A-, D-, and O-series) are used for cold-working operations. They generally have high resistance to wear and cracking, and are available as oil-hardening or air-hardening types. **Shock-resisting steels** (S-series) are designed for impact toughness and are used in applications such as header dies, punches, and chisels. Various other tool and die materials for a variety of manufacturing applications are given in Table 5.9.

SUMMARY

- The major categories of ferrous metals and alloys are carbon steels, alloy steels, stainless steels, and tool and die steels. Their wide range of properties, availability, and generally low cost have made them among the most useful of all metallic materials.
- Steelmaking processes increasingly involve continuous-casting and secondary-refining techniques, resulting in higher quality steels and higher efficiency and productivity.
- Carbon steels generally are classified as low-carbon (mild steel), medium-carbon, and high-carbon steels. Alloy steels contain several alloying elements, particularly chromium, nickel, and molybdenum.
- High-strength low-alloy (HSLA) steels have a low carbon content and consist of fine-grained ferrite as one phase and a second phase of martensite and austenite. Micro- and nanoalloyed steels are fine-grained, high-strength low-alloy steels that provide superior properties without the need for heat treatment.
- Stainless steels have chromium as the major alloying element; they are called stainless because they form a passivating chromium–oxide layer on their surface. These steels are generally classified as austenitic, ferritic, martensitic, and precipitation-hardening steels.

TABLE 5.9

Typical Tool and Die Materials for Metalworking Processes

Process	Material
Die casting	H13, P20
Powder metallurgy	
Punches	A2, S7, D2, D3, M2
Dies	WC, D2, M2
Molds for plastics and rubber	S1, O1, A2, D2, 6F5, 6F6, P6, P20, P21, H13
Hot forging	6F2, 6G, H11, H12
Hot extrusion	H11, H12, H13, H21
Cold heading	W1, W2, M1, M2, D2, WC
Cold extrusion	
Punches	A2, D2, M2, M4
Dies	O1, W1, A2, D2
Coining	52100, W1, O1, A2, D2, D3, D4, H11, H12, H13
Drawing	
Wire	WC, diamond
Shapes	WC, D2, M2
Bar and tubing	WC, W1, D2
Rolls	
Rolling	Cast iron, cast steel, forged steel, WC
Thread rolling	A2, D2, M2
Shear spinning	A2, D2, D3
Sheet metals	
Cold shearing	D2, A2, A9, S2, S5, S7
Hot shearing	H11, H12, H13
Pressworking	Zinc alloys, 4140 steel, cast iron, epoxy composites, A2, D2, O1
Deep drawing	W1, O1, cast iron, A2, D2
Machining	Carbides, high-speed steels, ceramics, diamond, cubic boron nitride

Notes: Tool and die materials usually are hardened 55–65 HRC for cold working and 30–55 HRC for hot working. Tool and die steels contain one or more of the following major alloying elements: chromium, molybdenum, tungsten, and vanadium. (For further details, see the bibliography at the end of this chapter.)

- Tool and die steels are among the most important metallic materials, and are used widely in casting, forming, and machining operations. They generally consist of high-speed steels, hot- and cold-work steels, and shock-resisting steels.

KEY TERMS

Alloy steels
Basic-oxygen furnace
Blast furnace
Carbon steels
Complex-phase steels
Continuous casting
Dual-phase steels
Electric furnace
High-strength low-alloy steels
Ingot
Killed steel
Martensitic steel
Microalloyed steels
Nanoalloyed steels
Open-hearth furnace
TWIP steels
Pig iron
Refining
Rimmed steel
Semi-killed steel
Stainless steels
Steel
Strand casting
Tool and die steels
Trace elements
TRIP steels
TWIP steels

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REVIEW QUESTIONS

5.1 What are the major categories of ferrous alloys?

5.2 Why is steel so commonly used?

5.3 List the basic raw materials used in making iron and steel, and explain their functions.

5.4 List the types of furnaces commonly used in steelmaking, and describe their characteristics.

5.5 List and explain the characteristics of the types of steel ingots.

5.6 What does refining mean? How is it done?

5.7 What is continuous casting? What advantages does continuous casting have over casting into ingots?

5.8 What is the role of a tundish in continuous casting?

5.9 Name the four alloying elements that have the greatest effect on the properties of steels.

5.10 What are trace elements?

5.11 What are the percentage carbon contents of low-carbon, medium-carbon, and high-carbon steels?

5.12 How do stainless steels become stainless?

5.13 What are the major alloying elements in tool and die steels and in high-speed steels?

5.14 How does chromium affect the surface characteristics of stainless steels?

5.15 What kinds of furnaces are used to refine steels?

5.16 What is high-speed steel?

5.17 What are TRIP and TWIP?

5.18 What are the applications of advanced high-strength steels?

5.19 What characteristics are common among die steels?

5.20 What effect does carbon content have on mechanical properties of steel? What effects does it have on physical properties?

QUALITATIVE PROBLEMS

5.21 Identify several different products that are made of stainless steel, and explain why they are made of that material.

5.22 Professional cooks generally prefer carbon-steel to stainless-steel knives, even though the latter are more popular with consumers. Explain the reasons for those preferences.

5.23 Why is the control of the structure of an ingot important?

5.24 Explain why continuous casting has been such an important technological advancement.

5.25 Describe applications in which you would not want to use carbon steels.

5.26 Explain what would happen if the speed of the continuous-casting process shown in Fig. 5.4a is (a) higher or (b) lower than that indicated, typically 25 mm/s.

5.27 The cost of mill products of metals increases with decreasing thickness and section size. Explain why.

5.28 Describe your observations regarding the information given in Table 5.9.

5.29 How do trace elements affect the ductility of steels?

5.30 Comment on your observations regarding Table 5.1.

5.31 In Table 5.9, D2 steel is listed as a more common tool and die material for most applications. Why is this so?

5.32 List the common impurities in steel. Which of these are the ones most likely to be minimized if the steel is melted in a vacuum furnace?

5.33 Explain the purpose of the oil shown at the top left of Fig. 5.4a given that the molten-steel temperatures are far above the ignition temperatures of the oil.

5.34 Recent research has identified mold-surface textures that will either (a) inhibit a solidified steel from separating from the mold or (b) force it to stay in contact in continuous casting. What is the advantage of a mold that maintains intimate contact with the steel?

5.35 Identify products that cannot be made of steel, and explain why this is so. (For example, electrical contacts commonly are made of gold or copper, because their softness results in low contact resistance, whereas for steel, the contact resistance would be very high.)

5.36 List and explain the advantages and disadvantages of using advanced high-strength steels.

QUANTITATIVE PROBLEMS

5.37 Conduct an Internet search and determine the chemical composition of (a) TRIP 450/800; (b) 304 stainless steel; and (c) 4140 steel. If a foundry ladle will pour 50,000 kg, calculate the weight of each element in the ladle.

5.38 Refer to the available literature, and estimate the cost of the raw materials for (a) an aluminum beverage can, (b) a stainless-steel two-quart cooking pot, and (c) the steel hood of a car.

5.39 In Table 5.1, more than one type of steel is listed for some applications. Refer to data available in the technical literature listed in the bibliography, and determine the range of properties for these steels in various conditions, such as cold worked, hot worked, and annealed.

5.40 Some soft drinks are now available in steel cans (with aluminum tops) that look similar to aluminum cans. Obtain one of each type, weigh them when empty, and determine their respective wall thicknesses.

5.41 Using strength and density data, determine the minimum weight of a 1-m-long tension member that must support a load of 4 kN, manufactured from (a) annealed 303 stainless steel, (b) normalized 8620 steel, (c) as-rolled 1080 steel, (d) any two aluminum alloys, (e) any brass alloy, and (f) pure copper.

5.42 The endurance limit (fatigue life) of steel is approximately one-half the ultimate tensile strength (see Fig. 2.16), but never higher than 700 MPa. For iron, the endurance limit is 40% of the ultimate strength, but never higher than 170 MPa. Plot the endurance limit versus the ultimate strength for the steels described in this chapter and for the cast irons shown in Table 12.3. On the same plot, show the effect of surface finish by plotting the endurance limit, assuming that the material is in the as-cast state. (See Fig. 2.29.)

5.43 Using the data given in Table 5.4, obtain the power-law curves for the advanced high-strength steels shown and plot the curves. Compare these materials with those given in Table 2.3.

SYNTHESIS, DESIGN, AND PROJECTS

5.44 Based on the information given in Section 5.5.1, make a table with columns for each improved property, such as hardenability, strength, toughness, and machinability. In each column, list the elements that improve that particular property and identify the element that has the most influence.

5.45 Assume that you are in charge of public relations for a large steel-producing company. Outline all of the attractive characteristics of steels that you would like your customers to be informed about.

5.46 Assume that you are in competition with the steel industry and are asked to list all of the characteristics of steels that are not attractive. Make a list of those characteristics and explain their relevance to engineering applications.

5.47 Section 5.5.1 noted the effects of various individual elements, such as lead alone or sulfur alone, on the properties and characteristics of steels. What was not discussed, however, was the role of combinations of these elements (such as lead and sulfur together). Review the technical literature, and prepare a table indicating the combined effects of several elements on steels.

5.48 In the past, waterfowl hunters used lead shot in their shotguns, but this practice resulted in lead poisoning of unshot birds that ingested lead pellets (along with gravel) to help them digest food. Steel and tungsten are being used as replacement materials. If all pellets have the same velocity upon exiting the shotgun barrel, what concerns would you have regarding this substitution of materials? Consider both performance and environmental effects.

5.49 Aluminum is being used as a substitute material for steel in automobiles. Describe your concerns, if any, in purchasing an aluminum automobile.

5.50 In the 1940s (the Second World War), the *Yamato* and its sister ship, the *Musashi*, were the largest battleships ever built. Find out the weight of these ships, and estimate the number of automobiles that could have been built from the steel used in just one such ship. Estimate the time it would take to cast that much steel by continuous casting.

5.51 Search the technical literature, and add more parts and materials to those shown in Table 5.1.

5.52 Referring to Fig. 5.4a, note that the mold has cooling channels incorporated to remove heat. Can continuous casting be done without such cooling channels? Can it be done with a heated mold? Explain your answer.

CHAPTER

6

Nonferrous Metals and Alloys: Production, General Properties, and Applications

CASE STUDY:

- Nonferrous metals include a wide variety of materials, ranging from aluminum to zinc, with special properties that are indispensable in most products.
- This chapter introduces each class of nonferrous metal and its alloys, and briefly describes their methods of production.
- Their physical and mechanical properties are then summarized, along with general guidelines for their selection and applications.
- Shape-memory alloys, amorphous alloys, and metal foams are also described, with examples of their unique applications.

6.1 Introduction

Nonferrous metals and alloys cover a very wide range, from the more common metals (such as aluminum, copper, and magnesium) to high-strength, high-temperature alloys (such as those of tungsten, tantalum, and molybdenum). Although generally more expensive than ferrous metals (Table 6.1), nonferrous metals have numerous important applications because of such properties as good corrosion resistance, high thermal and electrical conductivity, low density, and ease of fabrication (Table 6.2).

Typical examples of nonferrous metal and alloy applications are aluminum for cooking utensils and aircraft bodies, copper wire for electrical power cords, zinc for galvanized sheet metal for car bodies, titanium for jet-engine turbine blades and for orthopedic implants, and tantalum for rocket engine components. As an example, the turbofan jet engine (Fig. 6.1) for the Boeing 757 aircraft typically contains the following nonferrous metals and alloys: 38% Ti, 37% Ni, 12% Cr, 6% Co, 5% Al, 1% Nb, and 0.02% Ta.

This chapter introduces the general properties, production methods, and important engineering applications for nonferrous metals and alloys. The manufacturing properties of these materials (such as formability, machinability, and weldability) are described in various chapters throughout this text.

6.2 Aluminum and Aluminum Alloys

The important characteristics of **aluminum** (Al) and its alloys are their high strength-to-weight ratios, resistance to corrosion by many chemicals, high thermal and electrical conductivities, nontoxicity, reflectivity, appearance, and ease of formability and machinability; they are also nonmagnetic.

The principal uses of aluminum and its alloys, in decreasing order of consumption, are in containers and packaging (aluminum beverage cans and foil), architectural and structural applications, transportation (aircraft and aerospace applications, buses, automobiles, railroad cars, and marine craft), electrical applications (as economical and nonmagnetic electrical conductors), consumer durables (appliances, cooking utensils, and furniture), and portable tools (Tables 6.3 and 6.4). Nearly all high-voltage transmission wiring is made of aluminum.

In its structural (load-bearing) components, 82% of a Boeing 747 aircraft and 70% of a 777 aircraft is aluminum. The Boeing 787 Dreamliner (first placed into service in late 2012) is well recognized for its carbon-fiber reinforced composite fuselage, although it still uses 20% aluminum by weight, as compared to 15% titanium. The frame and the body panels of the Rolls Royce Phantom coupe are made of aluminum, improving the car's strength-to-weight and torsional rigidity-to-weight ratios.

Aluminum alloys are available as mill products—that is, as wrought products made into various shapes by rolling, extrusion, drawing, forging, and sheet forming (Chapters 13 through 16). Aluminum ingots are available for casting, as is aluminum in powder form for powder metallurgy applications (Chapter 17). Most aluminum alloys can be machined, formed, and welded with relative ease. There

TABLE 6.1

Approximate Cost-per-unit-volume for Wrought Metals and Plastics Relative to the Cost of Carbon Steel

Material	Relative cost
Gold	30,000
Silver	600
Molybdenum alloys	75–100
Nickel	20
Titanium alloys	20–40
Copper alloys	8–10
Zinc alloys	1.5–3.5
Stainless steels	2–9
Magnesium alloys	4–6
Aluminum alloys	2–3
High-strength low-alloy steels	1.4
Gray cast iron	1.2
Carbon steel	1
Nylons, acetals, and silicon rubber*	1.1–2
Other plastics and elastomers*	0.2–1

*As molding compounds.

Note: Costs vary significantly with quantity of purchase, supply and demand, size and shape, and various other factors.

TABLE 6.2

General Characteristics of Nonferrous Metals and Alloys

Material	Characteristics
Nonferrous alloys	More expensive than steels and plastics; wide range of mechanical, physical, and electrical properties; good corrosion resistance; high-temperature applications
Aluminum	Alloys have high strength-to-weight ratio; high thermal and electrical conductivity; good corrosion resistance; good manufacturing properties
Magnesium	Lightest metal; good strength-to-weight ratio
Copper	High electrical and thermal conductivity; good corrosion resistance; good manufacturing properties
Superalloys	Good strength and resistance to corrosion at elevated temperatures; can be iron-, cobalt-, and nickel-based alloys
Tin	Good corrosion resistance and bright appearance; used also in solders and as bearing materials
Titanium	Highest strength-to-weight ratio of all metals; good strength and corrosion resistance at high temperatures
Refractory metals	Molybdenum, niobium, tungsten, and tantalum; high strength at elevated temperatures
Precious metals	Gold, silver, and platinum; generally good corrosion resistance and aesthetic characteristics
Zinc	Very good corrosion resistance; commonly used in castings and galvanizing steel sheet for corrosion protection

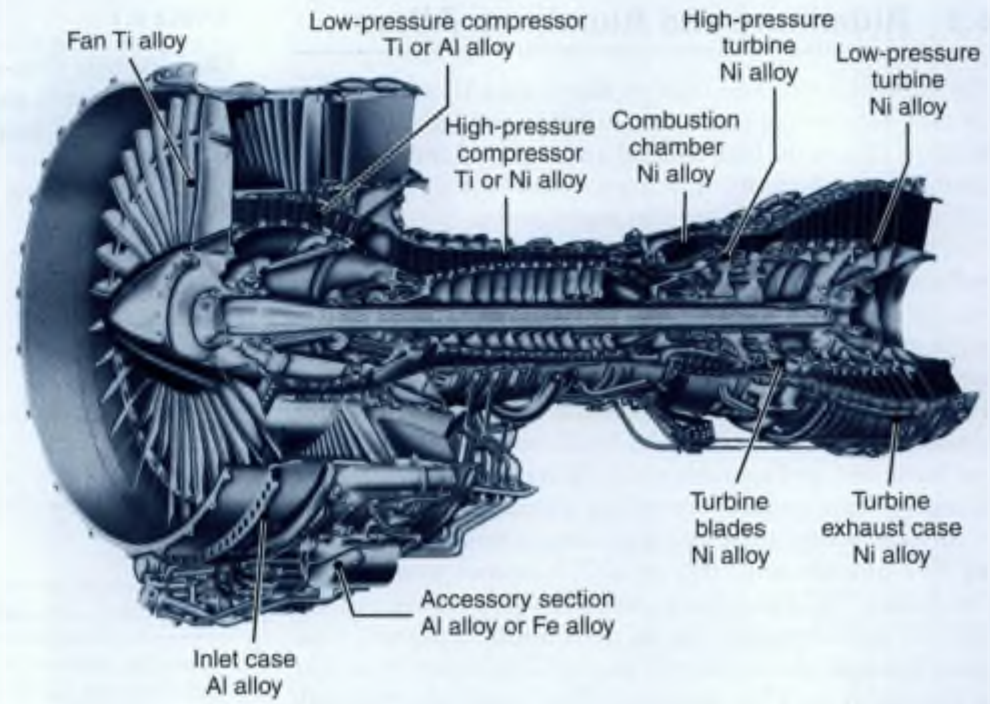

FIGURE 6.1 Cross-section of a jet engine (PW2037), showing various components and the alloys used in manufacturing them. *Source:* Courtesy of United Aircraft Pratt & Whitney.

TABLE 6.3

Properties of Selected Aluminum Alloys at Room Temperature

Alloy (UNS)	Temper	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)
1100 (A91100)	O	90	35	35–45
	H14	125	120	9–20
2024 (A92024)	O	190	75	20–22
	T4	470	325	19–20
3003 (A93003)	O	110	40	30–40
	H14	150	145	8–16
5052 (A95052)	O	190	90	25–30
	H34	260	215	10–14
6061 (A96061)	O	125	55	25–30
	T6	310	275	12–17
7075 (A97075)	O	230	105	16–17
	T6	570	500	11

are two types of wrought alloys of aluminum: (a) alloys that can be hardened by mechanical processing and are not heat treatable and (b) alloys that can be hardened by heat treatment.

Unified Numbering System. As is the case with steels, aluminum and other nonferrous metals and alloys are identified internationally by the Unified Numbering System (UNS), consisting of a letter, indicating the general class of the alloy, followed

TABLE 6.4

Manufacturing Characteristics and Typical Applications of Selected Wrought Aluminum Alloys

	Characteristics[*]			
Alloy	Corrosion resistance	Machinability	Weldability	Typical Applications
1100	A	C–D	A	Sheet-metal work, spun hollowware, tin stock
2024	C	B–C	B–C	Truck wheels, screw machine products, aircraft structures
3003	A	C–D	A	Cooking utensils, chemical equipment, pressure vessels, sheet-metal work, builders' hardware, storage tanks
5052	A	C–D	A	Sheet-metal work, hydraulic tubes, and appliances; bus, truck, and marine uses
6061	B	C–D	A	Heavy-duty structures where corrosion resistance is needed; truck and marine structures, railroad cars, furniture, pipelines, bridge railings, hydraulic tubing
7075	C	B–D	D	Aircraft and other structures, keys, hydraulic fittings

[*] A, excellent; D, poor.

by five digits, indicating its chemical composition. For example, A is for aluminum, C for copper, N for nickel alloys, P for precious metals, and Z for zinc; in the UNS designation, 2024 wrought aluminum alloy is A92024.

Production. Aluminum was first produced in 1825. It is the most abundant metallic element, making up about 8% of the Earth's crust, and is produced in a quantity second only to that of iron. The principal ore for aluminum is *bauxite*, which is a hydrous (water-containing) aluminum oxide and includes various other oxides. After the clay and dirt are washed off, the ore is crushed into powder and treated with hot caustic soda (sodium hydroxide) to remove impurities. Next, alumina (aluminum oxide) is extracted from this solution and then dissolved in a molten sodium-fluoride and aluminum-fluoride bath at 940° to 980°C. This mixture is then subjected to direct-current electrolysis. Aluminum metal forms at the cathode (negative pole), while oxygen is released at the anode (positive pole). *Commercially pure aluminum* is up to 99.99% Al. The production process consumes a great deal of electricity, which contributes significantly to the cost of aluminum.

Porous Aluminum. Blocks of *porous aluminum* are produced that are 37% lighter than solid aluminum and have uniform permeability (*microporosity*). This characteristic allows their use in applications where a vacuum or differential pressure has to be maintained. Examples are the (a) vacuum holding of fixtures for assembly and automation (Section 37.8) and (b) vacuum forming or thermoforming of plastics (Section 19.6). These blocks are 70–90% aluminum powder; the rest is epoxy resin. They can be machined with relative ease and can be joined using adhesives.

CASE STUDY 6.1 An All-aluminum Automobile

Aluminum use in automobiles and in light trucks has been increasing steadily. As recently as 1990, there were no aluminum-structured passenger cars in production, but by 1997 there were seven, including the Plymouth Prowler and the Audi A8 (Fig. 6.2). With weight savings of up to 47% over steel vehicles, such cars use less fuel, create less pollution, and are recyclable.

(a)

(b)

FIGURE 6.2 (a) The aluminum body structure, showing various components made by extrusion, sheet forming, and casting processes. (b) The Audi A8 automobile, which has an all-aluminum body structure. *Source:* (a) Courtesy of National Institute of Standards and Technology.

New alloys and new design and manufacturing methodologies had to be developed to enable the use of aluminum in automobiles. For example, welding and adhesive bonding procedures had to be refined, the structural frame design had to be optimized, and new tooling designs had to be developed. Because of these new technologies, the desired environmental savings were realized without an accompanying drop in performance or safety. In fact, the Audi A8 was the first luxury-class car to earn a dual five-star (highest safety) rating for both driver and front-seat passenger in the National Highway Transportation Safety Administration (NHSTA) New Car Assessment Program.

6.3 Magnesium and Magnesium Alloys

Magnesium (Mg) is the lightest engineering metal, and has good vibration-damping characteristics. Its alloys are used in structural and nonstructural applications wherever weight is of primary importance. Magnesium is also an alloying element in various nonferrous metals.

Typical uses of magnesium alloys are in aircraft and missile components, material-handling equipment, portable power tools, ladders, luggage, bicycles, sporting goods, and general lightweight components. Like aluminum, magnesium is finding increased use in the automotive sector, mainly in order to achieve weight savings. Magnesium alloys are available either as castings (such as die-cast camera frames) or as wrought products (such as extruded bars and shapes, forgings, and rolled plates and sheets). Magnesium alloys are also used in printing and textile machinery to minimize inertial forces in high-speed components.

Because it is not sufficiently strong in its pure form, magnesium is alloyed with various elements (Table 6.5) in order to impart certain specific properties, particularly a high strength-to-weight ratio. A variety of magnesium alloys have good casting, forming, and machining characteristics. Because they oxidize rapidly (i.e., they are *pyrophoric*), however, a fire hazard exists, and hence precautions must be taken when machining, grinding, or sand-casting magnesium alloys. Products made of magnesium and its alloys are not a fire hazard during normal use.

Magnesium is easy to cast but difficult to form. Efforts have been made to promote the increased use of magnesium in automobiles through improved welding and sheet formability. Alloys ZEK100, AZ31, and ZE10 are of current high interest.

TABLE 6.5

Properties and Typical Forms of Selected Wrought Magnesium Alloys

Alloy	Nominal composition	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical forms
AZ31B	3.0 Al, 1.0 Zn, 0.2 Mn	F	260	200	15	Extrusions
		H24	290	220	15	Sheet and plate
AZ80A	8.5 Al, 0.5 Zn, 0.2 Mn	T5	380	275	7	Extrusions and forgings
HK31A	0.7 Zr, 3 Th	H24	255	200	8	Sheet and plates
ZE10	1.0 Zn, 1.0 Ce	F	263	163	16	Sheet and plates
ZEK199	1.0 Zn, 0.3 Zr, 1.0 Ce	F	311	308	19	Extrusions and sheet
ZK60A	5.7 Zn, 0.55 Zr	T5	365	300	11	Extrusions and forgings

Production. Magnesium is the third most abundant metallic element (2%) in the Earth's crust, after iron and aluminum. Most magnesium comes from seawater, which contains 0.13% magnesium, in the form of magnesium chloride. First produced in 1808, magnesium metal can be obtained either electrolytically or by thermal reduction. In the *electrolytic method*, seawater is mixed with lime (calcium hydroxide) in settling tanks. Magnesium hydroxide precipitates to the bottom, is filtered and mixed with hydrochloric acid. The resulting solution is subjected to electrolysis (as is done with aluminum), producing magnesium metal, which is then cast into ingots for further processing into various shapes.

In the *thermal-reduction method*, magnesium ores (dolomite, magnesite, and other rocks) are broken down with reducing agents (such as powdered ferrosilicon, an alloy of iron and silicon) by heating the mixture in a vacuum chamber. As a result of this reaction, vapors of magnesium form, and they condense into magnesium crystals, which are then melted, refined, and poured into ingots to be further processed into various shapes.

6.4 Copper and Copper Alloys

First produced in about 4000 B.C., **copper** (Cu, from the Latin *cuprum*) and its alloys have properties somewhat similar to those of aluminum and its alloys. In addition, they have good corrosion resistance and are among the best conductors of electricity and heat (Tables 3.1 and 3.2). Copper and its alloys can be processed easily by various forming, machining, casting, and joining techniques.

Copper alloys often are attractive for applications in which a combination of electrical, mechanical, nonmagnetic, corrosion-resistant, thermally conductive, and wear-resistant qualities are required. Applications include electrical and electronic components, springs, coins, plumbing components, heat exchangers, marine hardware, and consumer goods (such as cooking utensils, jewelry, and other decorative objects). Although aluminum is the most common material for dies in polymer injection molding (Section 19.3), copper often is used because of its better thermal properties. Also, pure copper can be used as a solid lubricant in hot metal-forming operations (Section 33.7.6).

Copper alloys can develop a wide variety of properties by the addition of alloying elements and by heat treatment, to improve their manufacturing characteristics. The most common copper alloys are brasses and bronzes. **Brass** (an alloy of copper and zinc) is one of the earliest alloys developed and has numerous applications, including decorative objects (Table 6.6). **Bronze** is an alloy of copper and tin (Table 6.7); there are also other bronzes, such as aluminum bronze (an alloy of copper and aluminum) and tin bronzes. Beryllium copper (or beryllium bronze) and phosphor bronze have good strength and hardness, with applications such as springs and bearings; other major copper alloys are copper nickels and nickel silvers.

Production. Copper is found in several types of ores, the most common being sulfide ores. The ores are generally of low grade and usually are obtained from open-pit mines. The ore is ground into fine particles in ball mills (rotating cylinders with metal balls inside to crush the ore, as illustrated in Fig. 17.6b); the resulting particles are then suspended in water to form a slurry. Chemicals and oil are added, and the mixture is agitated. The mineral particles form a *froth*, which is scraped and dried. The dry copper concentrate (as much as one-third of which is copper)

TABLE 6.6

Properties and Typical Applications of Selected Wrought Copper and Brasses

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Electrolytic tough-pitch copper (C11000)	99.90 Cu, 0.04 O	220–450	70–365	55–4	Downspouts, gutters, roofing, gaskets, auto radiators, bus bars, nails, printing rolls, rivets
Red brass, 85% (C23000)	85.0 Cu, 15.0 Zn	270–725	70–435	55–3	Weather stripping, conduits, sockets, fasteners, fire extinguishers, condenser and heat-exchanger tubing
Cartridge brass, 70% (C26000)	70.0 Cu, 30.0 Zn	300–900	75–450	66–3	Radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, locks, hinges, ammunition components, plumbing accessories
Free-cutting brass (C36000)	61.5 Cu, 3.0 Pb, 35.5 Zn	340–470	125–310	53–18	Gears, pinions, automatic high-speed screw machine parts
Naval brass (C46400 to C46700)	60.0 Cu, 39.25 Zn, 0.75 Sn	380–610	170–455	50–17	Aircraft: turnbuckle barrels, balls, bolts; marine hardware: propeller shafts, rivets, valve stems, condenser plates

TABLE 6.7

Properties and Typical Applications of Selected Wrought Bronzes

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Architectural bronze (C38500)	57.0 Cu, 3.0 Pb, 40.0 Zn	415 (as extruded)	140	30	Architectural extrusions, storefronts, thresholds, trim, butts, hinges
Phosphor bronze, 5% A (C51000)	95.0 Cu, 5.0 Sn, trace P	325–960	130–550	64–2	Bellows, clutch disks, cotter pins, diaphragms, fasteners, wire brushes, chemical hardware, textile machinery
Free-cutting phosphor bronze (C54400)	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	300–520	130–435	50–15	Bearings, bushings, gears, pinions, shafts, thrust washers, valve parts
Low-silicon bronze, B (C65100)	98.5 Cu, 1.5 Si	275–655	100–475	55–11	Hydraulic pressure lines, bolts, marine hardware, electrical conduits, heat-exchanger tubing
Nickel silver, 65–10 (C74500)	65.0 Cu, 25.0 Zn, 10.0 Ni	340–900	125–525	50–1	Rivets, screws, slide fasteners, hollowware, nameplates

is traditionally **smelted** (melted and fused) and refined; this process is known as **pyrometallurgy,** because heat is used to refine the metal. For applications such as electrical conductors, the copper is further refined electrolytically to a purity of at least 99.95% (OFEC, *oxygen-free electrolytic copper*). Copper is also processed by **hydrometallurgy,** involving both chemical and electrolytic reactions.

6.5 Nickel and Nickel Alloys

Nickel (Ni) is a silver-white metal and a major alloying element in metals that imparts strength, toughness, and corrosion resistance, and is used extensively in stainless steels and nickel-based alloys (also called **superalloys**). Nickel alloys are used in high-temperature applications (such as jet engine components, rockets, and nuclear power plants), food-handling and chemical-processing equipment, coins, and marine applications. Because nickel is magnetic, its alloys also are used in electromagnetic applications, such as solenoids.

The principal use of nickel as a metal is in the electroplating of parts for their appearance and the improvement of their corrosion and wear resistance. Nickel alloys have high strength and corrosion resistance at elevated temperatures. Alloying elements in nickel are chromium, cobalt, and molybdenum. The behavior of nickel alloys in machining, forming, casting, and welding can be modified by various other alloying elements.

A variety of nickel alloys, with a wide range of strengths at different temperatures, have been developed (Table 6.8). Although trade names are still in wide use, nickel alloys are identified in the UNS system with the letter N. Thus, Hastelloy G is N06007; other common trade names are:

- **Monel** is a nickel–copper alloy
- **Hastelloy** (also a nickel–chromium alloy) has good corrosion resistance and high strength at elevated temperatures
- **Nichrome** (an alloy of nickel, chromium, and iron) has high electrical resistance and high resistance to oxidation, and is used for electrical heating elements
- **Invar** and **Kovar** (alloys of iron and nickel) have relatively low sensitivity to temperature changes (Section 3.6)

Production. The main sources of nickel are sulfide and oxide ores, all of which have low concentrations of nickel. The metal is produced by sedimentary and thermal processes, followed by electrolysis; this sequence yields 99.95% pure nickel. Nickel

TABLE 6.8

Properties and Typical Applications of Selected Nickel Alloys (All Are Trade Names)

Type and UNS number	Nominal composition (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Nickel 200 (annealed)	–	380–550	100–275	60–40	Chemical and food processing industry, aerospace equipment, electronic parts
Duranickel 301 (age hardened)	4.4 Al, 0.6 Ti	1300	900	28	Springs, plastics extrusion equipment, molds for glass, diaphragms
Monel R-405 (hot rolled)	30 Cu	525	230	35	Screw-machine products, water meter parts
Monel K-500 (age hardened)	29 Cu, 3 Al	1050	750	30	Pump shafts, valve stems, springs
Inconel 600 (annealed)	15 Cr, 8 Fe	640	210	48	Gas turbine parts, heat-treating equipment, electronic parts, nuclear reactors
Hastelloy C-4 (solution treated and quenched)	16 Cr, 15 Mo	785	400	54	Parts requiring high-temperature stability and resistance to stress-corrosion cracking

also is present in the ocean bed in significant amounts, but undersea mining does not currently account for significant nickel production.

6.6 Superalloys

Superalloys are important in high-temperature applications, hence they are also known as **heat-resistant** or **high-temperature alloys.** Superalloys generally have good resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, and creep and erosion at elevated temperatures. Major applications of superalloys are in jet engines and gas turbines; other applications are in reciprocating engines, rocket engines, tools and dies for hot working of metals, and in the nuclear, chemical, and petrochemical industries.

Generally, superalloys are identified by trade names or by special numbering systems, and are available in a variety of shapes. Most superalloys have a maximum service temperature of about 1000°C in structural applications. For nonload-bearing components, temperatures can be as high as 1200°C.

Superalloys are referred to as *iron-based, cobalt-based,* or *nickel-based.*

- **Iron-based superalloys** generally contain from 32-67% Fe, 15-22% Cr, and 9-38% Ni. Common alloys in this group are the *Incoloy* series.
- **Cobalt-based superalloys** generally contain from 35-65% Co, 19-30% Cr, and up to 35% Ni. These superalloys are not as strong as nickel-based superalloys, but they retain their strength at higher temperatures.
- **Nickel-based superalloys** are the most common of the superalloys and are available in a wide variety of compositions (Table 6.9). The proportion of nickel is from 38-76% and also contain up to 27% Cr and 20% Co. Common alloys in this group are the *Hastelloy, Inconel, Nimonic, René, Udimet, Astroloy,* and *Waspaloy* series.

TABLE 6.9

Properties and Typical Applications of Selected Nickel-based Superalloys at 870°C (1600°F) (All Are Trade Names)

Alloy	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Astroloy	Wrought	770	690	25	Forgings for high-temperature use
Hastelloy X	Wrought	255	180	50	Jet engine sheet parts
IN-100	Cast	885	695	6	Jet engine blades and wheels
IN-102	Wrought	215	200	110	Superheater and jet engine parts
Inconel 625	Wrought	285	275	125	Aircraft engines and structures, chemical processing equipment
Inconel 718	Wrought	340	330	88	Jet engine and rocket parts
MAR-M 200	Cast	840	760	4	Jet engine blades
MAR-M 432	Cast	730	605	8	Integrally cast turbine wheels
René 41	Wrought	620	550	19	Jet engine parts
Udimet 700	Wrought	690	635	27	Jet engine parts
Waspaloy	Wrought	525	515	35	Jet engine parts

6.7 Titanium and Titanium Alloys

Titanium (Ti, named after the Greek god Titan) is a silvery-white metal, discovered in 1791 but not produced commercially until the 1950s. Although titanium is expensive, its high strength-to-weight ratio and corrosion resistance at room and elevated temperatures make it attractive for numerous applications, including aircraft; jet engines (see Fig. 6.1); racing cars; golf clubs; chemical, petrochemical, and marine components; submarine hulls; armor plate; and medical applications, such as orthopedic implants (Table 6.10). Titanium alloys can be used for service at 550°C for long periods of time and at up to 750°C for shorter periods.

Unalloyed titanium, known as *commercially pure titanium*, has excellent corrosion resistance for applications where strength considerations are secondary. Aluminum, vanadium, molybdenum, manganese, and other alloying elements impart special properties, such as improved workability, strength, and hardenability.

The properties and manufacturing characteristics of titanium alloys are extremely sensitive to small variations in both alloying and residual elements. Control of composition and processing are therefore important, especially the prevention of surface contamination by hydrogen, oxygen, or nitrogen during processing. These elements cause embrittlement of titanium and, consequently, reduce toughness and ductility.

The body-centered cubic structure of titanium (*beta-titanium*) is above 880°C and is ductile, whereas its hexagonal close-packed structure (*alphatitanium*) is somewhat brittle and is very sensitive to stress corrosion. A variety of other structures (alpha, near-alpha, alpha–beta, and beta) can be obtained by alloying and heat treating, so that the properties can be optimized for specific applications. **Titanium aluminide intermetallics** (TiAl and Ti_3Al; see Section 4.2.2) have higher stiffness and lower density than conventional titanium alloys, and can withstand higher temperatures.

Production. Ores containing titanium are first reduced to titanium tetrachloride in an arc furnace, then converted to titanium chloride in a chlorine atmosphere. The compound is reduced further to titanium metal by distillation and leaching (dissolving). This sequence forms *sponge titanium*, which is then pressed into billets, melted, and poured into ingots to be later processed into various shapes. The complexity of these multistep thermochemical operations (the *Kroll process*, after

TABLE 6.10

Properties and Typical Applications of Selected Wrought Titanium Alloys at Various Temperatures

UNS number	Nominal composition (%)	Condition	Temperature (°C)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)
R50250	99.5 Ti	Annealed	25	330	240	30	55
			300	150	95		
R54520	5 Al, 2.5 Sn	Annealed	25	860	810	16	40
			300	565	450		
R56400	6 Al, 4 V	Annealed	25	1000	925	14	30
			300	725	650		
		Solution + age	25	1175	1100	10	20
			300	980	900		
R58010	13 V, 11 Cr, 3 Al	Solution + age	25	1275	1210	8	—
			425	1100	830		

the Luxembourg metallurgist W.J. Kroll) adds considerably to the cost of titanium. Recent developments in electrochemical extraction processes have reduced the number of steps involved and the energy consumption, thereby reducing the cost of producing titanium.

6.8 Refractory Metals and Alloys

There are four **refractory metals**: molybdenum, niobium, tungsten, and tantalum; they are called *refractory* because of their high melting points, and are important alloying elements in steels and superalloys. More than most other metals and alloys, refractory metals maintain their strength at elevated temperatures, and thus are of great importance in rocket engines, gas turbines, and various other aerospace applications; in the electronic, nuclear-power, and chemical industries; and as tool and die materials. The temperature range for some of these applications is on the order of 1100° to 2200°C, where strength and oxidation are of major concern.

6.8.1 Molybdenum

Molybdenum (Mo, from the Greek meaning lead) is a silvery-white metal and has a high melting point, high modulus of elasticity, good resistance to thermal shock, and good electrical and thermal conductivity. Molybdenum is used in greater amounts than any other refractory metal, in applications such as solid-propellant rockets, jet engines, honeycomb structures, electronic components, heating elements, and dies for die casting. The principal alloying elements are titanium and zirconium. Molybdenum is itself also an important alloying element in cast and wrought alloy steels and in heat-resistant alloys, imparting strength, toughness, and corrosion resistance. A major limitation of molybdenum alloys is their low resistance to oxidation at temperatures above 500°C, which necessitates the need for protective coatings.

Production. The main source of molybdenum is the mineral *molybdenite* (molybdenum disulfide). The ore is first processed and the molybdenum is concentrated; it is then chemically reduced, first with oxygen and then with hydrogen. Powder metallurgy techniques also are used to produce ingots for further processing into various shapes.

6.8.2 Niobium (Columbium)

Niobium (Nb, for niobium, after Niobe, the daughter of the mythical Greek king Tantalus), also called **columbium** (after its source mineral, *columbite*), possesses good ductility and formability, and has higher oxidation resistance than other refractory metals. With various alloying elements, niobium alloys can have moderate strength and good fabrication characteristics. These alloys generally are used in rockets and missiles and in nuclear, chemical, and superconductor applications. Niobium is also an alloying element in various alloys and superalloys. The metal is processed from ores by reduction and refinement, and from powder by melting and shaping into ingots.

6.8.3 Tungsten

Tungsten (W, for *wolfram*, its European name, and from its source mineral *wolframite*; in Swedish, *tung* means "heavy" and sten means "stone") is the most abundant of all the refractory metals. Tungsten has the highest melting point of any metal (3410°C) and is notable for its high strength at elevated temperatures. However, it has high density, hence it is used for balancing weights and counterbalances in mechanical systems, including self-winding watches. It is brittle at low temperatures and has poor resistance to oxidation. As an alloying element, tungsten imparts elevated-temperature strength and hardness to steels.

Tungsten alloys are used for applications involving temperatures above 1650°C, such as nozzle throat liners in missiles and rocket engines, circuit breakers, welding electrodes, tooling for electrical-discharge machining, and spark-plug electrodes. Tungsten carbide, with cobalt as a binder for the carbide particles, is one of the most important tool and die materials. Tungsten is processed from ore concentrates by chemical decomposition, then reduced, and further processed by powder metallurgy techniques in a hydrogen atmosphere.

6.8.4 Tantalum

Tantalum (Ta, after the mythical Greek king Tantalus) is characterized by its high melting point (3000°C), high density, good ductility, and resistance to corrosion; however, it has poor chemical resistance at temperatures above 150°C. Tantalum is used extensively in electrolytic capacitors and in various components in the electrical, electronic, and chemical industries. It also is used for thermal applications, such as in furnaces and in acid-resistant heat exchangers. A variety of tantalum-based alloys are available in various forms for use in missiles and aircraft. Tantalum also is used as an alloying element. It is processed by techniques similar to those used for processing niobium.

6.9 Beryllium

Steel-gray in color, **beryllium** (Be, from the ore *beryl*) has a high strength-to-weight ratio. Unalloyed beryllium is used in rocket nozzles, space and missile structures, aircraft disk brakes, and precision instruments and mirrors; it is also used in nuclear and X-ray applications because of its low neutron absorption. Beryllium is also an alloying element, and its alloys of copper and nickel are used in various applications, including springs (*beryllium copper*), electrical contacts, and nonsparking tools for use in such explosive environments as mines and metal-powder production. Beryllium and its oxide are toxic, and should be handled accordingly.

6.10 Zirconium

Zirconium (Zr, from the mineral *zircon*) is silvery in appearance; it has good strength and ductility at elevated temperatures and has good corrosion resistance because of an adherent oxide film. Zirconium is used in electronic components and in nuclear-power reactor applications because of its low neutron absorption.

6.11 Low-melting Alloys

Low-melting alloys are so named because of their relatively low melting points. The major metals in this category are lead, zinc, tin, and their alloys.

6.11.1 Lead

Lead (Pb, after *plumbum*, the root of the word "plumber") has the properties of high density, resistance to corrosion (by virtue of the stable lead-oxide layer that forms to protect the surface), softness, low strength, ductility, and good workability. Alloying lead with various elements (such as antimony and tin) enhances its desirable properties, making it suitable for piping, collapsible tubing, bearing alloys (Babbitt), cable sheathing, foil (as thin as 0.01 mm), roofing, and lead–acid storage batteries. Lead also is used for damping vibrations, radiation shielding against X-rays, ammunition, and as a solid lubricant for hot-metal-forming operations. The oldest known lead artifacts were made in about 3000 B.C. Lead pipes made by the Romans and installed in the Roman baths in Bath, England, two millennia ago, are still in use.

Because of its toxicity, major efforts are being made to replace lead with other elements, such as *lead-free solders* (Section 32.3.1). The most important mineral source of lead is *galena* (PbS); it is mined, smelted, and refined by chemical treatments.

6.11.2 Zinc

Zinc (Zn, from the Latin *zincum*, although its origins are not clear) is bluish-white in color and is the metal that is fourth most utilized industrially, after iron, aluminum, and copper. It has three major uses: for galvanizing iron, steel sheet, and wire; as an alloy in other metals; and as a metal for castings. In **galvanizing**, zinc serves as an anode and protects steel (cathode) from corrosive attack should the coating be scratched or punctured. Zinc is also used as an alloying element; brass, for example, is an alloy of copper and zinc. In zinc-based alloys the major alloying elements are aluminum, copper, and magnesium, imparting strength and providing dimensional control during casting of the metal.

Zinc-based alloys are used extensively in die casting, for making such products as fuel pumps and grills for automobiles, components for household appliances such as vacuum cleaners and washing machines, kitchen equipment, machinery parts, and photoengraving equipment. Another use for zinc is in superplastic alloys (Section 2.2.7). A very fine grained 78% Zn–22% Al sheet is a common example of a superplastic zinc alloy that can be formed by methods used for forming plastics or metals.

Production. The principal mineral source for zinc is zinc sulfide, also called *zincblende*. The ore is first roasted in air and converted to zinc oxide. It is then reduced to zinc, either electrolytically (using sulfuric acid) or by heating it in a furnace with coal, which causes the molten zinc to separate.

6.11.3 Tin

Although used in small amounts compared with iron, aluminum, or copper, **tin** (Sn, from the Latin *stannum*) is an important metal. The most extensive use of tin (a silver-white, lustrous metal) is as a protective coating on steel sheets (*tin plates*) used in making containers (*tin cans*), for food and various other products. The low shear strength of the tin coatings on steel sheet improves its deep drawability (Section 16.7.1). Unlike galvanized steels, if this coating is punctured or destroyed, the steel corrodes because the tin is cathodic.

Unalloyed tin is used in such applications as a lining for water distillation plants and as a molten layer of metal in the production of float glass plate (Section 18.3.1). Tin-based alloys (also called **white metals**) generally contain copper, antimony, and lead; these alloying elements impart hardness, strength, and corrosion resistance.

Tin itself is an alloying element for dental alloys and for bronze (copper–tin alloy), titanium, and zirconium alloys. Tin–lead alloys are common soldering materials (Section 32.3), with a wide range of compositions and melting points.

Because of their low friction coefficients (which result from low shear strength and low adhesion), some tin alloys are used as journal-bearing materials. Known as **babbitts** (after the American goldsmith I. Babbitt, 1799–1862), these alloys contain tin, copper, and antimony. **Pewter**, an alloy of tin, copper, and antimony, is used for tableware, hollowware, and decorative artifacts. Tin alloys are also used in making organ pipes. The most important tin mineral is *cassiterite* (tin oxide), which is of low grade. The ore is first mined, then concentrated by various techniques, smelted, refined, and cast into ingots for further processing.

6.12 Precious Metals

The most important precious (costly) metals, also called **noble metals**, are the following:

- **Gold** (Au, from the Latin *aurum*) is soft and ductile, and has good corrosion resistance at any temperature. Typical applications include jewelry, coinage, reflectors, gold leaf for decorative purposes, dental work, electroplating, and electrical contacts and terminals.
- **Silver** (Ag, from the Latin *argentum*) is ductile and has the highest electrical and thermal conductivity of any metal (see Table 3.2); however, it develops an oxide film that adversely affects its surface characteristics and appearance. Typical applications for silver include tableware, jewelry, coinage, electroplating, solders, bearing linings, and food and chemical equipment. *Sterling silver* is an alloy of silver and 7.5% copper.
- **Platinum** (Pt) is a soft, ductile, grayish-white metal that has good corrosion resistance, even at elevated temperatures. Platinum alloys are used as electrical contacts; for spark-plug electrodes; as catalysts for automobile pollution-control devices; in filaments and nozzles; in dies for extruding glass fibers (Section 18.3.4), in thermocouples; and in jewelry and dental work.

6.13 Shape-memory Alloys (Smart Materials)

Shape-memory alloys are unique in that, after being plastically deformed into various shapes at room temperature, they return to their original shape upon heating. For example, a piece of straight wire, made of such a material, can be wound into the shape of a helical spring; when heated, the spring uncoils and returns to its original straight shape. Shape-memory alloys can be used to generate motion and/or force in temperature-sensitive actuators. The behavior of these alloys, also called **smart materials**, can be reversible; that is, the shape can switch back and forth repeatedly upon application and removal of heat.

A typical shape-memory alloy is 55% Ni–45% Ti (*Nitinol*); other alloys are copper–aluminum–nickel, copper–zinc–aluminum, iron–manganese–silicon, and titanium–nickel–hafnium. Shape-memory alloys generally also have such properties as good ductility, corrosion resistance, and high electrical conductivity.

Applications of shape-memory alloys include sensors, stents for blocked arteries, relays, pumps, switches, connectors, clamps, fasteners, and seals. As an example, a nickel–titanium valve has been made to protect people from being scalded in sinks, tubs, and showers. It is installed directly into the piping system and brings the water flow down to a trickle within 3 s after the water temperature reaches 47°C. More recent developments include thin-film shape-memory alloys deposited on polished silicon substrates for use in microelectromechanical (MEMS) devices (Chapter 29).

6.14 Amorphous Alloys (Metallic Glasses)

A class of metal alloys that, unlike metals, do not have a long-range crystalline structure, is called **amorphous alloys**; they have no grain boundaries, and their atoms are packed randomly and tightly. The amorphous structure was first obtained in the late 1960s by **rapid solidification** of a molten alloy (Section 11.6). Because their structure resembles that of glasses, these alloys are also called **metallic glasses**.

Amorphous alloys typically contain iron, nickel, and chromium, which are alloyed with carbon, phosphorus, boron, aluminum, and silicon, and are available as wire, ribbon, strip, and powder. One application is for faceplate inserts on golf-club heads; the alloy has a composition of zirconium, beryllium, copper, titanium, and nickel and is made by die casting. Another application is in hollow aluminum baseball bats, coated with a composite of amorphous metal by thermal spraying, and is said to improve the performance of the bat.

Amorphous alloys exhibit excellent corrosion resistance, good ductility, high strength, and very low magnetic hysteresis (utilized in magnetic steel cores for transformers, generators, motors, lamp ballasts, magnetic amplifiers, and linear accelerators). The low magnetic hysteresis loss provides greatly improved efficiency; however, fabrication costs are significant. Amorphous steels have been demonstrated to have strengths twice those of high-strength steels, and with potential applications in large structures; however, they are presently cost prohibitive. A major application for the superalloys of rapidly solidified powders is the consolidation into near-net shapes for parts used in aerospace engines.

6.15 Metal Foams

Metal foams are structures where the metal consists of only 5–20% of the structure's volume, as shown in Fig. 6.3. Usually made of aluminum alloys (but also of titanium, tantalum, and others), metal foams can be produced by blowing air into molten metal and tapping the froth that forms at the surface; this froth then solidifies into a foam. Other approaches to producing **metal foam** include (a) chemical vapor deposition (Section 34.6.2) onto a carbon foam lattice, (b) depositing metal powders from a slurry onto a polymer foam lattice, followed by sintering (Section 17.4) to fuse the metals and burn off the polymer, (c) doping molten or powder metals with titanium hydride (TiH_2), which then releases hydrogen gas at the elevated casting or sintering temperatures, and (d) pouring molten metal into a porous salt and, upon cooling, leaching out the salt with acid.

Metal foams have unique combinations of strength-to-density and stiffness-to-density ratios, although these ratios are not as high as the base metals themselves. However, metal foams are very lightweight and thus are attractive materials, especially for aerospace applications. Because of their porosity, other applications of metal foams include filters and orthopedic implants. More recent developments include nickel–manganese–gallium metal foams with shape-memory characteristics.

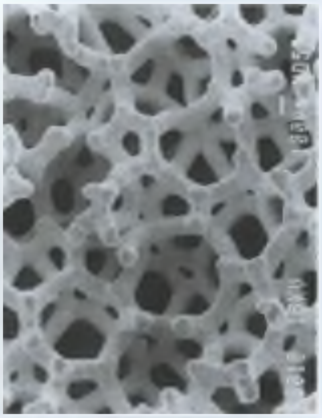

FIGURE 6.3 Structure of a metal foam used in orthopedic implants to encourage bone ingrowth. *Source:* Courtesy of Zimmer, Inc.

SUMMARY

- Nonferrous metals and alloys include a very broad range of materials. The most common are aluminum, magnesium, and copper and their alloys, with a wide range of applications. For high temperature service, nonferrous metals include nickel, titanium, refractory alloys (molybdenum, niobium, tungsten, tantalum), and superalloys. Other nonferrous metal categories include low-melting alloys (lead, zinc, tin) and precious metals (gold, silver, platinum).
- Nonferrous alloys have a wide variety of desirable properties, such as strength, toughness, hardness, and ductility; resistance to high temperature, creep, and oxidation; a wide range of physical, thermal, and chemical properties; and high strength-to-weight and stiffness-to-weight ratios (particularly for aluminum and titanium). Nonferrous alloys can be heat treated to impart certain specific properties.
- Shape-memory alloys (smart materials) have unique properties, with numerous applications in a variety of products as well as in manufacturing operations.
- Amorphous alloys (metallic glasses) have properties that are superior to other materials; available in various forms, they have numerous applications.
- Metal foams are very lightweight and thus are attractive for aerospace and various other applications.
- As with all materials, the selection of a nonferrous material for a particular application requires a careful consideration of several factors, including design and service requirements, long-term effects, chemical affinity to other materials, environmental attack, and cost.

KEY TERMS

Amorphous alloys
Babbitts
Brass
Bronze
Galvanizing
Low-melting alloys
Metal foam
Metallic glasses
Nonferrous
Pewter
Precious metals
Pyrometallurgy
Refractory metals
Shape-memory alloys
Smart materials
Smelted
Superalloys

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REVIEW QUESTIONS

6.1 Given the abundance of aluminum in the Earth's crust, explain why it is more expensive than steel.

6.2 Why is magnesium often used as a structural material in power hand tools? Why are its alloys used instead of pure magnesium?

6.3 What are the major uses of copper? What are the alloying elements in brass and bronze, respectively?

6.4 What are superalloys? Why are they so named?

6.5 What properties of titanium make it attractive for use in race-car and jet-engine components? Why is titanium not used widely for engine components in passenger cars?

6.6 Which properties of each of the major refractory metals define their most useful applications?

6.7 What are metallic glasses? Why is the word "glass" used for these materials?

6.8 What is the composition of (a) babbitts, (b) pewter, and (c) sterling silver?

6.9 Name the materials described in this chapter that have the highest (a) density, (b) electrical conductivity, (c) thermal conductivity, (d) strength, and (e) cost.

6.10 What are the major uses of gold and silver, other than in jewelry?

6.11 Describe the advantages to using zinc as a coating for steel.

6.12 What are nanomaterials? Why are they being developed?

6.13 Why are aircraft fuselages made of aluminum alloys, even though magnesium is the lightest metal?

6.14 How is metal foam produced?

6.15 What metals have the lowest melting points? What applications for these metals take advantage of their low melting points?

QUALITATIVE PROBLEMS

6.16 Explain why cooking utensils generally are made of stainless steels, aluminum, or copper.

6.17 Would it be advantageous to plot the data in Table 6.1 in terms of cost per unit weight rather than cost per unit volume? Explain and give some examples.

6.18 Compare the contents of Table 6.3 with those in various other tables and data on materials in this book, then comment on which of the two hardening processes (heat treating and work hardening) is more effective in improving the strength of aluminum alloys.

6.19 What factors other than mechanical strength should be considered in selecting metals and alloys for high-temperature applications? Explain.

6.20 Assume that, for geopolitical reasons, the price of copper increases rapidly. Name two metals with similar mechanical and physical properties that can be substituted for copper. Comment on your selection and any observations you make.

6.21 If aircraft, such as a Boeing 757, are made of 79% aluminum, why are automobiles made predominantly of steel?

6.22 Portable (notebook) computers and digital cameras can have their housing made of magnesium. Why?

6.23 Most household wiring is made of copper wire. By contrast, grounding wire leading to satellite dishes and the like is made of aluminum. Explain the reason.

6.24 The example in this chapter showed the benefits of making cars from aluminum alloys. However, the average amount of steel in cars has increased in the past decade. List reasons to explain these two observations.

6.25 If tungsten is the highest melting-point metal, why are no high temperature parts in Fig. 6.1 made from tungsten?

QUANTITATIVE PROBLEMS

6.26 A simply supported rectangular beam is 25 mm wide and 1 m long, and it is subjected to a vertical load of 10 kg at its center. Assume that this beam could be made of any of the materials listed in Table 6.1. Select three different materials, and for each, calculate the beam height that would cause each beam to have the same maximum deflection. Calculate the ratio of the cost for each of the three beams.

6.27 Obtain a few aluminum beverage cans, cut them, and measure their wall thicknesses. Using data in this chapter and simple formulas for thin-walled, closed-end pressure vessels, calculate the maximum internal pressure these cans can withstand before yielding. (Assume that the can is a thin-walled, closed-end, internally pressurized vessel.)

6.28 Beverage cans usually are stacked on top of each other in stores. Use the information from Problem 6.24, and, referring to textbooks on the mechanics of solids, estimate the crushing load each of these cans can withstand.

6.29 Using strength and density data, determine the minimum weight of a 1 m-long tension member that must support 3000 N if it is manufactured from (a) 3003-O aluminum, (b) 5052-H34 aluminum, (c) AZ31B-F magnesium, (d) any brass alloy, and (e) any bronze alloy.

6.30 Plot the following for the materials described in this chapter: (a) yield strength versus density, (b) modulus of elasticity versus strength, (c) modulus of elasticity versus relative cost, and (d) electrical conductivity versus density.

SYNTHESIS, DESIGN, AND PROJECTS

6.31 Because of the number of processes involved in making metals, the cost of raw materials depends on the condition (hot or cold rolled), shape (plate, sheet, bar, tubing), and size of the metals. Make a survey of the technical literature, obtain price lists or get in touch with suppliers, and prepare a list indicating the cost per 100 kg of the nonferrous materials described in this chapter, available in different conditions, shapes, and sizes.

6.32 The materials described in this chapter have numerous applications. Make a survey of the available literature in the bibliography, and prepare a list of several specific parts or components and applications, indicating the types of materials used.

6.33 Name products that would not have been developed to their advanced stages (as we find them today) if alloys having high strength, high corrosion resistance, and high creep resistance (all at elevated temperatures) had not been developed.

6.34 Assume that you are the technical sales manager of a company that produces nonferrous metals. Choose any one of the metals and alloys described in this chapter, and prepare a brochure, including some illustrations, for use as sales literature by your staff in their contact with potential customers.

6.35 Give some applications for (a) amorphous metals, (b) precious metals, (c) low-melting alloys, and (d) nanomaterials.

6.36 Describe the advantages of making products with multilayer materials. (For example, aluminum bonded to the bottom of stainless-steel pots.)

6.37 In the text, magnesium was described as the lightest engineering metal. Is it also the lightest metal? Explain.

6.38 Review the technical literature and the Internet and summarize the rare earth metals, their sources, and their main applications.

6.39 Review the technical literature, and write a detailed description of how magnesium is produced from sea water.

6.40 If you were to design an implant for use in the human body, what materials would you exclude? Which metals are possible for such applications? Of these, list three that you feel are best.

Polymers: Structure, General Properties, and Applications

CHAPTER 7

- Polymers display a wide range of properties and have several advantages over metallic materials, including low cost and ease of manufacturing; for these reasons, polymers continue to be among the most commonly used materials.
- This chapter first describes the structure of polymers, the polymerization process, crystallinity, and the glass-transition temperature.
- Mechanical properties and their dependence on temperature and deformation rate are then discussed.
- There are two basic types of polymers: thermoplastics and thermosets. Thermoplastics follow a basic manufacturing strategy of heating them until they soften or melt, and then shaping them into the desired product. Thermosets involve precursors that are formed to a desired shape and set through polymerization or cross-linking between polymer chains.
- The chapter also describes the properties and uses of elastomers, or rubbers.
- The general properties, typical applications, advantages, and limitations of polymers are discussed throughout the chapter, with several specific examples.

CASE STUDIES:

7.1 Introduction

The word **plastics** was first used as a noun in 1909 and is commonly employed as a synonym for **polymers**, a term first used in 1866. Plastics are unique in that they have extremely large molecules (*macromolecules* or *giant molecules*). Consumer and industrial products made of plastics include food and beverage containers, packaging, signs, housewares, housings for computers and monitors, textiles (clothing), medical devices, foams, paints, safety shields, toys, appliances, lenses, gears, electronic and electrical products, and automobile and aircraft bodies and components.

Because of their many unique and diverse properties, polymers increasingly have replaced metallic components in such applications as automobiles, civilian and military aircraft, sporting goods, toys, appliances, and office equipment. These substitutions reflect the advantages of polymers in terms of the following characteristics:

- Relatively low cost (see Table 6.1)
- Corrosion resistance and resistance to chemicals
- Low electrical and thermal conductivity
- Low density
- High strength-to-weight ratio, particularly when reinforced

- Noise reduction
- Wide choice of colors and transparencies
- Complexity of design possibilities and ease of manufacturing
- Other characteristics that may or may not be desirable (depending on the application), such as low strength and stiffness (Table 7.1), high coefficient of thermal expansion, low useful-temperature range—up to about 350°C—and lower dimensional stability in service over a period of time.

The word *plastic* is from the Greek *plastikos*, meaning "capable of being molded and shaped." Plastics can be formed, cast, machined, and joined into various shapes with relative ease. Minimal additional surface-finishing operations, if any at all, are required; this characteristic provides an important advantage over metals. Plastics are available commercially as film, sheet, plate, rods, and tubing of various crosssections.

Video Solution 7.1 Selection of Materials for a Lightweight Beam.

TABLE 7.1

Range of Mechanical Properties for Various Engineering Plastics at Room Temperature

Material	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Poisson's ratio, ν
Thermoplastics:				
Acrylonitrile-butadiene-styrene (ABS)	28–55	1.4–2.8	75–5	—
ABS, reinforced	100	7.5	—	0.35
Acetal	55–70	1.4–3.5	75–25	—
Acetal, reinforced	135	10	—	0.35–0.40
Acrylic	40–75	1.4–3.5	50–5	—
Cellulosic	10–48	0.4–1.4	100–5	—
Fluorocarbon	7–48	0.7–2	300–100	0.46–0.48
Nylon	55–83	1.4–2.8	200–60	0.32–0.40
Nylon, reinforced	70–210	2–10	10–1	—
Polycarbonate	55–70	2.5–3	125–10	0.38
Polycarbonate, reinforced	110	6	6–4	—
Polyester	55	2	300–5	0.38
Polyester, reinforced	110–160	8.3–12	3–1	—
Polyethylene	7–40	0.1–1.4	1000–15	0.46
Polypropylene	20–35	0.7–1.2	500–10	—
Polypropylene, reinforced	40–100	3.5–6	4–2	—
Polystyrene	14–83	1.4–4	60–1	0.35
Polyvinyl chloride	7–55	0.014–4	450–40	—
Thermosets:				
Epoxy	35–140	3.5–17	10–1	—
Epoxy, reinforced	70–1400	21–52	4–2	—
Phenolic	28–70	2.8–21	2–0	—
Polyester, unsaturated	30	5–9	1–0	—
Elastomers:				
Chloroprene (neoprene)	15–25	1–2	100–500	0.5
Natural rubber	17–25	1.3	75–650	0.5
Silicone	5–8	1–5	100–1100	0.5
Styrene-butadiene	10–25	2–10	250–700	0.5
Urethane	20–30	2–10	300–450	0.5

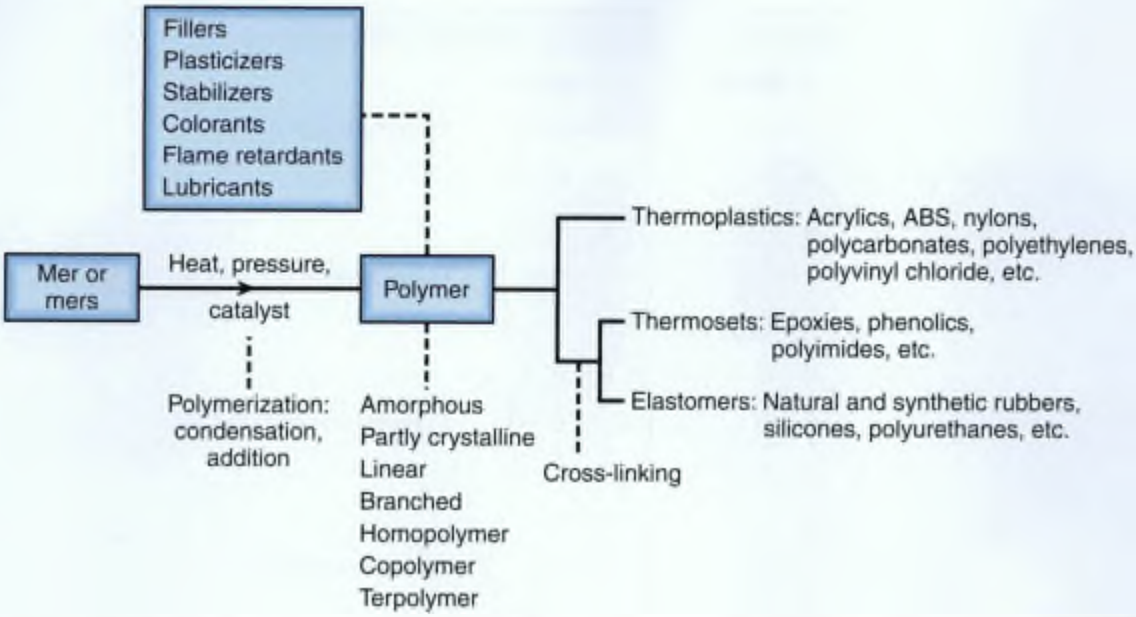


FIGURE 7.1 Outline of the topics described in this chapter.

An outline of the basic process for making synthetic polymers is given in Fig. 7.1. In polyethylene, only carbon and hydrogen atoms are involved, but other polymer compounds can be obtained by including chlorine, fluorine, sulfur, silicon, nitrogen, and oxygen. As a result, an extremely wide range of polymers—having among them an equally wide range of properties—has been developed.

7.2 The Structure of Polymers

The properties of polymers depend largely on the structures of individual polymer molecules, molecule shape and size, and the arrangement of molecules to form a polymer structure. Polymer molecules are characterized by their very large size, a feature that distinguishes them from most other organic chemical compositions. Polymers are **long-chain molecules** that are formed by *polymerization*, that is, by the linking and cross-linking of different monomers. A **monomer** is the basic building block of a polymer. The word mer (from the Greek *meros*, meaning "part") indicates the smallest repetitive unit, thus the term is similar to that of *unit cell* in crystal structures of metals (Section 1.3).

The word **polymer** means "many mers," generally repeated hundreds or thousands of times in a chainlike structure. Most monomers are *organic materials*, in which carbon atoms are joined in *covalent* (electron-sharing) bonds with other atoms (such as hydrogen, oxygen, nitrogen, fluorine, chlorine, silicon, and sulfur). An ethylene molecule (Fig. 7.2) is an example of a simple monomer, consisting of carbon and hydrogen atoms.

7.2.1 Polymerization

Monomers can be linked in repeating units to make longer and larger molecules by a chemical process called a **polymerization reaction**. Although there are several

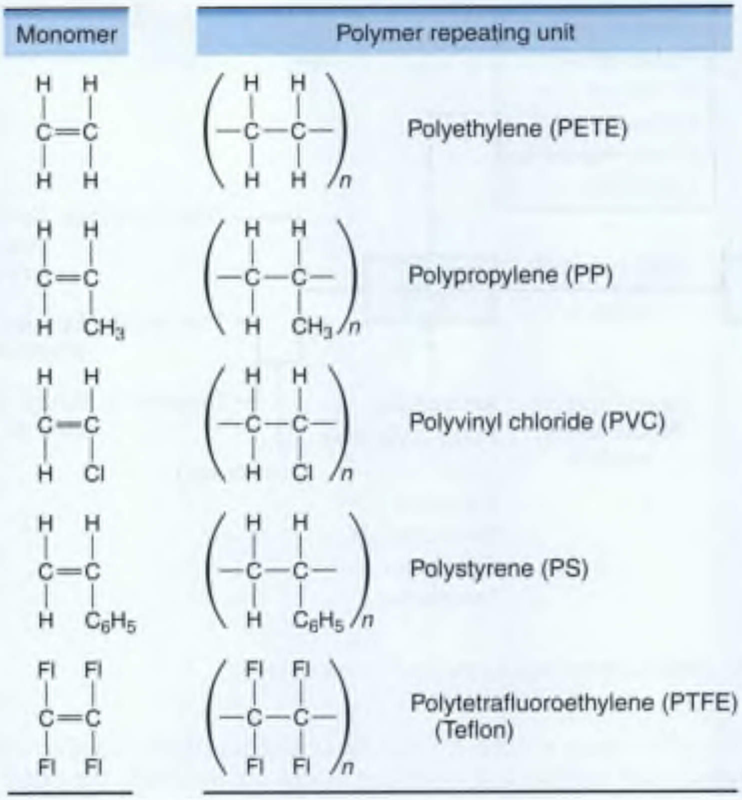


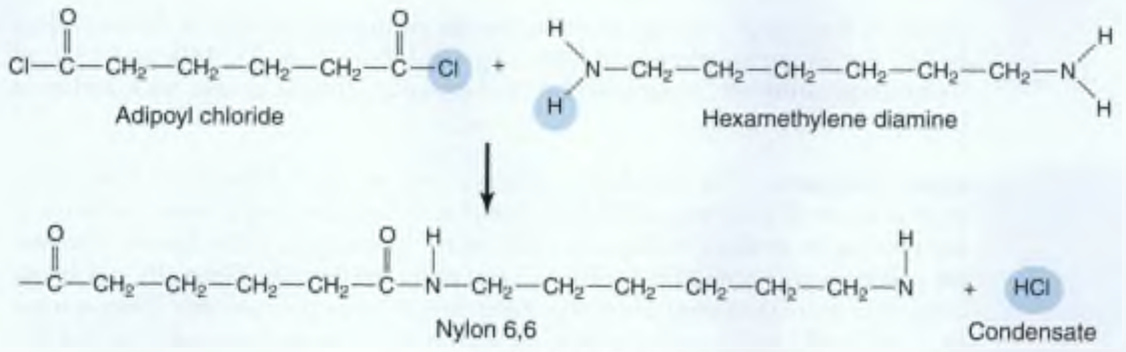
FIGURE 7.2 Molecular structure of various polymers; these are examples of the basic building blocks for plastics.

variations, two polymerization processes are important: condensation and addition polymerization.

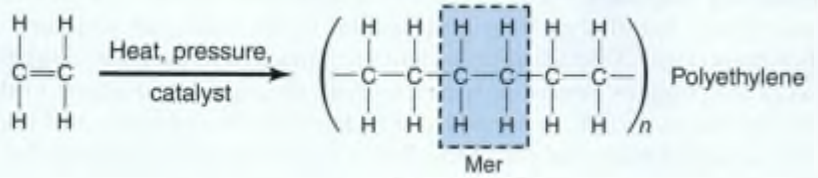
In **condensation polymerization** (Fig. 7.3a), polymers are produced by the formation of bonds between two types of reacting mers. A characteristic of this reaction is that reaction by-products (such as water) are condensed out (hence the word *condensation*). This process is also known as **step-growth** or **step-reaction polymerization,** because the polymer molecule grows step-by-step until all of one reactant is consumed.

In **addition polymerization,** also called **chain-growth** or **chain-reaction polymerization,** bonding takes place without reaction by-products, as shown in Fig. 7.3b. It is called *chain reaction* because of the high rate at which long molecules form simultaneously, usually within a few seconds. This rate is much higher than that in condensation polymerization. In addition polymerization, an *initiator* is added to open the double bond between two carbon atoms, which then begins the linking process by adding several more monomers to a growing chain. For example, ethylene monomers (Fig. 7.3b) link to produce *polyethylene*; other examples of addition-formed polymers are given in Fig. 7.2.

Molecular Weight. The sum of the molecular weights of the mers in a representative chain is known as the *molecular weight* of the polymer; the higher the molecular weight of a given polymer, the greater the average chain length. Most commercial polymers have a molecular weight between 10,000 and 10,000,000. Because polymerization is a random event, the polymer chains produced are not all of equal



(a) Condensation



(b) Addition

FIGURE 7.3 Examples of polymerization. (a) Condensation polymerization of nylon 6,6 and (b) addition polymerization of polyethylene molecules from ethylene mers.

length, although the chain lengths produced fall into a traditional distribution curve (as described in Section 36.7). The molecular weight of a polymer is determined on a statistical basis by averaging.

The spread of the molecular weights in a chain is called the **molecular weight distribution.** A polymer's molecular weight and its distribution have a major influence on its properties. For example, the tensile and the impact strength, the resistance to cracking, and the viscosity (in the molten state) of the polymer all increase with increasing molecular weight (Fig. 7.4).

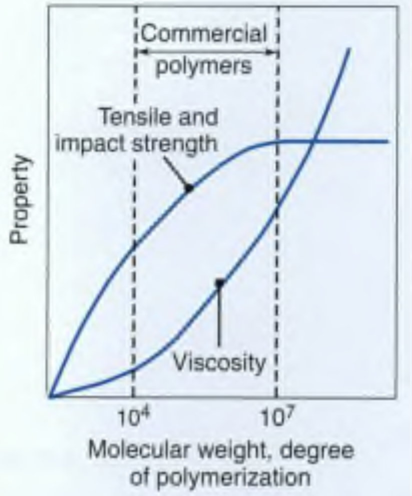


FIGURE 7.4 Effect of molecular weight and degree of polymerization on the strength and viscosity of polymers.

Degree of Polymerization. It is convenient to express the size of a polymer chain in terms of the *degree of polymerization* (DP), defined as the ratio of the molecular weight of the polymer to the molecular weight of the repeating unit. For example, polyvinyl chloride (PVC) has a mer weight of 62.5; thus, the DP of PVC with a molecular weight of 50,000 is $50{,}000/62.5 = 800$. In terms of polymer processing (described in Chapter 19), the higher the DP, the higher is the polymer's viscosity or its resistance to flow (Fig. 7.4). On the one hand, high viscosity adversely affects the ease of shaping and, thus, raises the overall cost of processing; moreover, high DP can result in stronger polymers.

Bonding. During polymerization, the monomers are linked together by **covalent bonds** (Section 1.2), forming a polymer chain. Because of their strength, covalent bonds also are called **primary bonds.** The polymer chains are, in turn, held together by **secondary bonds,** such as van der Waals bonds, hydrogen bonds, and ionic bonds. Secondary bonds are weaker than primary bonds by one to two orders of magnitude.

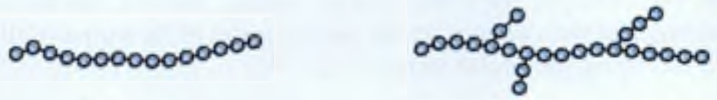
In a given polymer, the increase in strength and viscosity with molecular weight is due, in part, to the fact that the longer the polymer chain, the greater is the energy required to overcome the combined strength of the secondary bonds. For example, ethylene polymers having DPs of 1, 6, 35, 140, and 1350 at room temperature are, respectively, in the form of gas, liquid, grease, wax, and hard plastic.

Linear Polymers. The chainlike polymers shown in Fig. 7.2 are called *linear polymers* because of their sequential structure (Fig. 7.5a); however, a linear molecule is not necessarily straight in shape. In addition to those shown in the figure, other linear polymers are polyamides (nylon 6,6) and polyvinyl fluoride. Generally, a polymer consists of more than one type of structure; thus, a linear polymer may contain some branched and some cross-linked chains. As a result of branching and cross-linking, the polymer's properties are changed significantly.

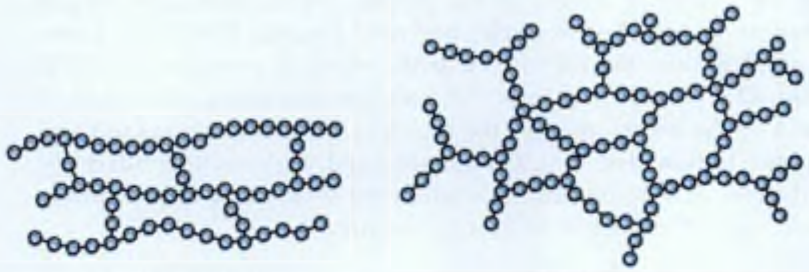
Branched Polymers. The properties of a polymer depend not only on the type of monomers, but also on their arrangement in the molecular structure. In *branched polymers* (Fig. 7.5b), side-branch chains are attached to the main chain during synthesis of the polymer. Branching interferes with the relative movement of the molecular chains, and as a result, their resistance to deformation and stress cracking is increased. The density of branched polymers is lower than that of linear-chain polymers, because the branches interfere with the packing efficiency of polymer chains.

The behavior of branched polymers can be compared to that of linear-chain polymers, by making an analogy with a pile of tree branches (*branched polymers*) and a bundle of straight logs (*linear polymers*). Note that it is more difficult to move a branch within the pile of branches than to move a log within its bundle. The three-dimensional entanglements of branches make their movements more difficult, a phenomenon akin to increased strength of the polymer.

Cross-linked Polymers. Generally three-dimensional in structure, *cross-linked polymers* have adjacent chains linked by covalent bonds (Fig. 7.5c). Polymers with a



(a) Linear (b) Branched



(c) Cross-linked (d) Network

FIGURE 7.5 Schematic illustration of polymer chains. (a) Linear structure—thermoplastics such as acrylics, nylons, polyethylene, and polyvinyl chloride have linear structures. (b) Branched structure, such as in polyethylene. (c) Cross-linked structure—many rubbers, or elastomers, have this structure, and the vulcanization of rubber produces this structure. (d) Network structure, which is basically highly cross-linked—examples are thermosetting plastics, such as epoxies and phenolics.

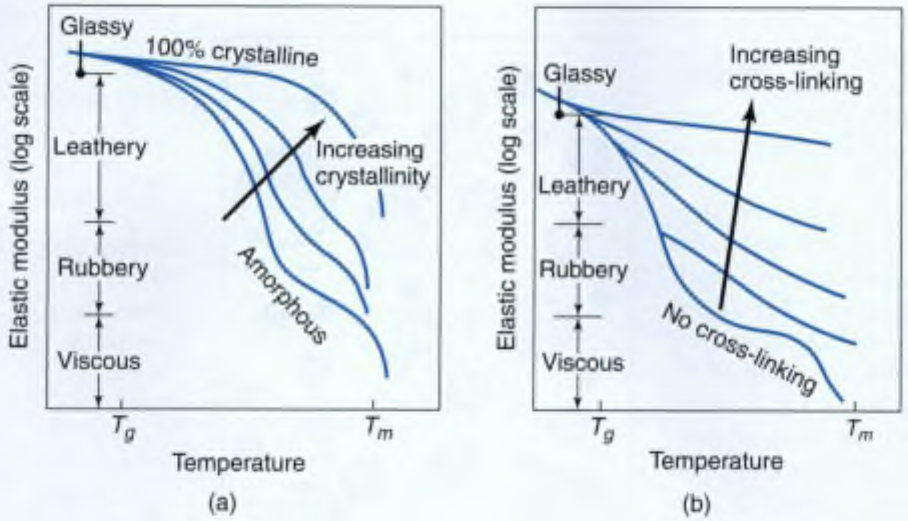


FIGURE 7.6 Behavior of polymers as a function of temperature and (a) degree of crystallinity and (b) cross-linking. The combined elastic and viscous behavior of polymers is known as viscoelasticity.

cross-linked structure are called **thermosets** or **thermosetting plastics**, such as epoxies, phenolics, and silicones. Cross-linking has a major influence on the properties of polymers, generally imparting hardness, strength, stiffness, brittleness, and better dimensional stability (see Fig. 7.6), and the on **vulcanization** of rubber (Section 7.9).

Network Polymers. These polymers consist of spatial (three-dimensional) networks consisting of three or more active covalent bonds (Fig. 7.5d). A highly cross-linked polymer also is considered a *network polymer*. Thermoplastic polymers that already have been shaped can be cross-linked, to obtain higher strength by subjecting them to high-energy radiation, such as ultraviolet light, X-rays, or electron beams. However, excessive radiation can cause degradation of the polymer.

Copolymers and Terpolymers. If the repeating units in a polymer chain are all of the same type, the molecule is called a *homopolymer*. However, as with solid-solution metal alloys (Section 4.2), two or three different types of monomers can be combined to develop certain properties and characteristics, such as improved strength, toughness, and formability of the polymer. (a) *Copolymers* contain two types of polymers; for example, styrene-butadiene, widely used for automobile tires. (b) *Terpolymers* contain three types; for example, acrylonitrile-butadiene-styrene (ABS), used for helmets, telephones, and refrigerator liners.

CASE STUDY 7.1 Dental and Medical Bone Cement

Polymethylmethacrylate (PMMA) is an acrylic polymer commonly used in dental and medical applications as an adhesive, often referred to as bone cement. There are several forms of PMMA, but the adhesive is one common form involving an addition-polymerization reaction. PMMA is delivered in two parts: a powder and a liquid, which are hand-mixed. The liquid wets and partially dissolves

(*continued*)

the powder, resulting in a liquid with a viscosity similar to that of vegetable oil. The viscosity increases markedly until a doughy state is reached, in about five minutes. The dough fully hardens in an additional five minutes.

The powder consists of high-molecular-weight poly[(methylmethacrylate)-costyrene] particles, about 50 μm in diameter, and contain a small volume fraction of benzoyl peroxide. The liquid consists of methyl methacrylate (MMA) monomer, with a small amount of dissolved n, n dimethyl-ptoluidine (DMPT). When the liquid and powder are mixed, the DMPT cleaves the benzoyl peroxide molecule into two parts, to form a catalyst with a free electron (sometimes referred to as a free radical). This catalyst causes rapid growth of PMMA from the MMA mers, so that the final material is a composite of high-molecular-weight PMMA particles interconnected by PMMA chains. An illustration of a fully set bone cement is given in Fig. 7.7.

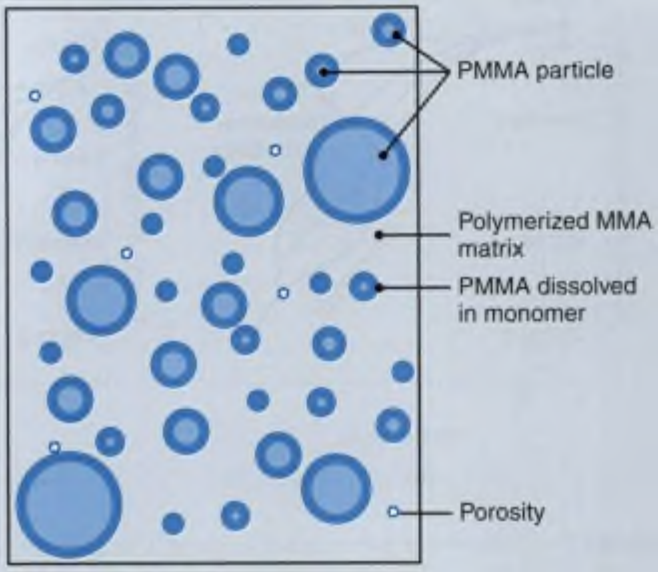


FIGURE 7.7 Schematic illustration of the microstructure of polymethylmethacrylate cement used in dental and medical applications.

7.2.2 Crystallinity

Polymers such as PMMA, polycarbonate, and polystyrene are generally **amorphous;** that is, the polymer chains exist without long-range order. (See also *amorphous alloys,* Section 6.14.) The amorphous arrangement of polymer chains is often described as being like a bowl of spaghetti, or like worms in a bucket, all intertwined with each other. In some polymers, however, it is possible to impart some crystallinity and thereby modify their characteristics. This arrangement may be fostered either during the synthesis of the polymer or by deformation during its subsequent processing.

The crystalline regions in polymers are called **crystallites** (Fig. 7.8). They are formed when the long molecules arrange themselves in an orderly manner, similar to the folding of a fire hose in a cabinet or of facial tissues in a box. A partially crystalline (**semicrystalline**) polymer can be regarded as a two-phase material, one phase being crystalline and the other amorphous.

By controlling the chain structure as well as the rate of solidification during cooling, it is possible to impart different **degrees of crystallinity** to polymers, although never 100%. Crystallinity ranges from an almost complete crystal (up to about 95% by volume in the case of polyethylene) to slightly crystallized (and mostly amorphous) polymers. The degree of crystallinity is also affected by branching. A linear polymer can become highly crystalline; a highly branched polymer cannot, although it may develop some low level of crystallinity. It will never achieve a high crystallite content, because the branches interfere with the alignment of the chains into a regular crystal array.

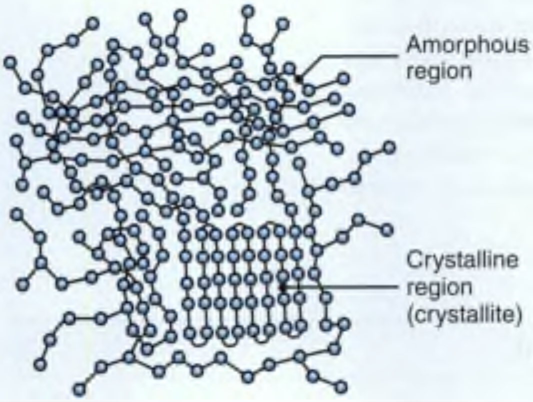


FIGURE 7.8 Amorphous and crystalline regions in a polymer; the crystalline region (crystallite) has an orderly arrangement of molecules. The higher the crystallinity, the harder, stiffer, and less ductile the polymer.

Effects of Crystallinity. The mechanical and physical properties of polymers are greatly influenced by the degree of crystallinity. As crystallinity increases, polymers become stiffer, harder, less ductile, more dense, less rubbery, and more resistant to solvents and heat (Fig. 7.6). The increase in density with increasing crystallinity is called *crystallization shrinkage*, and is caused by more efficient packing of the molecules in the crystal lattice. For example, the highly crystalline form of polyethylene, known as high-density polyethylene (HDPE), has a specific gravity in the range of 0.941–0.970 (80–95% crystalline). It is stronger, stiffer, tougher, and less ductile than low-density polyethylene (LDPE), which is about 60–70% crystalline and has a specific gravity in the range of 0.910–0.925.

Optical properties of polymers also are affected by the degree of crystallinity. The reflection of light from the boundaries between the crystalline and the amorphous regions in the polymer (Fig. 7.8) causes opaqueness. Furthermore, because the index of refraction is proportional to density, the greater the density difference between the amorphous and crystalline phases, the greater is the opaqueness of the polymer. Polymers that are completely amorphous can be transparent, such as polycarbonate and acrylics.

7.2.3 Glass-transition Temperature

Although amorphous polymers do not have a specific melting point, they undergo a distinct change in their mechanical behavior across a narrow range of temperatures. At low temperatures, they are hard, rigid, brittle, and glassy; at high temperatures, they are rubbery or leathery. The temperature at which a transition occurs is called the **glass-transition temperature** (T_g), also called the *glass point* or *glass temperature*. The term "glass" is used in this description because glasses, which are amorphous solids, behave in the same manner. (See *metallic glasses*, Section 6.14 and *glass*, Section 8.4.) Although most amorphous polymers exhibit this behavior, an exception is polycarbonate, which is neither rigid nor brittle below its glass-transition temperature. Polycarbonate is tough at ambient temperatures and is thus used for safety helmets and shields.

To determine T_g, a plot of the specific volume of the polymer as a function of temperature is produced; T_g occurs where there is a sharp change in the slope of the curve (Fig. 7.9). In the case of highly cross-linked polymers, the slope of the curve changes gradually near T_g, thus it can be difficult to determine T_g for these polymers. The glass-transition temperature varies with the type of polymer (Table 7.2), and it can be above or below room temperature. Unlike amorphous polymers, partly crystalline polymers have a distinct melting point, T_m (Fig. 7.9; see also Table 7.2). Because of the structural changes (called first-order changes) that occur, the specific volume of the polymer drops rapidly as its temperature is reduced.

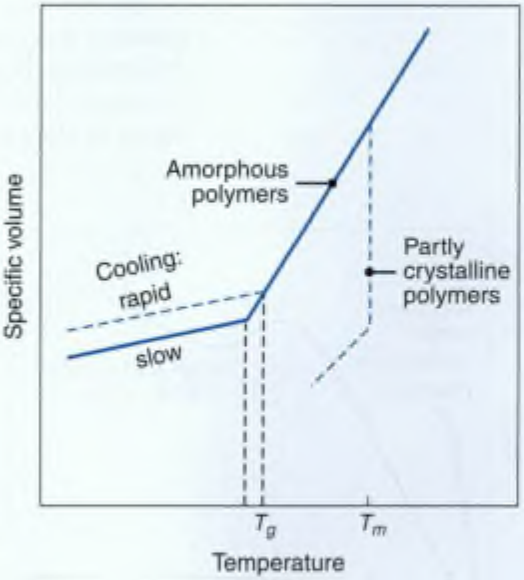


FIGURE 7.9 Specific volume of polymers as a function of temperature. Amorphous polymers, such as acrylic and polycarbonate, have a glass-transition temperature, but do not have a specific melting point. Partly crystalline polymers, such as polyethylene and nylons, contract sharply while passing through their melting temperatures during cooling.

7.2.4 Polymer Blends

The brittle behavior of amorphous polymers below their glass-transition temperature can be reduced by *blending* them, usually with small quantities of an **elastomer** (Section 7.9). The tiny particles that make up the elastomer are dispersed throughout the amorphous polymer, enhancing its toughness and impact strength by improving its resistance to crack propagation. These polymer blends are known as **rubber-modified polymers.**

Blending involves combining several components, creating **polyblends** that utilize the favorable properties of different polymers. **Miscible blends** (mixing without separation of two phases) are produced by a process, similar to the alloying of metals, that enables polymer blends to become more ductile. Polymer blends account for about 20% of all polymer production.

TABLE 7.2

Glass-transition and Melting Temperatures of Some Polymers

Material	T_g (°C)	T_m (°C)
Nylon 6,6	57	265
Polycarbonate	150	265
Polyester	73	265
Polyethylene		
High density	−90	137
Low density	−110	115
Polymethylmethacrylate	105	—
Polypropylene	−14	176
Polystyrene	100	239
Polytetrafluoroethylene	−90	327
Polyvinyl chloride	87	212
Rubber	−73	—

7.3 Thermoplastics

It was noted above that within each molecule, the bonds between adjacent long-chain molecules (secondary bonds) are much weaker than the covalent bonds between mers (primary bonds). It is the strength of the secondary bonds that determines the overall strength of the polymer. Linear and branched polymers have weak secondary bonds.

As the temperature is raised above the glass-transition temperature, T_g, or melting point, T_m, certain polymers become easier to form or mold into desired shapes. When the polymer is cooled, it returns to its original hardness and strength; in other words, the process is reversible. Polymers that exhibit this behavior are known as **thermoplastics,** common examples of which are acrylics, cellulosics, nylons, polyethylenes, and polyvinyl chloride.

The behavior of thermoplastics also depends on other variables, including their structure and composition; among the most important are temperature and rate of deformation. Below the glass-transition temperature, most polymers are *glassy* (brittle) and behave like an elastic solid. The relationship between stress and strain is linear, as shown in Fig. 2.2. The behavior depends on the particular polymer. For example, PMMA is glassy below its T_g, whereas polycarbonate is not glassy below its T_g. When the applied stress is increased further, polycarbonate eventually fractures, just as a piece of glass does at ambient temperature.

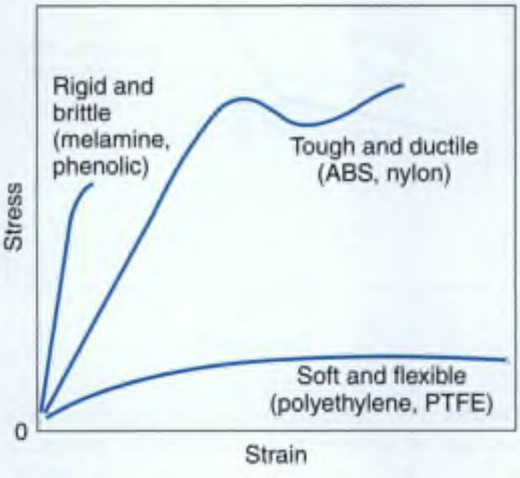


FIGURE 7.10 General terminology describing the behavior of three types of plastics. PTFE (polytetrafluoroethylene) has *Teflon* as its trade name. *Source:* After R.L.E. Brown.

Typical stress–strain curves for some thermoplastics and thermosets at room temperature are shown in Fig. 7.10. Their various behavior may be described as rigid, soft, brittle, flexible, and so on. As can be noted from the mechanical properties of the polymers listed in Table 7.1, thermoplastics are about two orders of magnitude less stiff than metals, and their ultimate tensile strength is about one order of magnitude lower than that of metals (see Table 2.2).

Effects of Temperature. If the temperature of a thermoplastic polymer is raised above its T_g, it first becomes *leathery* and then, with increasing temperature, *rubbery* (Fig. 7.6). Finally, at higher temperatures (above T_m for crystalline thermoplastics), the polymer becomes a *viscous fluid*, and its viscosity decreases with increasing temperature. As a viscous fluid, it can be softened, molded into shapes, resolidified, remelted, and remolded several times. In practice, however, repeated heating and cooling causes **degradation** or **thermal aging** of thermoplastics.

As with metals, the strength and the modulus of elasticity of thermoplastics decrease with increasing temperature while the ductility increases (see Figs. 2.6 and 7.11). The effect of temperature on impact strength is shown in Fig. 7.12; note the large difference in the impact behavior among various polymers.

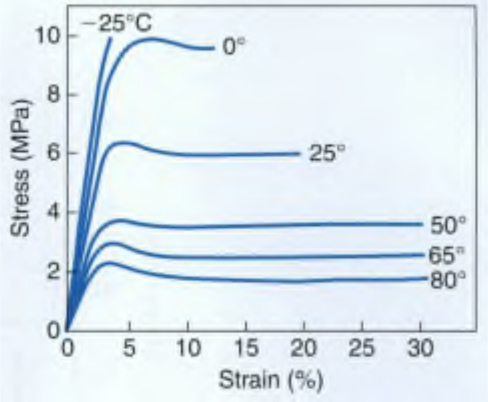


FIGURE 7.11 Effect of temperature on the stress–strain curve for cellulose acetate, a thermoplastic. Note the large drop in strength and the large increase in ductility with a relatively small increase in temperature. *Source:* After T.S. Carswell and H.K. Nason.

Effect of Rate of Deformation. When deformed rapidly, the behavior of thermoplastics is similar to metals, as was shown by the strain-rate sensitivity exponent, m, in Eq. (2.9). Thermoplastics, in general, have high m values, indicating that they can undergo large *uniform deformation* in tension before fracture. Note in Fig. 7.13 how, unlike in ordinary metals, the necked region of the specimen elongates considerably.

This phenomenon can be easily demonstrated by stretching a piece of the plastic holder for a 6-pack of beverage cans, and observing the sequence of the necking and stretching behavior shown in Fig. 7.13a. This characteristic, which is the same in the superplastic metals (Section 2.2.7), enables the thermoforming of thermoplastics (Section 19.6) into such complex shapes as candy trays, lighted signs, and packaging.

Orientation. When thermoplastics are deformed (say, by stretching), the long-chain molecules tend to align in the general direction of the elongation: a behavior called *orientation*. As in metals, the polymer becomes *anisotropic* (see also Section 1.6): the specimen becomes stronger and stiffer in the elongated (stretched) direction than in its transverse direction. Stretching is an important technique for enhancing the strength and toughness of polymers, and is especially exploited in producing high-strength fibers for use in composite materials, as described in Chapter 9.

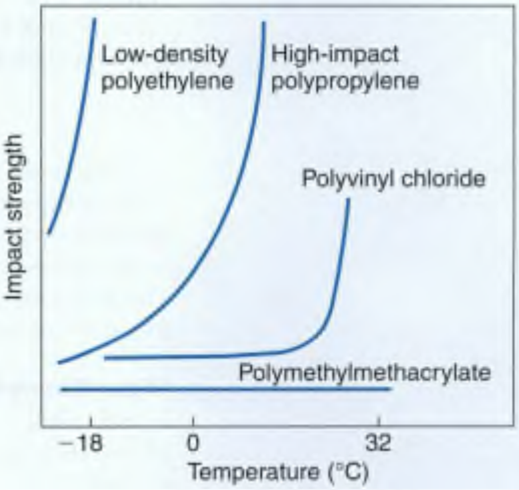


FIGURE 7.12 Effect of temperature on the impact strength of various plastics. Small changes in temperature can have a significant effect on impact strength. *Source:* After P.C. Powell.

Creep and Stress Relaxation. Because of their viscoelastic behavior, thermoplastics are particularly susceptible to creep and stress relaxation, and to a larger extent than metals (Section 2.8). The extent of these phenomena depends on the particular polymer, stress level, temperature, and time. Thermoplastics exhibit creep and stress relaxation at room temperature, whereas most metals do so only at elevated temperatures.

Crazing. When subjected to tensile or bending stresses, some thermoplastics (such as polystyrene and PMMA) develop localized, wedge-shaped narrow regions of highly deformed material, a behavior called *crazing*. Although they may appear to be like cracks, crazes are spongy material, typically containing about 50% voids. With increasing tensile load on the specimen, these voids coalesce to form a crack, which eventually can lead to fracture of the polymer. Crazing has been observed both in transparent, glassy polymers and in other types. The environment (particularly the presence of solvents, lubricants, or water vapor) can enhance the formation of crazes, called **environmental-stress cracking** and **solvent crazing**. Residual stresses in the material also contribute to crazing and cracking of the polymer.

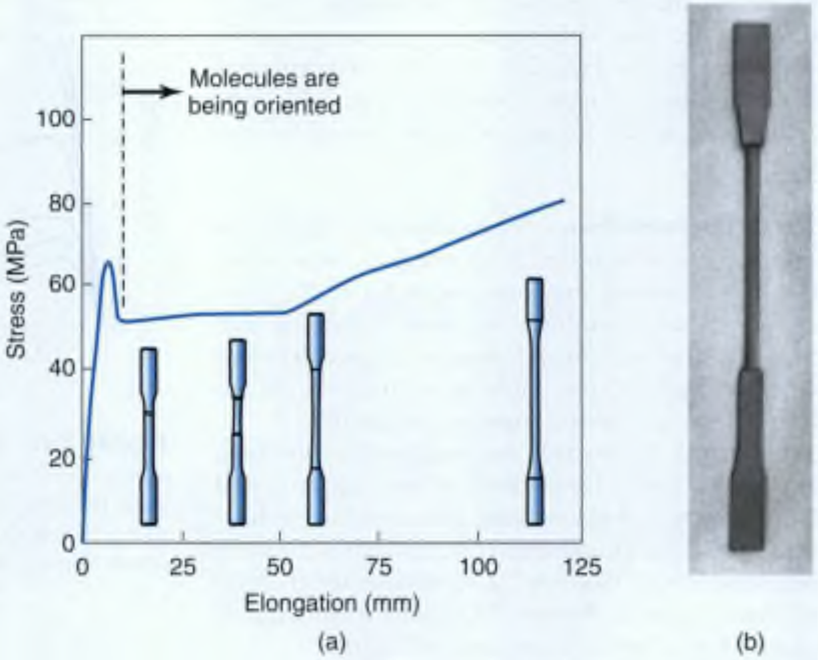


FIGURE 7.13 (a) Stress-elongation curve for polycarbonate, a thermoplastic. *Source:* Courtesy of R.P. Kambour and R.E. Robertson. (b) High-density polyethylene tensile-test specimen, showing uniform elongation (the long, narrow region in the specimen).

A behavior related to crazing is **stress whitening**. When subjected to tensile stresses (such as those caused by bending or folding), the polymer becomes lighter in color, a phenomenon usually attributed to the formation of microvoids in the material. As a result, the polymer becomes less translucent (transmits less light), or more opaque. This behavior can easily be demonstrated by bending plastic components commonly found in colored binder strips for report covers, household products, and toys.

Water Absorption. An important characteristic of some polymers, such as nylons, is their ability to absorb water, known as *hygroscopic* behavior; water acts as a plasticizing agent, making the polymer more plastic. (See Section 7.5.) In a sense, it lubricates the chains in the amorphous regions. With increasing moisture absorption, the glass-transition temperature, the yield stress, and the elastic modulus of the polymer typically becomes rapidly lower. Dimensional changes also occur, especially in a humid environment.

Thermal and Electrical Properties. Compared to metals, plastics generally are characterized by low thermal and electrical conductivity, low specific gravity (ranging from 0.90 to 2.2), and a high coefficient of thermal expansion (about an order of magnitude higher, as shown in Tables 3.1 and 3.2). Because most polymers have low electrical conductivity, they can be used for insulators and as packaging material for electronic components.

The electrical conductivity of some polymers can be increased by **doping** (introducing impurities, such as metal powders, salts, and iodides, into the polymer). Discovered in the late 1970s, **electrically conducting polymers** include polyethylene oxide, polyacetylene, polyaniline, polypyrrole, and polythiophene. The electrical conductivity of polymers increases with moisture absorption; their electronic properties also can be changed by irradiation. Applications for conducting polymers include adhesives, microelectronic devices, rechargeable batteries, capacitors, catalysts, fuel cells, fuel-level sensors, deicer panels, radar dishes, antistatic coatings, and thermoactuating motors (used in linear-motion applications, such as for power antennae, sun roofs, and power windows).

Thermally conducting polymers are being developed for applications requiring dimensional stability and heat transfer (such as heat sinks), as well as for reducing cycle times in molding and processing of thermoplastics. These polymers are typically thermoplastics (such as polypropylene, polycarbonate, and nylon), embedded with thermally conducting particles. Their conductivity can be as much as 100 times that of conventional plastics. (See also *sprayed-metal tooling*, Section 20.6.1.)

Shape-memory Polymers. Polymers also can behave in a manner similar to the shape-memory alloys, described in Section 6.13. The polymers can be stretched or compressed to very large strains, and then, when subjected to heat, light, or a chemical environment, they recover their original shape. The potential applications for these polymers are similar to those for shape-memory alloys, such as in opening blocked arteries, probing neurons in the brain, and improving the toughness of spines.

CASE STUDY 7.2 Use of Electrically Conducting Polymers in Rechargeable Batteries

One of the earliest applications of conducting polymers was in rechargeable batteries. Modern rechargeable batteries use lithium, or an oxide of lithium, as the cathode and lithium carbide (Li_yC_6) as the anode, separated by a conducting polymer layer. Lithium is the lightest of all metals and has a high electrochemical potential, so that its energy per volume is highest.

The polymer, usually polyethylene oxide (PEO), with a dissolved lithium salt, is placed between the cathode and anode. During discharge of the battery, Li_yC_6 is oxidized, emitting free electrons and lithium ions. The electrons are available to power devices, and the Li^+ ions are stored in the polymer. When the cathode is depleted, the battery must be recharged to restore the cathode. During charging, Li^+ is transferred through the polymer electrolytes to the cathode. Lithium-ion batteries have good capacity, can generate up to 4.2 V each, and can be placed in series to obtain higher voltages, such as 18 V for hand tools. Battery cells are now being developed in which both electrodes are made of conducting polymers; one has been constructed with a capacity of 3.5 V.

7.4 Thermosetting Plastics

When the long-chain molecules in a polymer are cross-linked in a three-dimensional arrangement, the structure in effect becomes one *giant molecule*, with strong covalent bonds. These polymers are called **thermosetting polymers** or **thermosets** because, during polymerization, the network is completed and the shape of the part is permanently set; this **curing** (**cross-linking**) reaction, unlike that of thermoplastics, is irreversible. The response of a thermosetting plastic to a sufficiently elevated temperature can be likened to what happens when baking a cake or boiling an egg: Once the cake is baked and cooled, or the egg boiled and cooled, reheating it will not change its shape.

Some thermosets (such as epoxy, polyester, and urethane) cure at room temperature, because the heat produced by the exothermic reaction is sufficient to cure the plastic. A typical thermoset is **phenolic**, which is a product of the reaction between phenol and formaldehyde. Common products made from this polymer are the handles and knobs on cooking pots and pans and components of light switches and outlets.

The polymerization process for thermosets generally takes place in two stages. The first occurs at the chemical plant, where the molecules are partially polymerized into linear chains. The second stage occurs during the final step of part production, where cross-linking is completed under *heat* and *pressure* during molding and shaping of the part (Chapter 19).

Thermosetting polymers do not have a sharply defined glass-transition temperature. Because of the nature of the bonds, the strength and hardness of a thermoset are not affected by temperature or by rate of deformation, unlike those for thermoplastics. If the temperature is increased sufficiently, a thermosetting polymer instead begins to burn, degrade, and char. Thermosets generally possess better mechanical, thermal, and chemical properties; electrical resistance; and dimensional stability than do thermoplastics.

7.5 Additives in Plastics

Polymers usually are compounded with *additives* which modify and improve certain characteristics, such as stiffness, strength, color, weatherability, flammability, arc resistance (for electrical applications), and ease of subsequent processing. Additives may consist of:

- **Plasticizers.** These are added to polymers to impart *flexibility* and *softness* by lowering their glass-transition temperature. *Plasticizers* are low-molecular-weight solvents with high boiling points (nonvolatility); they reduce the strength of the secondary bonds between the long-chain molecules, and thus make the polymer flexible and soft. The most common use of plasticizers is in PVC, which remains flexible during its numerous uses; other applications are in thin sheets, films, tubing, shower curtains, and clothing materials.
- **Colorants.** The wide variety of colors available in plastics is obtained by adding *colorants*, which are either *dyes* (organic) or *pigments* (inorganic).
- **Fillers.** Because of their low cost, *fillers* are important in reducing the overall cost of polymers. Depending on their type, fillers may also improve the strength, hardness, toughness, abrasion resistance, dimensional stability, or stiffness of plastics. These properties are greatest at specific percentages of different types of polymer-filler combinations. Fillers are generally wood flour (fine sawdust), silica flour (fine silica powder), clay, powdered mica, talc, calcium carbonate, and short fibers of cellulose, glass, or asbestos.
- **Flame Retardants.** If the temperature is sufficiently high, most polymers will ignite and burn. The **flammability** (ability to support combustion) of polymers varies considerably, depending on their composition (especially on their chlorine and fluorine content). The flammability of polymers can be reduced either by making them from less flammable raw materials or by adding flame retardants, such as compounds of chlorine, bromine, and phosphorus. Cross-linking also reduces polymer flammability.
- **Other Additives.** Most polymers are affected adversely by *ultraviolet radiation* (such as from sunlight) and by *oxygen*, which weaken and break the primary bonds and cause the scission (splitting) of the long-chain molecules. The polymer

then degrades and becomes stiff and brittle. A typical example of protection against ultraviolet radiation is the compounding of certain plastics and rubber with **carbon black** (soot). Protection against degradation caused by oxidation, particularly at elevated temperatures, is achieved by adding **antioxidants** to the polymer.

7.6 General Properties and Applications of Thermoplastics

The general characteristics and typical applications of major classes of thermoplastics, particularly as they relate to the manufacturing and service life of plastic products and components, are outlined in this section. General recommendations for various plastics applications are given in Table 7.3, and Table 7.4 lists some of the more common trade names for thermoplastics.

Acetals (from *acetic* and *alcohol*) have good strength and stiffness, and good resistance to creep, abrasion, moisture, heat, and chemicals. Typical applications include mechanical parts and components requiring high performance over a long period (e.g., bearings, cams, gears, bushings, and rolls), impellers, wear surfaces, pipes, valves, shower heads, and housings.

TABLE 7.3

General Recommendations for Plastic Products

Design requirement	Typical applications	Plastics
Mechanical strength	Gears, cams, rolls, valves, fan blades, impellers, pistons	Acetals, nylon, phenolics, polycarbonates, polyesters, polypropylenes, epoxies, polyimides
Wear resistance	Gears, wear strips and liners, bearings, bushings, roller blades	Acetals, nylon, phenolics, polyimides, polyurethane, ultrahigh-molecular-weight polyethylene
Frictional properties		
High	Tires, nonskid surfaces, footware, flooring	Elastomers, rubbers
Low	Sliding surfaces, artificial joints	Fluorocarbons, polyesters, polyimides
Electrical resistance	All types of electrical components and equipment, appliances, electrical fixtures	Polymethylmethacrylate, ABS, fluorocarbons, nylon, polycarbonate, polyester, polypropylenes, ureas, phenolics, silicones, rubbers
Chemical resistance	Containers for chemicals, laboratory equipment, components for chemical industry, food and beverage containers	Acetals, ABS, epoxies, polymethylmethacrylate, fluorocarbons, nylon, polycarbonate, polyester, polypropylene, ureas, silicones
Heat resistance	Appliances, cookware, electrical components	Fluorocarbons, polyimides, silicones, acetals, polysulfones, phenolics, epoxies
Functional and decorative	Handles, knobs, camera and battery cases, trim moldings, pipe fittings	ABS, acrylics, cellulosics, phenolics, polyethylenes, polypropylenes, polystyrenes, polyvinyl chloride
Functional and transparent	Lenses, goggles, safety glazing, signs, food-processing equipment, laboratory hardware	Acrylics, polycarbonates, polystyrenes, polysulfones
Housings and hollow shapes	Power tools, housings, sport helmets, telephone cases	ABS, cellulosics, phenolics, polycarbonates, polyethylenes, polypropylene, polystyrenes

TABLE 7.4

Trade Names for Thermoplastic Polymers

Acetal: Delrin, Duracon, Lupital, Ultraform
Acrylic: Lucite, Acrylite, Acrysteel, Cyrolite, Diakon, Implex, Kamax, Korad, Plexiglass, XT, Zylar
Acrylic-polyvinyl chloride: Kydex
Acrylonitrile-butadiene-styrene: Cycolac, Delta, Denka, Magnum, Novodur, Royalite, Terluran
Aramid: Kevlar
Fluorocarbon: Teflon (polytetrafluoroethylene)
Polyamide: Capron, Celanese, Durethan, Grilamid, Maranyl, Nylon, Rilsan, Ultramid, Vespel, Vydyne, Zytel
Polycarbonate: APEC, Calibre, Hyzod, Lexan, Makrolon, Merlon
Polyester: Dacron, Eastpac, Ektar, Kodel, Mylar, Rynite
Polyetherimide: Ultem
Polyethylene: Alathon, Dowlex, Forar, Fortiflex, Hostalen, Marlex, Petrothene
Polyimide: Aurum, Avimid, Estamid, Envex, Kapton, Lenzing, VTEC
Polyphenylene: Forton, Fortron, Noryl
Polypropylene: Fortilene, Oleplate, Olevac, Pro-Fax
Polystyrene: Dylene, Fosta Tuf-Flex, Fostalite, Fostarene, Lustrex, Polystrol, Styron, Syrofoam
Polysulfone: Mindel, Udel
Polyurethane: Estane, Isoplast, Pellethane
Polyvinyl chloride: Fiberloc, Geon, Saran, Sintra, Tygon
Polyvinylidene fluoride: Foraflon, Kynar
Styrene-methylmethacrylate: Zerlon

Acrylics (such as PMMA) possess moderate strength, good optical properties, and weather resistance. They are transparent (but can be made opaque), are generally resistant to chemicals, and have good electrical resistance. Typical applications include optical lenses, lighted signs, displays, window glazing, skylights, automotive headlight lenses, windshields, lighting fixtures, and furniture.

Acrylonitrile-butadiene-styrene is rigid and dimensionally stable. It has good impact, abrasion, and chemical resistance; good strength and toughness; good low-temperature properties; and high electrical resistance. Typical applications include pipes, fittings, chrome-plated plumbing supplies, helmets, tool handles, automotive components, boat hulls, telephones, luggage, housing, appliances, refrigerator liners, and decorative panels.

Cellulosics have a wide range of mechanical properties, depending on their composition. They can be made rigid, strong, and tough; however, they weather poorly and are affected by heat and chemicals. Typical applications include tool handles, pens, knobs, frames for eyeglasses, safety goggles, machine guards, helmets, tubing and pipes, lighting fixtures, rigid containers, steering wheels, packaging film, signs, billiard balls, toys, and decorative parts.

Fluorocarbons possess good resistance to high temperature (e.g., a melting point of 327°C for *Teflon*), chemicals, weather, and electricity. They also have unique nonadhesive properties and low friction. Typical applications include linings for chemical-processing equipment, nonstick coatings for cookware, electrical insulation for high-temperature wire and cable, gaskets, low-friction surfaces, bearings, and seals.

Polyamides (from the words *poly*, *amine*, and *carboxyl acid*) are available in two main types: *nylons* and *aramids*:

- **Nylons** have good mechanical properties and abrasion resistance; they also are self-lubricating and resistant to most chemicals. All nylons are *hygroscopic* (absorb water); the moisture absorption reduces desirable mechanical properties and increases part dimensions. Typical applications include gears, bearings, bushings, rolls, fasteners, zippers, electrical parts, combs, tubing, wear-resistant surfaces, guides, and surgical equipment.
- **Aramids** (aromatic polyamides) have very high tensile strength and stiffness. Typical applications include fibers for reinforced plastics, bulletproof vests, cables, and radial tires.

Polycarbonates are versatile; they have good mechanical and electrical properties, high impact resistance, and they can be made resistant to chemicals. Typical applications include safety helmets, optical lenses, bullet-resistant window glazing, signs, bottles, food-processing equipment, windshields, load-bearing electrical components, electrical insulators, medical apparatus, business machine components, guards for machinery, and parts requiring dimensional stability.

Polyesters (thermoplastic polyesters; see also Section 7.7) have good mechanical, electrical, and chemical properties; good abrasion resistance; and low friction. Typical applications include gears, cams, rolls, load-bearing members, pumps, and electromechanical components.

Polyethylenes possess good electrical and chemical properties; their mechanical properties depend on composition and structure. Three major polyethylene classes are: (1) *low density* (LDPE), (2) *high density* (HDPE), and (3) *ultrahigh molecular weight* (UHMWPE). Typical applications for LDPE and HDPE are housewares, bottles, garbage cans, ducts, bumpers, luggage, toys, tubing, bottles, and packaging materials. UHMWPE is used in parts requiring high-impact toughness and resistance to abrasive wear; examples include artificial knee and hip joints.

Polyimides have the structure of a thermoplastic, but the nonmelting characteristic of a thermoset. (See also Section 7.7.)

Polypropylenes have good mechanical, electrical, and chemical properties and good resistance to tearing. Typical applications include automotive trim and components, medical devices, appliance parts, wire insulation, TV cabinets, pipes, fittings, drinking cups, dairy-product and juice containers, luggage, ropes, and weather stripping.

Polystyrenes generally have average properties and are somewhat brittle, but inexpensive. Typical applications include disposable containers; packaging; trays for meats, cookies, and candy; foam insulation; appliances; automotive and radio/TV components; housewares; and toys and furniture parts (as a substitute for wood).

Polysulfones have excellent resistance to heat, water, and steam; they have dielectric properties that remain virtually unaffected by humidity, are highly resistant to some chemicals, but are attacked by organic solvents. Typical applications include steam irons, coffeemakers, hot-water containers, medical equipment that requires sterilization, power-tool and appliance housings, aircraft cabin interiors, and electrical insulators.

Polyvinyl chloride has a wide range of properties, is inexpensive and water resistant, and can be made rigid or flexible; it is not suitable for applications requiring strength and heat resistance. *Rigid* PVC is tough and hard; it is used for signs and in the construction industry (e.g., in pipes and conduits). *Flexible* PVC is used in wire and cable coatings, in low-pressure flexible tubing and hoses, and in footwear, imitation leather, upholstery, records, gaskets, seals, trim, film, sheet, and coatings.

7.7 General Properties and Applications of Thermosetting Plastics

This section outlines the general characteristics and typical applications of the major thermosetting plastics.

Alkyds (from *alkyl*, meaning alcohol, and *acid*) possess good electrical insulating properties, impact resistance, dimensional stability, and low water absorption. Typical applications are in electrical and electronic components.

Aminos have properties that depend on composition; generally, they are hard, rigid, and resistant to abrasion, creep, and electrical arcing. Typical applications include small-appliance housings, countertops, toilet seats, handles, and distributor caps. **Urea** typically is used for electrical and electronic components; and **melamine** for dinnerware.

Epoxies have excellent mechanical and electrical properties, good dimensional stability, strong adhesive properties, and good resistance to heat and chemicals. Typical applications include electrical components requiring mechanical strength and high insulation, tools and dies, and adhesives. **Fiber-reinforced epoxies** have excellent mechanical properties and are used in pressure vessels, rocket-motor casings, tanks, and similar structural components.

Phenolics are rigid (though brittle) and dimensionally stable; they have high resistance to heat, water, electricity, and chemicals. Typical applications include knobs, handles, laminated panels, and telephones; bonding material to hold abrasive grains together in grinding wheels; and electrical components (such as wiring devices, connectors, and insulators).

Polyesters (thermosetting polyesters; see also Section 7.6) have good mechanical, chemical, and electrical properties; they generally are reinforced with glass (or other) fibers and also are available as casting resins. Typical applications include boats, luggage, chairs, automotive bodies, swimming pools, and materials for impregnating cloth and paper.

Polyimides possess good mechanical, physical, and electrical properties at elevated temperatures; they also have good creep resistance, low friction, and low wear characteristics. Polyimides have the non-melting characteristic of a thermoset, but the structure of a thermoplastic. Typical applications include pump components (bearings, seals, valve seats, retainer rings, and piston rings), electrical connectors for high-temperature use, aerospace parts, high-strength impact-resistant structures, sports equipment, and safety vests.

Silicones have properties that depend on their composition; generally, they weather well, possess excellent electrical properties over a wide range of humidity and temperature, and resist chemicals and heat (Section 7.9). Typical applications include electrical components requiring strength at elevated temperatures, oven gaskets, heat seals, and waterproof materials.

Health Hazards. There is increasing concern that some of the chemicals used in polymers may present health hazards, especially in such products as polycarbonate water containers and baby bottles, and also medical devices, sports safety equipment, and eating utensils. The chemical that is of particular concern is bisphenol A (BPA), a widely used chemical; several worldwide investigations are being conducted to determine whether there is any link to human diseases, specifically heart disease and diabetes.

CASE STUDY 7.3 Materials for a Refrigerator Door Liner

In the selection of candidate materials for a refrigerator door liner (where eggs, butter, salad dressings, and small bottles are typically stored) the following factors should be considered:

1. *Mechanical requirements*: strength, toughness (to withstand impacts, door slamming, and racking), stiffness, resilience, and resistance to scratching and wear at operating temperatures.
2. *Physical requirements*: dimensional stability and electrical insulation.
3. *Chemical requirements*: resistance to staining, odor, chemical reactions with food and beverages, and cleaning fluids.
4. *Appearance*: color, stability of color over time, surface finish, texture, and feel.
5. *Manufacturing properties*: methods of manufacturing and assembly, effects of processing on material properties and behavior over a period of time, compatibility with other components in the door, and cost of materials and manufacturing.

An extensive study, considering all of the factors involved, identified two candidate materials for door liners: ABS and HIPS (high-impact polystyrene). One aspect of the study involved the effect of vegetable oils, such as from salad dressing stored in the door shelf, on the strength of those plastics. Experiments showed that the presence of vegetable oils significantly reduced the load-bearing capacity of HIPS. It was found that HIPS becomes brittle in the presence of oils (solvent stress cracking), whereas ABS is not affected to any significant extent.

7.8 Biodegradable Plastics

Plastic wastes contribute about 16% of municipal solid waste by weight, and make up 50–80% of waste littering beaches, oceans, and sea beds; on a volume basis, they contribute between two and three times their weight. Only about one-third of plastic production goes into disposable products, such as bottles, packaging, and garbage bags. With the growing use of plastics and great concern over environmental issues regarding the disposal of plastic products and the shortage of landfills, major efforts continue to develop completely biodegradable plastics.

Traditionally, most plastic products have been made from synthetic polymers that are derived from nonrenewable natural resources, are not biodegradable, and are difficult to recycle. **Biodegradability** means that microbial species in the environment (e.g., microorganisms in soil and water) will degrade all or part of the polymeric material under the proper environmental conditions, without producing toxic by-products. The end products of the degradation of the biodegradable portion of the material are carbon dioxide and water. Because of the variety of constituents in biodegradable plastics, these plastics can be regarded as composite materials; consequently, only a portion of them may be truly biodegradable.

Three different *biodegradable plastics* have thus far been developed. They have different degradability characteristics, and they degrade over different periods of time (anywhere from a few months to a few years).

1. The **starch-based system** is the farthest along in terms of production capacity. Starch may be extracted from potatoes, wheat, rice, or corn. The starch granules are processed into a powder, which is heated and becomes a sticky liquid; the liquid is then cooled, shaped into pellets, and processed in conventional plastic-processing equipment. Various additives and binders are blended with the starch to impart specific characteristics to the bioplastic materials; for example, a

composite of polyethylene and starch is produced commercially as degradable garbage bags.

2. In the **lactic-based system,** fermenting feedstocks produce lactic acid, which is then polymerized to form a polyester resin. Typical uses include medical and pharmaceutical applications.
3. In the **fermentation of sugar**, organic acids are added to a sugar feedstock. The resulting reaction produces a highly crystalline and very stiff polymer, which, after further processing, behaves in a manner similar to polymers developed from petroleum.

Studies continue to be conducted on producing fully biodegradable plastics, by using various agricultural waste (*agrowastes*), plant carbohydrates, plant proteins, and vegetable oils. Typical applications of this approach include

- Disposable tableware made from a cereal substitute, such as rice grains or wheat flour
- Plastics made almost entirely from starch extracted from potatoes, wheat, rice, or corn
- Plastic articles made from coffee beans and rice hulls, dehydrated and molded under high pressure and temperature
- Water-soluble and compostable polymers for medical and surgical use
- Food and beverage containers made from potato starch, limestone, cellulose, and water, that can dissolve in storm sewers and oceans without affecting wildlife or marine life

Recycling of Plastics. Much effort continues to be expended globally on the collecting and recycling of used plastic products. Thermoplastics are recycled by melting, blending, and reforming them into other products. The products carry *recycling symbols* (for efficient separation of different types), in the shape of a triangle outlined by three clockwise arrows and with a number in the middle. These numbers developed in 1988 and used internationally, correspond to the following plastics:

1. PETE (polyethylene terephthalate)
2. HDPE (high-density polyethylene)
3. V (vinyl) or PVC (polyvinyl chloride)
4. LDPE (low-density polyethylene)
5. PP (polypropylene)
6. PS (polystyrene)
7. Other, or O (acrylic, nylon, polycarbonate, etc.)

Recycled plastics are increasingly being used for a variety of products. For example, a recycled polyester (filled with glass fibers and minerals) is used for the engine cover for an F-series Ford pickup truck; it has the appropriate stiffness, chemical resistance, and shape retention up to 180°C.

7.9 Elastomers (Rubbers)

Elastomers (derived from the words *elastic* and *mer*) consist of a large family of amorphous polymers (Section 7.2.1) with a low glass-transition temperature. They have the characteristic ability of undergoing large elastic deformations without rupture; also, they are soft and have a low elastic modulus.

The structure of elastomer molecules is highly kinked (tightly twisted or curled) when stretched, but then return to their original shape after the load is removed

(Fig. 7.14). They can also be cross-linked, the best example of which is the elevated-temperature **vulcanization** of rubber with sulfur, discovered by the American inventor C. Goodyear in 1839 and named for Vulcan, the Roman god of fire. Once the elastomer is cross-linked, it cannot be reshaped; for example, an automobile tire, which is one giant molecule, cannot be softened and reshaped.

The terms *elastomer* and *rubber* often are used interchangeably. Generally, however, an **elastomer** is defined as being capable of recovering substantially in shape and size after the load has been removed; a **rubber** is defined as being capable of recovering from large deformations quickly.

The hardness of elastomers, which is measured with a durometer (Section 2.6.1), increases with the cross-linking of the molecular chains. As with plastics, a variety of additives can be blended into elastomers to impart specific properties. Elastomers have a wide range of applications, such as high-friction and nonskid surfaces, protection against corrosion and abrasion, electrical insulation, and shock and vibration insulation. Examples include tires, hoses, weather stripping, footwear, linings, gaskets, seals, printing rolls, and flooring.

One unique property of elastomers is their *hysteresis loss* in stretching or compression (Fig. 7.14). The clockwise loop indicates energy loss, whereby mechanical energy is converted into heat; this property is important for absorbing vibrational energy (damping) and sound insulation.

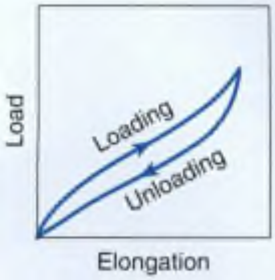


FIGURE 7.14 Typical load-elongation curve for rubbers; the clockwise loop, indicating the loading and the unloading paths, displays the hysteresis loss. Hysteresis gives rubbers the capacity to dissipate energy, damp vibration, and absorb shock loading, as is necessary in automobile tires and in vibration dampers placed under machinery.

Natural Rubber. The base for *natural rubber* is **latex**, a milk-like sap obtained from the inner bark of a tropical tree. Natural rubber has good resistance to abrasion and fatigue, and high friction, but low resistance to oil, heat, ozone, and sunlight. Typical applications are tires, seals, couplings, and engine mounts.

Synthetic Rubbers. Examples of *synthetic rubbers* are butyl, styrene butadiene, polybutadiene, and ethylene propylene. Compared to natural rubber, they have better resistance to heat, gasoline, and chemicals, and have a higher range of useful temperatures. Synthetic rubbers that are resistant to oil are neoprene, nitrile, urethane, and silicone. Typical applications of synthetic rubbers are tires, shock absorbers, seals, and belts.

Silicones. *Silicones* (Section 7.7) have the highest useful temperature range of elastomers (up to 315°C), but other properties, such as strength and resistance to wear and oils, generally are inferior to those of other elastomers. Typical applications of silicones are seals, gaskets, thermal insulation, high-temperature electrical switches, and electronic apparatus.

Polyurethane. This elastomer has very good overall properties of high strength, stiffness, and hardness, and it has exceptional resistance to abrasion, cutting, and tearing. Typical applications of *polyurethane* are seals, gaskets, cushioning, diaphragms for the rubber forming of sheet metals (Section 16.8), and auto body parts.

SUMMARY

- Polymers are a major class of materials, and possess a very wide range of mechanical, physical, chemical, and optical properties. Compared to metals, polymers are generally characterized by (a) lower density, strength, elastic modulus, thermal and electrical conductivity, cost; (b) higher strength-to-weight ratio, higher resistance to corrosion, higher thermal expansion, (c) wide choice of colors and transparencies; and (d) greater ease of manufacture into complex shapes.

- Plastics are composed of polymer molecules and various additives. The smallest repetitive unit in a polymer chain is called a mer. Monomers are linked by polymerization processes (condensation or addition) to form larger molecules. The glass-transition temperature separates the region of brittle behavior in polymers from that of ductile behavior.
- The properties of polymers depend on their molecular weight, structure (linear, branched, cross-linked, or network), degrees of polymerization and crystallinity, and on the additives present in their formulation. Additives have such functions as improving strength, flame retardation, lubrication, imparting flexibility and color, and providing stability against ultraviolet radiation and oxygen. Polymer structures can be modified by various means to impart a wide range of desirable properties.
- Two major classes of polymers are thermoplastics and thermosets. Thermoplastics become soft and easy to form at elevated temperatures; their behavior includes such phenomena as creep and stress relaxation, crazing, and water absorption. Thermosets, which are obtained by cross-linking polymer chains, do not become soft to any significant extent with increasing temperature; they are much more rigid and harder than thermoplastics.
- Elastomers have a characteristic ability to undergo large elastic deformations and then return to their original shapes when unloaded. Consequently, they have important applications in tires, seals, footwear, hoses, belts, and shock absorbers.
- Among important considerations in polymers are their recyclability and biodegradability. Several formulations of biodegradable plastics are available, and others are under continued development.

KEY TERMS

Additives
Biodegradable
Blends
Bonding
Branched polymers
Colorants
Crazing
Cross-linked polymers
Crystallinity
Curing
Degradation
Degree of crystallinity
Degree of polymerization
Doping
Elastomer
Fillers
Flame retardants
Glass-transition temperature
Latex
Linear polymers
Lubricants
Mer
Molecular weight
Monomer
Network polymers
Orientation
Plasticizers
Plastics
Polyblends
Polymer
Polymerization
Primary bonds
Recycling
Rubber
Secondary bonds
Shape-memory polymers
Silicones
Stress whitening
Thermal aging
Thermoplastics
Thermosets
Vulcanization

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REVIEW QUESTIONS

7.1 Summarize the important mechanical and physical properties of plastics.

7.2 What are the major differences between the (a) mechanical and (b) physical properties of plastics and metals?

7.3 List properties that are influenced by the degree of polymerization.

7.4 What is the difference between condensation polymerization and addition polymerization?

7.5 Explain the differences between linear, branched, and cross-linked polymers.

7.6 What is the glass-transition temperature?

7.7 List and explain the additives commonly used in plastics.

7.8 What is crazing?

7.9 What are polyblends?

7.10 List the major differences between thermoplastics and thermosets.

7.11 What is an elastomer?

7.12 What effects does a plasticizing agent have on a polymer?

7.13 Define the following abbreviations: PMMA, PVC, ABS, HDPE, UHDPE, and LDPE.

7.14 Explain why it would be advantageous to produce a polymer with a high degree of crystallinity.

7.15 What are the differences and similarities of addition and condensation polymerization?

7.16 Are molecular weight and degree of polymerization related? Explain.

7.17 Why do polymers need to be dried before processing?

QUALITATIVE PROBLEMS

7.18 What characteristics of polymers make them attractive for clothing?

7.19 Do polymers strain harden more than metals or vice versa? Explain.

7.20 Inspect various plastic components in an automobile, and state whether they are made of thermoplastic materials or of thermosetting plastics.

7.21 Give applications for which flammability of plastics would be of major importance.

7.22 What characteristics make polymers advantageous for applications such as gears? What characteristics are drawbacks in such applications?

7.23 What properties do elastomers have that thermoplastics in general do not have?

7.24 Do you think that the substitution of plastics for metals in products traditionally made of metal may be viewed negatively by the public at large? If so, why?

7.25 Is it possible for a material to have a hysteresis behavior that is the opposite of that shown in Fig. 7.14, so that the two arrows run counterclockwise? Explain.

7.26 Observe the behavior of the specimen shown in Fig. 7.13, and state whether the material has a high or a low strain-rate sensitivity exponent, m (see Section 2.2.7).

7.27 Add more to the applications column in Table 7.3.

7.28 Discuss the significance of the glass-transition temperature, T_g, in engineering applications.

7.29 Describe how a rechargeable lithium battery works.

7.30 Explain how cross-linking improves the strength of polymers.

7.31 Describe the methods by which the optical properties of polymers can be altered.

7.32 How can polymers be made to conduct electricity? Explain.

7.33 Explain the reasons for which elastomers were developed.

7.34 Give several examples of plastic products or components in which creep and stress relaxation would be important considerations.

7.35 Describe your opinions regarding the recycling of plastics versus the development of plastics that are biodegradable.

7.36 Explain how you would go about determining the hardness of plastics.

7.37 Compare the values of the elastic modulus, given in Table 7.1, to the values for metals given in Chapters 2, 5, and 6. Comment on your observations.

7.38 Why is there so much variation in the stiffness of products made of polymers? Explain.

7.39 Explain why thermoplastics are easier to recycle than thermosets.

7.40 Give an example where crazing is desirable.

7.41 Describe the principle behind shrink wrapping.

7.42 List and explain some environmental pros and cons of using plastic shopping bags versus paper bags.

7.43 List the characteristics required of a polymer for (a) a bucket, (b) a golf ball, (c) an automobile dashboard, (d) clothing, (e) flooring, and (f) fishing nets.

7.44 How can you tell whether a part is made of a thermoplastic or a thermoset?

7.45 As you know, there are plastic paper clips available in various colors. Why are there no plastic staples?

7.46 By incorporating small amounts of a blowing agent, it is possible to manufacture hollow polymer fibers with gas cores. List possible applications for such fibers.

7.47 In injection-molding operations (Section 19.3), it is common practice to remove the part from its runner, to place the runner into a shredder, and to recycle the resultant pellets. List the concerns you would have in using such recycled pellets as opposed to so-called virgin pellets.

7.48 From an environmental standpoint, do you feel it is best to incorporate polymers or metals into designs? Explain.

QUANTITATIVE PROBLEMS

7.49 Calculate the areas under the stress–strain curve (toughness) for the materials shown in Fig. 7.11, plot them as a function of temperature, and describe your observations.

7.50 Note in Fig. 7.11 that, as expected, the elastic modulus of the polymer decreases as temperature increases. Using the stress–strain curves in the figure, make a plot of the modulus of elasticity versus the temperature. Comment on the shape of the curve.

7.51 A rectangular cantilever beam 75 mm high, 20 mm wide, and 1 m long is subjected to a concentrated load of 50 kg at its end. From Table 7.1, select three unreinforced and three reinforced materials and calculate the maximum deflection of the beam in each case. Then select aluminum and steel for the same beam dimensions, calculate the maximum deflection, and compare the results.

7.52 Estimate the number of molecules in a typical automobile tire, then estimate the number of atoms in the tire.

7.53 Using strength and density data, determine the minimum weight of a 1-m-long tension member that must support a load of 5000 N, if it is manufactured from (a) high-molecular-weight polyethylene, (b) polyester, (c) rigid PVC, (d) ABS, (e) polystyrene, and (e) reinforced nylon.

7.54 Plot the following for any five polymers described in this chapter: (a) UTS versus density and (b) elastic modulus versus UTS. Where appropriate, plot a range of values.

SYNTHESIS, DESIGN, AND PROJECTS

7.55 Conduct an Internet search, and describe differential scanning calorimetry. What does this technique measure?

7.56 Describe the design considerations involved in replacing a metal beverage container with one made of plastic.

7.57 Assume that you are manufacturing a product in which all of the gears are made of metal. A salesperson visits you and asks you to consider replacing some of these metal gears with plastic ones. Make a list of the questions that you would raise before making a decision.

7.58 Assume you work for a company that produces polymer gears. You have arranged to meet with a potential new customer, who currently uses gears made of metal. Make a list of the benefits that plastic gears present, and prepare a presentation for the meeting.

7.59 Sections 7.6 and 7.7 list several plastics and their applications. Rearrange this information, making a table of products (gears, helmets, luggage, electrical parts, etc.) that shows the types of plastic that can be used to make these products.

7.60 Make a list of products or parts that currently are not made of plastics, and offer possible reasons why they are not.

7.61 Review the three curves shown in Fig. 7.10, and give some applications for each type of behavior. Explain your choices.

7.62 Repeat Problem 7.61 for the curves shown in Fig. 7.12.

7.63 In order to use a steel or aluminum container for an acidic liquid, such as tomato sauce, a polymeric barrier is usually placed between the container and its contents. Describe possible methods of producing such a barrier.

7.64 Conduct a study of plastics used for some products. Measure the hardness and stiffness of these plastics. (For example, dog chew toys use plastics with a range of properties.) Describe your observations.

7.65 Add a column to Table 7.1 that describes the appearance of these plastics, including available colors and opaqueness.

7.66 With Table 7.3 as a guide, inspect various products, both in a typical kitchen and in an automobile, and describe the types of plastics that were used or could be used in making their individual components.

CHAPTER

8

Ceramics, Glass, Graphite, Diamond, and Nanomaterials: Structure, General Properties, and Applications

CASE STUDIES:

- Ceramics, glass, and various forms of carbon possess unique combinations of mechanical and physical properties that cannot be obtained with other metallic or nonmetallic materials.
- Ceramic materials are first described, in terms of their chemistry, microstructure, mechanical and physical properties, and applications.
- The basic types of ceramics include oxide ceramics, such as aluminum or zirconium oxide, and carbides and nitrides.
- Glasses have numerous formulations, all containing at least 50% silica. Their general properties and typical uses are described.
- Various forms of carbon are commercially important; graphite is the most common, with numerous uses, including as reinforcement in composite materials, electrodes for electrical discharge machining, and solid lubricant.
- Diamond is the hardest material known and, as such, is used for precision and abrasive machining and for polishing operations.
- Nanomaterials, such as carbon nanotubes, are becoming increasingly important, with numerous applications for nanoscale electrical and microelectronic devices.

8.1 Introduction

The various types of materials described in the preceding chapters are not all suitable for certain applications, including

1. An electrical insulator for use at high temperatures
2. Floor tiles to resist scuffing and abrasion
3. A transparent baking dish
4. Small ball bearings that are light, rigid, hard, and resist high temperatures
5. Automobile windshields that are hard, abrasion resistant, and transparent

It is apparent from these examples that the properties required include high-temperature strength; hardness; inertness to chemicals, foods, and the environment; resistance to wear and corrosion; and low electrical and thermal conductivity.

The general characteristics and applications of those ceramics, glasses, and glass ceramics that are of importance in engineering applications and in manufacturing are first described. Because of their unique properties and uses, the various forms of carbon (graphite, diamond, and carbon nanotubes) are described next. The manufacturing of ceramic and of glass components and various shaping and finishing operations are detailed in Chapter 18; composites, which contain the materials described, are described in Chapter 9.

8.2 The Structure of Ceramics

Ceramics are compounds of metallic and nonmetallic elements. The term *ceramics* (from the Greek *keramos*, meaning "potter's clay," and *keramikos*, meaning "clay products") refers both to the material and to the ceramic product itself. Because of the large number of possible combinations of elements, a wide variety of ceramics is now available for a broad range of consumer and industrial applications. The earliest use of ceramics was in pottery and bricks, dating back to before 4000 B.C. They have become increasingly important in tool and die materials, heat engines, and automotive components, such as exhaust-port liners, automotive spark plugs, coated pistons, and cylinder liners.

Ceramics can be divided into two general categories:

1. **Traditional ceramics**, such as whiteware, tiles, brick, sewer pipe, pottery, and abrasive wheels
2. **Industrial ceramics**, also called **engineering**, **high-tech**, or **fine ceramics**, such as automotive, turbine, structural, and aerospace components (Fig. 8.1), heat exchangers, semiconductors, seals, prosthetics, and cutting tools

The structure of ceramic crystals, containing various atoms of different sizes, is among the most complex of all material structures. The bonding between these atoms

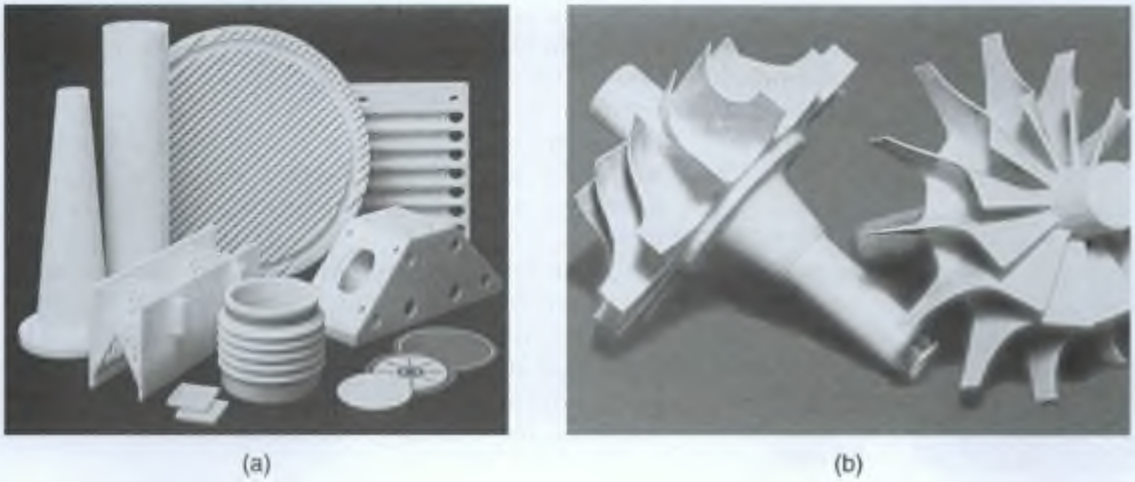

(a) (b)

FIGURE 8.1 A variety of ceramic components. (a) High-strength alumina for high-temperature applications. (b) Gas-turbine rotors made of silicon nitride. *Source:* Courtesy of Wesgo Div., GTE.

is generally **covalent** or **ionic** (see Section 1.2), and as such are much stronger than metallic bonds. Consequently, properties such as hardness and thermal and electrical resistance are significantly higher in ceramics than in metals (Tables 3.1 and 3.2). Ceramics are available in *single-crystal* or in *polycrystalline* form. Grain size has a major influence on the strength and properties of ceramics; the finer the grain size (hence the term **fine ceramics**), the higher the strength and toughness.

8.2.1 Raw Materials

Among the oldest of the raw materials used for making ceramics is **clay**, which has a fine-grained sheetlike structure. The most common example is *kaolinite* (from Kaoling, a hill in China); it is a white clay consisting of silicate of aluminum, with alternating weakly bonded layers of silicon and aluminum ions (Fig. 8.2). When added to kaolinite, water attaches itself to these layers (*adsorption*); this makes the layers slippery and gives wet clay both its well-known softness and the plastic properties (*hydroplasticity*) that make it easily formable.

Other major raw materials for ceramics that are found in nature are **flint** (a rock composed of very fine-grained silica, SiO_2) and **feldspar** (a group of crystalline minerals consisting of aluminum silicates and potassium, calcium, or sodium). **Porcelain** is a **white ceramic**, composed of kaolin, quartz, and feldspar; its largest use is in appliances and kitchen and bath ware. In their natural state, these raw materials generally contain impurities of various kinds, which have to be removed prior to their further processing into useful products.

8.2.2 Oxide Ceramics

There are two major types of oxide ceramics: alumina and zirconia (Table 8.1).

Alumina. Also called **corundum** or **emery**, *alumina* (aluminum oxide, Al_2O_3) is the most widely used *oxide ceramic*, either in pure form or as a raw material to be blended with other oxides. It has high hardness and moderate strength. Although alumina exists in nature, it contains varying levels of impurities and possesses nonuniform properties; as a result, its performance also varies. Aluminum oxide, silicon carbide, and most other ceramics are now manufactured almost totally synthetically, so that their quality can be controlled at a consistently high level. First made in 1893, synthetic aluminum oxide is obtained from the fusion of molten bauxite (an aluminum-oxide ore, which is the principal source of aluminum), iron filings, and coke, in electric furnaces. The cooled product is then crushed and graded by size, by passing it through standard screens. Aluminum oxide can be blended with small amounts of other ceramics, such as titanium oxide and titanium carbide.

Structures containing alumina and various other oxides are known as **mullite** and **spinel**, used as refractory materials for high-temperature applications. The mechanical and physical properties of alumina are suitable particularly in such applications as electrical and thermal insulation and in cutting tools and abrasives.

Zirconia. Zirconia (zirconium oxide, ZrO_2, white in color) has good toughness, good resistance to thermal shock, wear, and corrosion, low thermal conductivity, and a low friction coefficient. **Partially stabilized zirconia**

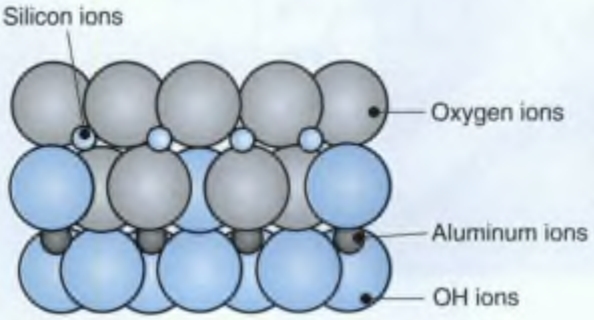


FIGURE 8.2 The crystal structure of kaolinite, commonly known as clay; compare with Figs. 1.3–1.5 for metals.

TABLE 8.1

Types, General Characteristics, and Principal Uses of Ceramics

Type	General characteristics and uses
Oxide ceramics	
Alumina	High hardness and moderate strength; most widely used ceramic; cutting tools; abrasives; electrical and thermal insulation
Zirconia	High strength and toughness; thermal expansion close to cast iron; suitable for high-temperature applications such as metallurgical furnace linings, jet-engine components, and nuclear fuel cladding
Carbides	
Tungsten carbide	Hardness, strength, and wear resistance depend on cobalt binder content; commonly used for dies and cutting tools
Titanium carbide	Not as tough as tungsten carbide; has nickel and molybdenum as the binder; used as cutting tools
Silicon carbide	High-temperature strength and wear resistance; used for heat engines and as abrasives in grinding wheels
Nitrides	
Cubic boron nitride	Second-hardest substance known, after diamond; used as abrasives and cutting tools
Titanium nitride	Gold in color; used as coatings because of low frictional characteristics
Silicon nitride	High resistance to creep and thermal shock; used in high-temperature applications such as turbocharger components, rolling element bearings and cutting tools
Sialon	Consists of silicon nitrides and other oxides and carbides; used as cutting tools and feed tubes and linings for non-ferrous metal casting
Cermets	Consist of oxides, carbides, and nitrides; used in high-temperature applications such as cutting tools and composite armor for military applications
Silica	High-temperature resistance; quartz exhibits piezoelectric effect; silicates containing various oxides are used in nonstructural applications such as fiber glass, plate glass, and optical glass
Glasses	Contain at least 50% silica; amorphous structures; several types available with a wide range of mechanical and physical properties
Glass ceramics	Have a high crystalline component to their structure; good thermal-shock resistance and strong. Typical applications include glass-ceramic cooking tops for stoves and cookware
Graphite	Crystalline form of carbon; high electrical and thermal conductivity; good thermal-shock resistance; used for structural reinforcement in composite materials, electrical discharge machining electrodes, piston rings
Diamond	Hardest substance known; available as single crystal or in polycrystalline form; used as cutting tools and abrasives and as dies for drawing fine wire
Carbon nanotubes	Unique crystalline form of graphite, with high electrical and thermal conductivity; under investigation for MEMS and microelectronics applications and in composite materials
Nanophase ceramics	Stronger and easier to fabricate and machine than conventional ceramics; used in automotive and jet-engine applications

(PSZ) has higher strength and toughness and better reliability in performance than does zirconia. It is obtained by doping zirconia with oxides of calcium, yttrium, or magnesium; this process forms a material with fine particles of tetragonal zirconia in a cubic lattice. Typical applications include dies for the hot extrusion of metals, and zirconia beads used as grinding and polishing media for aerospace coatings, for automotive primers, paint, and fine glossy print on flexible food packaging.

Two important characteristics of PSZ are its high coefficient of thermal expansion (which is only about 20% lower than that of cast iron), and its low thermal conductivity (which is about one-third that of other ceramics). Consequently, PSZ is very suitable for heat-engine components, such as cylinder liners and valve bushings, to help keep the cast-iron engine assembly intact. **Transformation-toughened zirconia** (TTZ) has higher toughness, because of dispersed tough phases in the ceramic matrix.

CASE STUDY 8.1 Ceramic Knives

Generally made of zirconium oxide, ceramic knives are produced by a process described in Section 18.2. It starts with a ceramic powder mixed with various binders, and compacted (molded) into blanks under high pressure. The blanks are then fired (sintered) at temperatures above 1000°C for several days. An optional hot isostatic pressing operation (Section 17.3.2) can be used to densify and toughen the ceramic. Next, the blanks are ground and polished on a diamond wheel to form a sharp edge, and the handle is attached. The Mohs hardness (Section 2.6) of the zirconium oxide ceramic is 8.2, as compared to 6 for hardened steel and a maximum of 10 for diamond.

Among the advantages of ceramic knives over steel knives are: (a) Because of their very high hardness and wear resistance, ceramic knives can last months and even years before resharpening. (b) They are chemically inert; consequently, they do not stain and food does not stick to them, hence they are easy to clean, and leave no metallic taste or smell. (c) Because they are lightweight, they are easier to use.

The knives should, however, be stored in wooden knife blocks and handled carefully. Sharp impact against other objects (such as dishes or dropping it on its edge on a hard surface) should be avoided, as the sharp edges of the knife can chip. Also, they should be used only for cutting (not for prying); in cutting meat, contact with bones is not advisable. Furthermore, the knives have to be sharpened at the factory to a precise edge, using diamond grinding wheels. Ceramic knives are comparable in cost to high-quality steel knives, typically ranging from $20–80 for a 75 mm paring knife to $50–200 for a 150 mm serrated knife.

Source: Courtesy of Kyocera Corporation.

8.2.3 Other Ceramics

Carbides. *Carbides* are typically used as cutting tools and die materials, and as an abrasive, especially in grinding wheels. Common examples of carbides are:

- **Tungsten carbide** (WC) consists of tungsten-carbide particles with cobalt as a binder. The amount of binder has a major influence on the material's properties; toughness increases with cobalt content, whereas hardness, strength, and wear resistance decrease.
- **Titanium carbide** (TiC) has nickel and molybdenum as the binder, and is not as tough as tungsten carbide.
- **Silicon carbide** (SiC) has good resistance to wear (thus suitable for use as an abrasive), thermal shock, and corrosion. It has a low friction coefficient and retains strength at elevated temperatures, and thus it is suitable for high-temperature components in heat engines. First produced in 1891, synthetic silicon carbide is made from silica sand, coke, and small amounts of sodium chloride and sawdust; the process is similar to that for making synthetic aluminum oxide (Section 8.2.2).

Nitrides. Examples of *nitrides* are:

- **Cubic boron nitride** (cBN) is the second-hardest known substance (after diamond), and has special applications, such as in cutting tools and as abrasives in grinding wheels. It does not exist in nature, and was first made synthetically in the 1970s, using techniques similar to those used in making synthetic diamond (Section 8.7).

- **Titanium nitride** (TiN) is used widely as a coating on cutting tools; it improves tool life by virtue of its low friction characteristics.
- **Silicon nitride** (Si_3N_4) has high resistance to creep at elevated temperatures, low thermal expansion, and high thermal conductivity, thus it resists thermal shock (Section 3.6). It is suitable for high-temperature structural applications, such as components in automotive-engine and gas-turbine, cam-follower rollers, bearings, sandblast nozzles, and components for the paper industry.

Sialon. Derived from the words *si*licon, *al*uminum, *o*xygen, and *n*itrogen, *sialon* consists of silicon nitride, with various additions of aluminum oxide, yttrium oxide, and titanium carbide. It has higher strength and thermal-shock resistance than silicon nitride, and is used primarily as a cutting-tool material.

Cermets. *Cermets* are combinations of a *cer*amic phase bonded with a *met*allic phase. Introduced in the 1960s and also called **black ceramics** or **hot-pressed ceramics**, they combine the high-temperature oxidation resistance of ceramics with the toughness, thermal-shock resistance, and ductility of metals. A common application of cermets is in cutting tools, with a typical composition being 70% Al_2O_3 and 30% TiC; other cermets contain various oxides, carbides, and nitrides.

Cermets have been developed for high-temperature applications, such as nozzles for jet engines and brakes for aircraft, as well as electrical resistors and capacitors that may experience high temperatures. Cermets can be regarded as *composite* materials and can be used in various combinations of ceramics and metals bonded by powder metallurgy techniques (Chapter 17).

8.2.4 Silica

Abundant in nature, *silica* is a polymorphic material—that is, it can have different crystal structures. The cubic structure is found in refractory bricks, used for high-temperature furnace applications. Most glasses contain more than 50% silica. The most common form of silica is **quartz**, a hard, abrasive hexagonal crystal, used extensively in communications applications as an oscillating crystal of fixed frequency, because it exhibits the piezoelectric effect (Section 3.7).

Silicates are products of the reaction of silica with oxides of aluminum, magnesium, calcium, potassium, sodium, and iron; examples are clay, asbestos, mica, and silicate glasses. **Lithium aluminum silicate** has very low thermal expansion and thermal conductivity, and good thermal-shock resistance. However, it also has very low strength and fatigue life, thus it is suitable only for nonstructural applications, such as catalytic converters, regenerators, and heat-exchanger components.

8.2.5 Nanoceramics and Composites

In order to improve the ductility and manufacturing properties of ceramics, the particle size in ceramics has been reduced by means of various techniques, most commonly gas condensation, use of sol-gels, or combustion synthesis. Called *nanoceramics* or **nanophase ceramics**, the structure of these materials consists of atomic clusters, each containing a few thousand atoms. Control of particle size, distribution, and contamination are important in nanoceramics, which exhibit ductility at significantly lower temperatures than do conventional ceramics, and are stronger and easier to fabricate and machine with fewer flaws. Applications are in automotive components such as valves, rocker arms, turbocharger rotors, and cylinder liners, and in jet-engine components.

Nanocrystalline second-phase particles (on the order of 100 nm or less) and fibers also are used as reinforcements in *composites* (Chapter 9). These composites have such enhanced properties as better tensile strength and creep resistance.

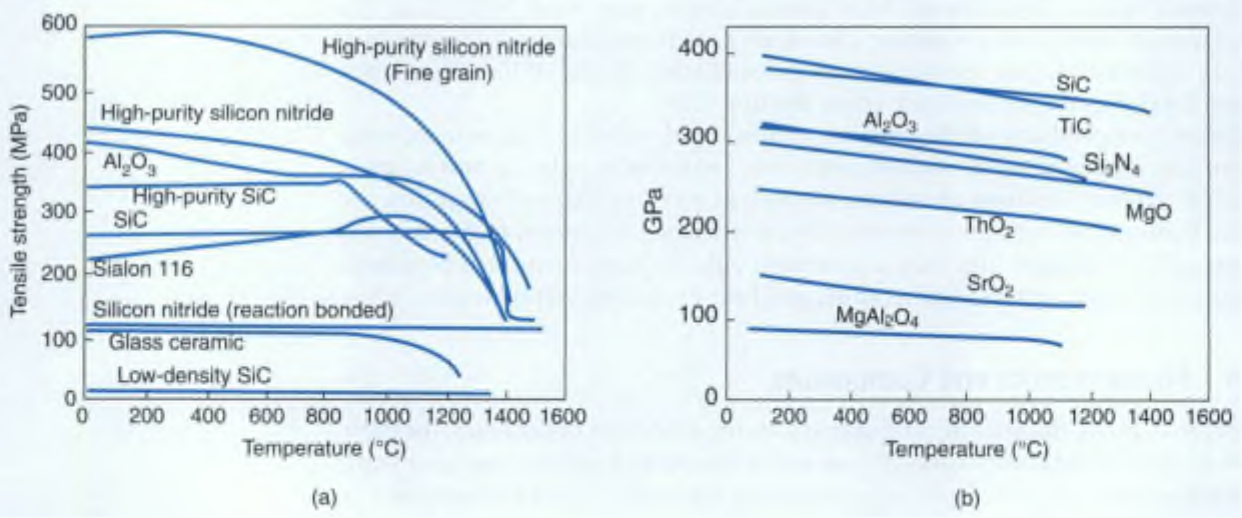
8.3 General Properties and Applications of Ceramics

Video Solution 8.1 Calculation of the Mechanical Properties of Ceramic Materials

Compared with metals, ceramics typically have the following relative characteristics: brittleness; high strength, elastic modulus, and hardness at elevated temperatures; low toughness, density, and thermal expansion; and low thermal and electrical conductivity. Because of the wide variety of material compositions and grain size, the mechanical and physical properties of ceramics vary considerably. Properties of ceramics can also vary widely because of their sensitivity to flaws, defects, and surface or internal cracks. The presence of different types and levels of impurities; and different methods of manufacturing also affect their properties.

8.3.1 Mechanical Properties

The mechanical properties of selected engineering ceramics are given in Fig. 8.3 and Table 8.2. Note that their strength in tension (transverse rupture strength, Section 2.5) is approximately one order of magnitude lower than their compressive strength, because of their sensitivity to cracks, impurities, and **porosity.** Such defects lead to the initiation and propagation of cracks under tensile stresses, and thus significantly reduce the tensile strength of the ceramic; thus, reproducibility and reliability are important aspects in the service life of ceramic components.



(a) (b)

FIGURE 8.3 (a) Effect of temperature on the strength of various engineering ceramics; note that much of the strength is maintained at high temperatures; compare with Fig. 5.5. (b) Effect of temperature on the modulus of elasticity for various ceramics; compare with Fig. 2.6.

TABLE 8.2

Properties of Various Ceramics at Room Temperature

Material	Symbol	Transverse rupture strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Hardness (HK)	Poisson's ratio, ν	Density (kg/m^3)
Aluminum oxide	Al_2O_3	140–240	1000–2900	310–410	2000–3000	0.26	4000–4500
Cubic boron nitride	cBN	725	7000	850	4000–5000	—	3480
Diamond	—	1400	7000	830–1000	7000–8000	—	3500
Silica, fused	SiO_2	—	1300	70	550	0.25	—
Silicon carbide	SiC	100–750	700–3500	240–480	2100–3000	0.14	3100
Silicon nitride	Si_3N_4	480–600	—	300–310	2000–2500	0.24	3300
Titanium carbide	TiC	1400–1900	3100–3850	310–410	1800–3200	—	5500–5800
Tungsten carbide	WC	1030–2600	4100–5900	520–700	1800–2400	—	10,000–15,000
Partially stabilized zirconia	PSZ	620	—	200	1100	0.30	5800

Note: These properties vary widely depending on the condition of the material.

The tensile strength of polycrystalline ceramic increases with decreasing grain size and porosity. This relationship is represented approximately by the expression

$$\text{UTS} = \text{UTS}_o e^{-nP}, \tag{8.1}$$

where P is the volume fraction of pores in the solid, thus if the porosity is 15%, $P = 0.15$, UTS_o is the tensile strength at zero porosity; and the exponent n ranges between 4 and 7. The modulus of elasticity of ceramics is related to porosity by the expression

$$E \simeq E_o\left(1 - 1.9P + 0.9P^2\right), \tag{8.2}$$

where E_o is the elastic modulus at zero porosity.

Unlike most metals and thermoplastics, ceramics generally lack impact toughness and thermal-shock resistance, because of their inherent lack of ductility; once initiated, a crack propagates rapidly. In addition to undergoing fatigue failure under cyclic loading, ceramics exhibit a phenomenon called **static fatigue**, also exhibited by glasses (Section 8.4). When subjected to a static tensile load over time, these materials may suddenly fail; this phenomenon occurs in environments where water vapor is present. Static fatigue, which does not occur in a vacuum or in dry air, has been attributed to a mechanism similar to the stress–corrosion cracking of metals (Section 2.10.2).

Ceramic components that are to be subjected to tensile stresses may be *prestressed*, in much the same way that concrete is prestressed. Prestressing the shaped ceramic components subjects them to compressive stresses; the methods used include

- Heat treatment and chemical tempering (Section 18.4)
- Laser treatment of surfaces (Section 34.8)
- Coating with ceramics having different thermal-expansion coefficients (Section 3.6)
- Surface-finishing operations, such as grinding, in which compressive residual stresses are induced on the surfaces (Section 26.3)

Major advances have been made in improving the toughness and other properties of ceramics, including the development of **machinable** and **grindable ceramics**

(Section 18.2.5). Among these advances are the proper selection and processing of raw materials, the control of purity and structure, and the use of reinforcements—with particular emphasis on advanced methods of stress analysis during the design of ceramic components.

8.3.2 Physical Properties

Most ceramics have a relatively low specific gravity, ranging from about 3 to 5.8 for oxide ceramics as compared to 7.86 for iron (Table 3.1). They have very high melting or decomposition temperatures.

Thermal conductivity in ceramics varies by as much as three orders of magnitude, depending on their composition, whereas in metals it varies by only one order. Like that of other materials, the thermal conductivity of ceramics decreases with increasing temperature and porosity, because air is a poor thermal conductor. The thermal conductivity, k, is related to porosity by the expression

$$k = k_o (1 - P), \tag{8.3}$$

where k_o is the thermal conductivity at zero porosity and P is the porosity, as a fraction of the total volume.

Thermal expansion and thermal conductivity induce internal stresses that can lead to thermal shock or to thermal fatigue in ceramics. The tendency toward **thermal cracking** (called **spalling**, when a small piece or a layer from the surface breaks off) is lower with the combination of low thermal expansion and high thermal conductivity. For example, fused silica has high thermal-shock resistance, because of its virtually zero thermal expansion. (See also Sections 3.5 and 3.6.)

The *optical properties* of ceramics can be controlled by using various formulations and by controlling the structure. These methods make possible the imparting of different degrees of transparency and translucency, and of different colors. For example, single-crystal sapphire is completely transparent, zirconia is white, and fine-grained polycrystalline aluminum oxide is a translucent gray. Porosity influences the optical properties of ceramics in much the same way as air trapped in ice cubes, making them less transparent and giving a white appearance. Although ceramics are basically resistors, they can be made *electrically conducting* by alloying them with certain elements in order to make the ceramic behave like a semiconductor or even like a superconductor.

8.3.3 Applications

Ceramics have numerous consumer and industrial applications. Various types of ceramics are used in the electrical and electronics industries, because they have high electrical resistivity, high dielectric strength (voltage required for electrical breakdown per unit thickness), and magnetic properties suitable for such applications as magnets for speakers.

The capability of ceramics to maintain their strength and stiffness at elevated temperatures makes them very attractive for high-temperature applications. The higher operating temperatures made possible by the use of ceramic components mean more efficient combustion of fuel and reduction of emissions in automobiles. Currently, internal combustion engines are only about 30% efficient, but with the use of ceramic components, the operating performance can be improved by at least 30%.

Ceramics that are being used successfully, especially in automotive gas-turbine engine components (such as rotors), are: silicon nitride, silicon carbide, and partially stabilized zirconia. Other attractive properties of ceramics are their low density and high elastic modulus; they enable product weight to be reduced and allow the inertial forces generated by moving parts to be lower. Ceramic turbochargers, for example, are about 40% lighter than conventional ones. High-speed components for machine tools also are candidates for ceramics (Section 25.3). Furthermore, the high elastic modulus of ceramics makes them attractive for improving the stiffness of machines, while reducing the weight. Their high resistance to wear also makes them suitable for such applications as cylinder liners, bushings, seals, bearings, and liners for gun barrels. Coating metal with ceramics is another application, often done to reduce wear, prevent corrosion, or provide a thermal barrier.

CASE STUDY 8.2 Ceramic Gun Barrels

The wear resistance and low density of ceramics have led to research into their use as liners for gun barrels. Their limited success has led to more recent developments in making composite ceramic gun barrels, which have improved performance over traditional steel barrels. For example, a 50-caliber zirconia ceramic barrel is formed in several separate segments, each 150–200 mm long and with a wall thickness of 3.75 mm, using the shaping and sintering processes described in Chapter 17.

The segments are subsequently machined to the required dimensions and surface finish. Zirconia is used because of its high toughness, flexural strength, specific heat, operating temperature, and very low thermal conductivity. The thermal properties are important for gun performance.

The separate ceramic segments are then assembled, and the barrel is wrapped with a carbon-fiber/polymer-matrix composite that subjects the ceramic barrel to a compressive stress of 690MPa, thus greatly improving its capacity to withstand tensile stresses developed during firing. Finally, the inside of the barrel is rifled (cut to produce internal spiral grooves that give rotation to the exiting bullet for gyroscopic stability) and fitted to a breech.

Source: Courtesy of K.H. Kohnken, Surface Conversion Technologies, Inc., Cumming, Georgia.

CASE STUDY 8.3 Ceramic Ball and Roller Bearings

Silicon-nitride ceramic ball and roller bearings (Fig. 8.4) are used when high temperature, high speed, or marginally lubricated conditions exist. The bearings can be made entirely from ceramics, or just the ball and rollers are ceramic and the races are metal, in which case they are referred to as *hybrid bearings*. Examples of applications for ceramic and hybrid bearings include high-performance machine tool spindles, metal-can seaming heads, high-speed flow meters, and bearings for motorcycles, go karts, and snowmobiles.

The ceramic spheres have a diametral tolerance of 0.13 μm and a surface roughness of 0.02 μm. They have high wear resistance, high fracture toughness, low density, and perform well with little or no lubrication. The balls have a coefficient of thermal expansion one-fourth that of steel, and they can withstand temperatures of up to 1400°C.

Produced from titanium and carbon nitride by powder metallurgy techniques, the full-density titanium carbonitride (TiCN) or silicon nitride (Si_3N_4) bearing-grade material can be twice as hard as chromium steel and 40% lighter. Components up to 300 mm in diameter have been produced.

(*continued*)


(a) (b)

FIGURE 8.4 A selection of ceramic bearings and races. *Source:* Courtesy of The Timken Company.

Bioceramics. Because of their strength and inertness, ceramics are also used as biomaterials (*bioceramics*), to replace joints in the human body, as prosthetic devices, and in dental work. Commonly used bioceramics are aluminum oxide, hydroxyapatite (a naturally occurring mineral), tricalcium phosphate, silicon nitride, and various compounds of silica. Ceramic implants can be made porous, so that bone can grow into the porous structure (as is the case with porous titanium implants) and develop a strong bond with structural integrity.

8.4 Glasses

Glass is an amorphous solid with the structure of a liquid (Fig. 8.5), a condition that is obtained by supercooling (cooling at a rate too high to allow crystals to form). Technically, glass is defined as an inorganic product of fusion that has cooled to a

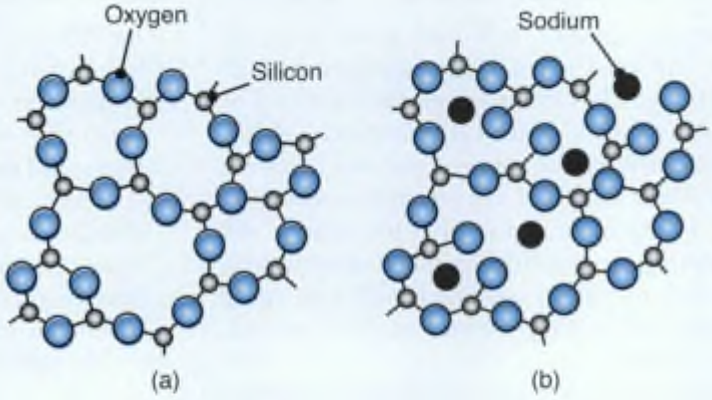


FIGURE 8.5 Schematic illustration of the structure of silica glass. (a) Pure silica glass, in the form of $(SiO_2)_n$ random structure and (b) partially depolymerized glass; note that a fourth bond for each silicon is outside the plane shown.

rigid state without crystallizing. Glass has no distinct melting or freezing point; thus, its behavior is similar to that of amorphous alloys (see metallic glasses, Section 6.14) and amorphous polymers (Section 7.2.2).

Glass beads were first produced in about 2000 B.C., and the art of glassblowing began in about 200 B.C. Silica solely was used for all glass products until the late 1600s. Rapid developments in glasses began in the early 1900s. There are about 750 different types of commercially available glasses, with applications ranging from window glass to glass for containers, cookware, lighting, and mobile phones, and to glasses with special mechanical, electrical, high-temperature, antichemical, corrosion, and optical characteristics. Special glasses are used in fiber optics (for communication by light with little loss in signal power) and in **glass fibers**, with very high strength (for use in reinforced plastics, Section 9.2.1).

All glasses contain at least 50% silica, which is known as a **glass former**. The composition and properties of glasses can be modified by the addition of oxides of aluminum, sodium, calcium, barium, boron, magnesium, titanium, lithium, lead, and potassium. Depending on their function, these oxides are known as **intermediates** or **modifiers**.

8.4.1 Types of Glasses

Almost all *commercial glasses* are categorized by the following types (Table 8.3):

- **Soda-lime glass** (the most common type)
- **Lead-alkali glass**
- **Borosilicate glass**
- **Aluminosilicate glass**
- **96%-silica glass**
- **Fused silica glass**

Glasses also are classified as colored, opaque (white and translucent), multiform (a variety of shapes), optical, photochromatic (darkens when exposed to light, as in some sunglasses), photosensitive (changing from clear to opaque), fibrous (drawn into long fibers, as in fiberglass), and foam or cellular (containing bubbles, thus a good thermal insulator). Glasses also can be referred to as **hard** or **soft**, usually in the sense of a thermal rather than mechanical property (see also hardness of glasses, Section 8.4.2); thus, a soft glass softens at a lower temperature than

TABLE 8.3

Properties of Various Glasses

Property	Soda-lime glass	Lead-alkali glass	Borosilicate glass	96% silica	Fused silica
Density	High	Highest	Medium	Low	Lowest
Strength	Low	Low	Moderate	High	Highest
Resistance to thermal shock	Low	Low	Good	Better	Best
Electrical resistivity	Moderate	Best	Good	Good	Good
Hot workability	Good	Best	Fair	Poor	Poorest
Heat treatability	Good	Good	Poor	None	None
Chemical resistance	Poor	Fair	Good	Better	Best
Impact-abrasion resistance	Fair	Poor	Good	Good	Best
Ultraviolet-light transmission	Poor	Poor	Fair	Good	Good
Relative cost	Lowest	Low	Medium	High	Highest

does a hard glass. Soda-lime and lead-alkali glasses are considered soft, and the rest as hard.

8.4.2 Mechanical Properties

The behavior of glass, like that of most ceramics, is generally regarded as perfectly elastic and brittle. The modulus of elasticity for commercial glasses ranges from 55 to 90 GPa, and their Poisson's ratio from 0.16 to 0.28. The hardness of glasses, as a measure of resistance to scratching, ranges from 5 to 7 on the Mohs scale, which is equivalent to a range from around 350–500 HK. (See Fig. 2.15.)

Glass in **bulk** form generally has a strength lower than 140 MPa. The relatively low strength of bulk glass is attributed to the presence of small flaws and microcracks on its surface, some or all of which may be introduced during normal handling of the glass by inadvertently abrading it. These defects reduce the strength of glass by two to three orders of magnitude, compared to its ideal (defect free) strength. Glasses can be strengthened by thermal or chemical treatments to obtain high strength and toughness (Section 18.4).

The strength of glass theoretically can reach 35 GPa. When molten glass is drawn into fibers (**fiberglass**), its tensile strength ranges from 0.2 to 7 GPa, with an average of about 2 GPa. These fibers are stronger than steel, and are used to reinforce plastics in such applications as boats, automobile bodies, furniture, and sporting equipment (see Tables 2.2 and 9.2).

8.4.3 Physical Properties

Glasses are characterized by low thermal conductivity and high electrical resistivity and dielectric strength. Their coefficient of thermal expansion is lower than those for metals and plastics, and may even approach zero. For example, titanium silicate glass (a clear, synthetic high-silica glass) has a near-zero coefficient of thermal expansion. Fused silica (a clear, synthetic amorphous silicon dioxide of very high purity) also has a near-zero coefficient of expansion. The optical properties of glasses, such as reflection, absorption, transmission, and refraction, can be modified by varying their composition and treatment. Glasses generally are resistant to chemical attack, and are ranked by their resistance to corrosion by acids, alkalis, or water.

8.5 Glass Ceramics

Although glasses are amorphous, *glass ceramics* have a high crystalline component to their microstructure. Glass ceramics, such as *Pyroceram* (a trade name), contain large proportions of several oxides; thus, their properties are a combination of those for glass and those for ceramics. Most glass ceramics are stronger than glass. The products are first shaped and then heat treated, whereby **devitrification** (recrystallization) of the glass occurs. Glass ceramics are generally white or gray in color.

The hardness of glass ceramics ranges approximately from 520 to 650 HK. Because they have a near-zero coefficient of thermal expansion, they also have high thermal-shock resistance, and because of the absence of the porosity usually found in conventional ceramics, they are strong. The properties of glass ceramics can be improved by modifying their composition and by heat-treatment techniques. First developed in 1957, glass ceramics are typically used for cookware, heat exchangers in gas-turbine engines, radomes (housings for radar antennas), and electrical and electronics components.

8.6 Graphite

Graphite is a crystalline form of carbon, and has a *layered structure*, with basal planes or sheets of close-packed carbon atoms (see Fig. 1.5); consequently, graphite is weak when sheared along the layers. This characteristic, in turn, gives graphite its low frictional properties, and explains its use as a lubricant, especially at elevated temperatures. However, its frictional properties are low only in an environment of air or moisture; in a vacuum, it is abrasive and thus a poor lubricant. Unlike with other materials, strength and stiffness of graphite increase with temperature. Amorphous graphite is known as **lampblack** (black soot) and is used as a pigment. Ordinary pencil "lead" is a mixture of graphite and clay; graphite deposits found in the early 16th century were first thought of as being a form of lead.

Although brittle, graphite has high electrical and thermal conductivity and good resistance to thermal shock and to high temperature, although it begins to oxidize at 500°C. It is an important material for applications such as electrodes, heating elements, brushes for motors, high-temperature fixtures and furnace parts, mold materials (such as crucibles for the melting and casting of metals), and seals (Fig. 8.6). A characteristic of graphite is its resistance to chemicals, thus it is used in filters for corrosive fluids; its low absorption cross-section and high scattering cross-section for thermal neutrons make graphite also suitable for nuclear applications.

Graphite Fibers. An important use of graphite is as *fibers* in reinforced plastics and composite materials, as described in Section 9.2.

Carbon and Graphite Foams. These foams have high service temperatures, chemical inertness, low thermal expansion, and thermal and electrical properties that can be tailored to specific applications. *Carbon foams* are available in either graphitic or nongraphitic structures. *Graphitic foams* (typically produced from petroleum, coal tar, and synthetic pitches) have low density, high thermal and electrical conductivity, but lower mechanical strength, and are much more expensive than nongraphitic foams (produced from coal or organic resins), which are highly amorphous.

These foams have a cellular microstructure, with interconnected pores, thus their mechanical properties depend on density (see also Section 8.3). Blocks of foam


(a)

(b)

FIGURE 8.6 (a) Various engineering components made of graphite. *Source:* Courtesy of Poco Graphite, Inc., a Unocal Co. (b) Examples of graphite electrodes for electrical discharge machining (Section 27.5). *Source:* Courtesy of Unicor, Inc.

can easily be machined into various complex shapes. Applications of carbon foams include their use as core materials for aircraft and ship interior panels, structural insulation, sound-absorption panels, substrates for spaceborne mirrors, lithium-ion batteries, and for fire and thermal protection.

8.6.1 Fullerenes

Carbon molecules (typically C60) are now produced in the shape of soccer balls, called *fullerenes* or **buckyballs**, after B. Fuller (1895–1983), the inventor of the geodesic dome. These chemically–inert spherical molecules are produced from soot, and act much like solid lubricant particles. When mixed with metals, fullerenes can become superconductors at low temperatures (around 40 K). Despite their promise, no commercial applications of buckyballs currently exist.

8.6.2 Nanotubes

Carbon nanotubes can be thought of as tubular forms of graphite, and are of interest for the development of nanoscale devices. (See also *nanomaterials*, Section 8.8.) *Nanotubes* are produced by laser ablation of graphite, carbon-arc discharge, and, most often, by chemical vapor deposition (CVD, Section 34.6.2). They can be single-walled (SWNT) or multi-walled (MWNT) and can be doped with various species.

Carbon nanotubes have exceptional strength, thus making them attractive as reinforcing fibers for composite materials; however, because they have very low adhesion with most materials, delamination with a matrix can limit their reinforcing effectiveness. It is difficult to disperse nanotubes properly because they have a tendency to clump, and this limits their effectiveness as a reinforcement. A few products have used carbon nanotubes, such as bicycle frames, specialty baseball bats, golf clubs, and tennis racquets. Nanotubes provide only a fraction of the reinforcing material (by volume), graphite fibers playing the major role.

An additional characteristic of carbon nanotubes is their very high electrical-current carrying capability. They can be made as semiconductors or conductors, depending on the orientation of the graphite in the nanotube (Fig. 8.7). Armchair nanotubes are theoretically capable of carrying a current density higher than 1,000

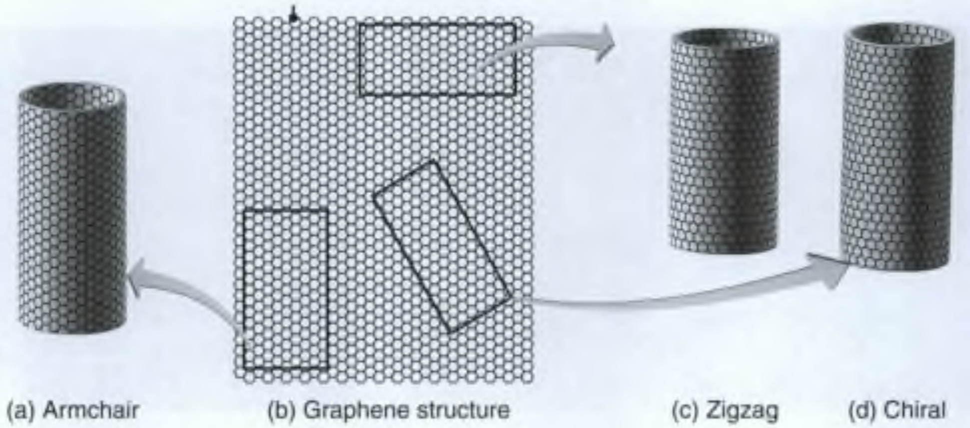


FIGURE 8.7 Forms of carbon nanotubes produced from a section of graphene: armchair, zigzag, and chiral. Armchair nanotubes are noteworthy for their high electrical conductivity, whereas zigzag and chiral nanotubes are semiconductors.

times that for silver or copper, thus making them attractive for electrical connections in nanodevices (Section 29.5). Carbon nanotubes have been incorporated into polymers to improve their static-electricity discharge capability, especially in fuel lines for automotive and aerospace applications.

Among the numerous proposed uses for carbon nanotubes are storage of hydrogen for use in hydrogen-powered vehicles, flat-panel displays, human tissue engineering, electrical cables for nano-scale circuitry, catalysts, and X-ray and microwave generators. Highly sensitive sensors using aligned carbon nanotubes are now being developed for detecting deadly gases, such as sarin.

8.6.3 Graphene

Graphene can be considered to be a single sheet of graphite, or an unwrapped nanotube, as shown in Fig. 8.7b. It is one of the most commonly encountered materials, but its direct observation in transmission electron microscopes dates only to the early 1960s. A number of methods have been developed for producing graphene, including epitaxy (Section 28.5) on silicon carbide or metal substrates and by chemical reduction of graphite. Research interest in graphene has grown considerably in the past few years, and applications of graphene as a transistor in integrated circuits (Chapter 28) and in solar cells have been suggested.

8.7 Diamond

Diamond is a form of carbon, with a covalently bonded structure. It is the hardest substance known (7000–8000 HK); however, it is brittle and begins to decompose in air at about 700°C, but resists higher temperatures in a nonoxidizing environment.

Synthetic or **industrial diamond** was first made in 1955. A common method of manufacturing it is to subject graphite to a hydrostatic pressure of 14 GPa and a temperature of 3000°C, referred to as *high-pressure, high-temperature* (HPHT) synthesis. An alternative is to produce diamonds through a chemical vapor deposition process (CVD; Section 34.6.2), depositing carbon onto a starting *seed* of diamond powder. The CVD process is used most often for synthetic gemstones. Synthetic diamond has identical, and sometimes slightly superior, mechanical properties as natural diamond, because of the presence of fewer and smaller impurities. The gemstones have a characteristic orange or yellow tint due to impurities, resulting from the CVD process, whereas laser treatment of the diamond can change the tint to pink or blue. However, since most of a gemstone's cost is attributed to grinding and finishing (Chapter 26) to achieve a desired shape, synthetic diamonds are only slightly less expensive than natural ones.

Synthetic diamond is available in a variety of sizes and shapes; for use in abrasive machining, the most common grit size is 0.01 mm in diameter. Diamond particles can be coated with nickel, copper, or titanium for improved performance in grinding operations **Diamond-like carbon** also has been developed and is used as a diamond film coating, described in Section 34.13.

In addition to its use in jewelry, gem-quality synthetic diamond has applications as heat sinks for computers, in telecommunications and integrated-circuit industries, and in high-power lasers. Its electrical conductivity is 50 times higher than that of natural diamond, and it is 10 times more resistant to laser damage.

Because of its favorable characteristics, diamond has numerous important applications, such as:

- Cutting-tool materials, as a single crystal or in polycrystalline form
- Abrasives in grinding wheels, for hard materials
- Dressing of grinding wheels (e.g., sharpening of the abrasive grains)
- Die inserts, for drawing wire less than 0.06 mm in diameter
- Coatings for cutting tools and dies

8.8 Nanomaterials

Important developments continue to take place in the production of materials as particles, fibers, wire, tube, films, and composites, with features typically on the order of 1 nm to up to 100 nm. First investigated in the early 1980s and generally called *nanomaterials* or *nanostructured*, *nanocrystalline*, or *nanophase* materials, they have certain properties that are often superior to traditional materials. These characteristics include high strength, hardness, ductility, toughness, resistance to wear and corrosion, and suitable for structural (load bearing) and nonstructural applications in combination with unique electrical, magnetic, thermal, and optical properties.

The composition of a nanomaterial can be any combination of chemical elements; among the more important compositions are carbides, oxides, nitrides, metals and their alloys, organic polymers, semiconductors, and various composites. *Nanometal-polymer hybrid nanomaterials* have been developed for very lightweight components. More recent investigations include the development of *nanopaper*, with very high strength and toughness, produced from wood pulp, with fibers rearranged into an entangled porous mesh.

Production methods for nanomaterials include inert-gas condensation, sputtering, plasma synthesis, electrode position, sol–gel synthesis, and mechanical alloying or ball milling. The synthesized powders are consolidated into bulk materials by various techniques, including compaction and sintering. Nanoparticles have a very high surface area-to-volume ratio, thus affecting their behavior in such processes as diffusion and agglomeration. Because the synthesis of nanomaterials is at atomic levels, their purity is on the order of 99.9999%, and their homogeneity and uniformity of their microstructure are highly controlled. As a result, their mechanical, electrical, magnetic, optical, and chemical properties also can be controlled precisely. Nanomaterials are very expensive to produce and process them into products, thus their cost-effectiveness is under continued study.

Applications of Nanomaterials. The unique properties of nanomaterials enable manufacturing of products that are strong and light. The following are some current and potential applications for nanomaterials:

1. Cutting tools and inserts, made of nanocrystalline carbides and other ceramics
2. Nanophase ceramics, that are ductile and machinable
3. Specialty bicycle frames, baseball bats, and tennis racquets, using carbon nanotubes (see also Section 8.6.2)
4. Next-generation computer chips, using nanocrystalline starting materials with very high purity, better thermal conductivity, and more durable interconnections

5. Flat-panel displays for laptop computers and televisions, made by synthesizing nanocrystalline phosphorus to improve screen resolution
6. Spark-plug electrodes, igniters and fuels for rockets, medical implants, high-sensitivity sensors, catalysts for elimination of pollutants, high-power magnets, and high-energy-density batteries
7. Switches, valves, motor, and pumps
8. Coatings made of nanomaterials are being investigated for improved wear, abrasion, corrosion resistance, and thermal insulation; nanocrystalline materials; and nanophase materials because of their lower thermal conductivity

Health Hazards. Nanoparticles can present various health hazards by virtue of their very small size and absorption through the skin, lungs, or the digestive track; they can also penetrate human cells. There is also increasing evidence that nanoparticles can pollute air, water, and the ground. Consequently, there is growing research on the risks of nanoparticles to humans and the environment.

SUMMARY

- Ceramics, glasses, and various forms of carbon are of major importance in engineering applications and in manufacturing processes. Ceramics, which are compounds of metallic and nonmetallic elements, generally are characterized by high hardness, high compressive strength, high elastic modulus, low thermal expansion, high temperature resistance, good chemical inertness, low density, and low thermal and electrical conductivity. They are brittle and have low toughness.
- Ceramics are generally classified as either traditional ceramics or industrial (or high-tech) ceramics; the latter are particularly attractive for applications such as engine components, cutting tools, and components requiring resistance against wear and corrosion. Ceramics of importance in design and manufacturing are the oxide ceramics (alumina and zirconia), tungsten and silicon carbides, nitrides, and cermets.
- Glasses are supercooled liquids and are available in a wide variety of compositions and mechanical, physical, and optical properties. Glass ceramics are predominantly crystalline in structure, and have properties that are more desirable than those of glasses.
- Glass in bulk form has relatively low strength, but it can be strengthened by thermal and chemical treatments. Glass fibers are used widely as a reinforcement in composite materials.
- Graphite, fullerenes, carbon nanotubes, and diamond are forms of carbon that display unique combinations of properties. Graphite has high-temperature use and electrical applications; graphite fibers are used to reinforce plastics and other composite materials.
- Diamond is used as cutting tools for precision machining operations, as dies for drawing of thin wire and as abrasives for grinding wheels. Diamond-like carbon has applications as a coating material for improved wear resistance.
- Nanomaterials have physical, mechanical, optical, chemical, and thermal properties, with several unique applications. Carbon nanotubes are of continued research interest, particularly because of their applications in nanoscale electrical and electromechanical systems.

KEY TERMS

Alumina
Bioceramics
Buckyballs
Carbides
Carbon
Carbon foam
Carbon nanotubes
Ceramics
Cermets
Clay
Devitrification
Diamond
Diamond-like carbon
Feldspar
Flint
Fullerenes
Glass
Glass ceramics
Glass fibers
Glass former
Graphene
Graphite
Industrial ceramics
Industrial diamond
Nanoceramics
Nanophase ceramics
Nanotubes
Nitrides
Oxide ceramics
Partially stabilized zirconia
Porcelain
Porosity
Sialon
Silica
Static fatigue
Transformation-toughened zirconia
White ceramics
Zirconia

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REVIEW QUESTIONS

8.1 What is a ceramic?

8.2 List the major differences between the properties of ceramics and those of metals and plastics.

8.3 List the major types of ceramics that are useful in engineering applications.

8.4 What do the following materials typically consist of: (a) carbides, (b) cermets, and (c) sialon?

8.5 What is porcelain?

8.6 What is glass? Why is it called a supercooled material?

8.7 How is glass different from a glass ceramic?

8.8 What is devitrification?

8.9 List the major types of glasses and their applications.

8.10 What is static fatigue? What is its significance?

8.11 Describe the major uses of graphite.

8.12 How are alumina ceramics produced?

8.13 What features of PSZ differentiate it from other ceramics?

8.14 What are buckyballs?

8.15 List the major uses of diamond.

8.16 What is a carbon nanotube? Explain why they are not as prevalent as other forms of carbon.

8.17 What is graphene? How is it related to graphite?

8.18 What do the terms "armchair," "zigzag," and "chiral" have in common?

QUALITATIVE PROBLEMS

8.19 Explain why ceramics are weaker in tension than in compression.

8.20 What are the advantages of cermets? Suggest applications in addition to those given in this chapter.

8.21 Explain why the electrical and thermal conductivity of ceramics decreases with increasing porosity.

8.22 Explain why the mechanical property data given in Table 8.2 have such a broad range. What is the significance of this in engineering practice?

8.23 Describe the reasons that have encouraged the development of synthetic diamond.

8.24 Explain why the mechanical properties of ceramics generally differ from those of metals.

8.25 Explain how ceramics can be made tougher.

8.26 List and describe situations in which static fatigue can be important.

8.27 What properties are important in making heat-resistant ceramics for use on oven tops? Why?

8.28 A large variety of glasses is now available. Why is this so?

8.29 What is the difference between the structure of graphite and that of diamond? Is it important? Explain.

8.30 List and explain materials that are suitable for use as a coffee cup.

8.31 Aluminum oxide and PSZ are described as white in appearance. Can they be colored? If so, how would you accomplish this?

8.32 Why does the strength of a ceramic part depend on its size?

8.33 In old castles and churches in Europe, the glass windows display pronounced ripples and are thicker at the bottom than at the top. Explain.

8.34 Is a carbide an example of a composite material? Explain.

8.35 Ceramics are hard and strong in both compression and shear. Why, then, are they not used as nails or other fasteners? Explain.

8.36 Perform an Internet search and determine the chemistry of glass used for (a) fiber-optic communication lines, (b) crystal glassware, and (c) high-strength glass fibers.

8.37 Investigate and list the ceramics used for high-temperature superconductor applications.

8.38 Explain why synthetic diamond gemstones are not appreciably less expensive than natural diamond gemstones.

QUANTITATIVE PROBLEMS

8.39 In a fully dense ceramic, $\text{UTS}_o = 200$ MPa and $E_o = 330$ GPa. What are these properties at 15% porosity for values of $n = 4, 5, 6,$ and 7, respectively?

8.40 Plot the UTS, E, and k values for ceramics as a function of porosity P. Describe and explain the trends that you observe in their behavior.

8.41 What would be the tensile strength and the modulus of elasticity of the ceramic in Problem 8.39 for porosities of 25% and 50%, for the four n values given?

8.42 Calculate the thermal conductivities for ceramics at porosities of 10%, 20%, and 40% for $k_o = 0.7$ W/mK.

8.43 A ceramic has $k_o = 0.80$ W/mK. If this ceramic is shaped into a cylinder with a porosity distribution given by $P = 0.1(x/L)(1 - x/L)$, where x is the distance from one end of the cylinder and L is the total cylinder length, plot the porosity as a function of distance, evaluate the average porosity, and calculate the average thermal conductivity.

8.44 It can be shown that the minimum weight of a column which will support a given load depends on the ratio of the material's stiffness to the square root of its density. Plot this property for a ceramic as a function of porosity.

SYNTHESIS, DESIGN, AND PROJECTS

8.45 Make a list of the ceramic parts that you can find around your house or in your car. Give reasons why those parts are made of ceramics.

8.46 Assume that you are working in technical sales and are fully familiar with all the advantages and limitations of ceramics. Which of the markets traditionally using nonceramic materials do you think ceramics can penetrate? What would you like to talk about to your potential customers during your sales visits? What questions do you think they may ask you about ceramics?

8.47 Describe applications in which a ceramic material with a near-zero coefficient of thermal expansion would be desirable.

8.48 The modulus of elasticity of ceramics is typically maintained at elevated temperatures. What engineering applications could benefit from this characteristic?

8.49 List and discuss the factors that you would take into account when replacing a metal component with a ceramic component in a specific product.

8.50 Obtain some data from the technical literature in the Bibliography of this chapter, and show quantitatively the effects of temperature on the strength and the modulus of elasticity of several ceramics. Comment on how the shape of these curves differs from those for metals.

8.51 Conduct a literature search and write a brief paper summarizing the properties and potential applications of graphene.

8.52 It was noted in Section 8.4.1 that there are several basic types of glasses available. Make a survey of the technical literature and prepare a table for these glasses, indicating various mechanical, physical, and optical properties.

8.53 Ceramic pistons are being considered for high-speed combustion engines. List the benefits and concerns that you would have regarding this application.

8.54 It has been noted that the strength of brittle materials (such as ceramics and glasses) is very sensitive to surface defects, such as scratches (known as *notch sensitivity*). Obtain several pieces of these materials, scratch them, and test them by carefully clamping them in a vise and bending them. Comment on your observations.

8.55 Electric space heaters for home use commonly utilize a ceramic filament as the heating element. List the required properties for this filament, explain why a ceramic is a suitable material, and perform an Internet search to determine the specific ceramic material actually utilized in this application.

Composite Materials: Structure, General Properties, and Applications

CHAPTER 9

- With their attractive properties, especially high strength-to-weight and stiffness-to-weight ratios, composites are among the most important engineered materials.
- Composites are widely used as structural components, especially in the aerospace industry, where weight savings are a major consideration.
- This chapter describes the major types of composite materials, the characteristics of the commonly used reinforcing fibers, and their effect in improving mechanical properties.
- The role of the matrix is then described, and the three principal classes of matrix materials (plastic, metal, and ceramic) are examined.
- The chapter ends with a discussion of the selection and applications of a variety of reinforced plastics and composites.

EXAMPLE:

CASE STUDIES:

9.1 Introduction

A **composite material** is a combination of two or more chemically distinct and insoluble phases with a recognizable interface, in such a manner that its properties and structural performance are superior to those of the constituents acting independently. These combinations are known as **polymer-matrix, metal-matrix,** and **ceramic-matrix composites.** As shown in Table 7.1, fiber reinforcements significantly improve the strength, stiffness, and creep resistance of plastics, particularly their strength-to-weight and stiffness-to-weight ratios. Composite materials have found increasingly wider applications in aircraft (Fig. 9.1), space vehicles, satellites, offshore structures, piping, electronics, automobiles, boats, and sporting goods.

The oldest example of composites, dating back to 4000 B.C., is the addition of straw to clay to make bricks stronger. In this combination, the straws are the reinforcing fibers and the clay is the matrix. Another example of a composite material is reinforced concrete, which was developed in the 1800s. By itself, concrete is brittle and has little or no useful tensile strength; reinforcing steel rods (*rebar*) impart the necessary tensile strength to the concrete.

Composites, in a general sense, can include a wide variety of materials: cermets (Section 8.2.3), two-phase alloys (Section 4.2), natural materials such as wood and bone, and reinforced or combined materials such as steel-wire reinforced automobile tires. This chapter describes the structure, properties, and applications of

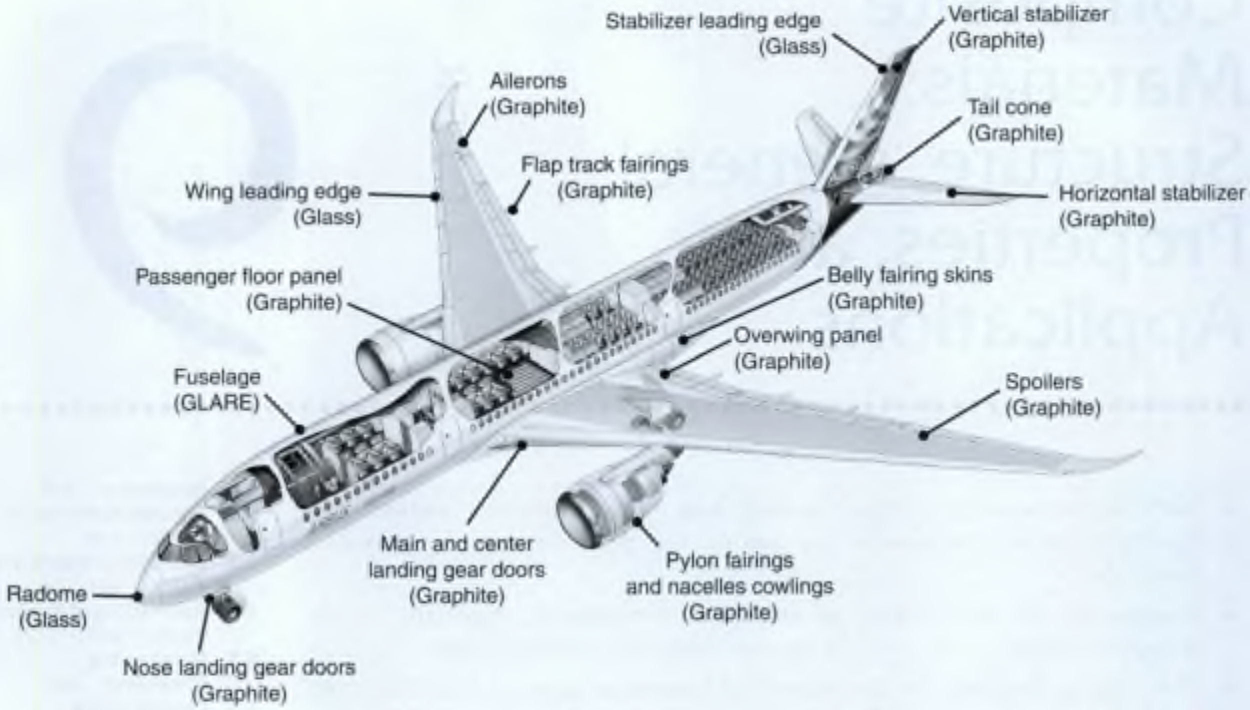

FIGURE 9.1 Application of advanced composite materials in the Airbus 350. The reinforcement type is shown, with the fuselage made of GLARE (a glass-reinforced polymer/aluminum laminate). *Source:* Reuse courtesy of Flight Global, http://www.flightglobal.com/news/articles/paris-air-show-a350-xwb-ready-to-rock-327500/.

composite materials; the processing and shaping of composite materials are described in Chapter 19.

9.2 The Structure of Reinforced Plastics

Reinforced plastics, also known as **polymer-matrix composites** (PMC) and **fiber-reinforced plastics** (FRP), consist of **fibers** (the discontinuous, or dispersed, phase) in a polymer **matrix** (the continuous phase), as shown in Fig. 9.2. These fibers are strong and stiff (Table 9.1), and they have high specific strength (strength-to-weight ratio) and specific stiffness (stiffness-to-weight ratio); see Fig. 9.3. In addition, reinforced-plastic structures have improved fatigue resistance, and higher toughness and creep resistance than those made of unreinforced plastics.

The fibers in reinforced plastics, by themselves, have little structural value; they are stiff in their longitudinal direction but have no transverse stiffness or strength. Although the polymer matrix is less strong and less stiff than the fibers, it is tougher and often more chemically inert; thus, reinforced plastics combine the advantages of each of the two constituents. The percentage of fibers (by volume) in reinforced plastics usually ranges between 10 and 60%.

9.2.1 Reinforcing Fibers

Glass, carbon, ceramics, aramids, and boron are the most common reinforcing fibers for PMCs (Table 9.2).

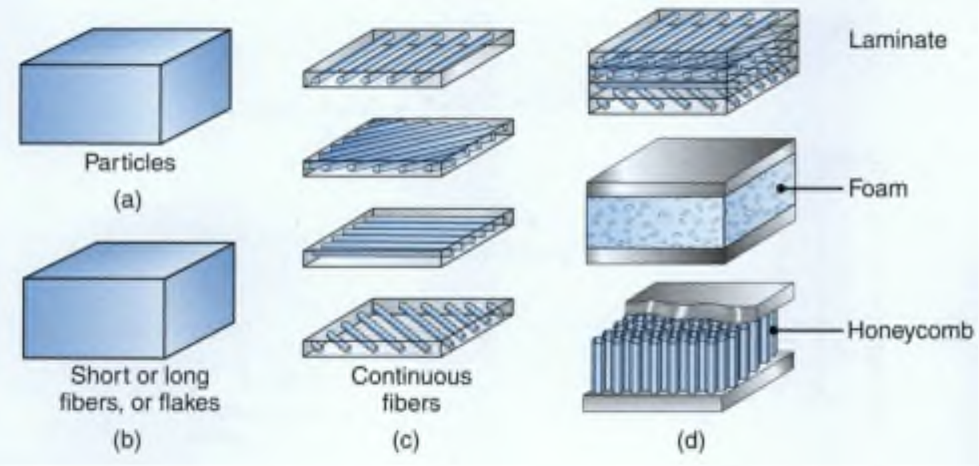

FIGURE 9.2 Schematic illustration of methods of reinforcing plastics (matrix) with (a) particles, (b) short or long fibers or flakes, and (c) continuous fibers. The laminate structures shown in (d) can be produced from layers of continuous fibers or sandwich structures using a foam or honeycomb core (see also Fig. 16.58).

TABLE 9.1

Types and General Characteristics of Composite Materials

Material	Characteristics
Fibers	
Glass	High strength, low stiffness, high density; lowest cost; E (calcium aluminoborosilicate) and S (magnesia aluminosilicate) types commonly used
Carbon	Available as high modulus or high strength; low cost; less dense than glass; sometimes used in combination with carbon nanotubes (see Section 8.6.2)
Boron	High strength and stiffness; highest density; highest cost; has tungsten filament at its center
Aramids (Kevlar)	Highest strength-to-weight ratio of all fibers; high cost
Other fibers	Nylon, silicon carbide, silicon nitride, aluminum oxide, boron carbide, boron nitride, tantalum carbide, steel, tungsten, molybdenum
Matrix materials	
Thermosets	Epoxy and polyester, with the former most commonly used; others are phenolics, fluorocarbons, polyethersulfone, silicon, and polyimides
Thermoplastics	Polyetheretherketone; tougher than thermosets, but lower resistance to temperature
Metals	Aluminum, aluminum–lithium, magnesium, and titanium; fibers are carbon, aluminum oxide, silicon carbide, and boron
Ceramics	Silicon carbide, silicon nitride, aluminum oxide, and mullite; fibers are various ceramics

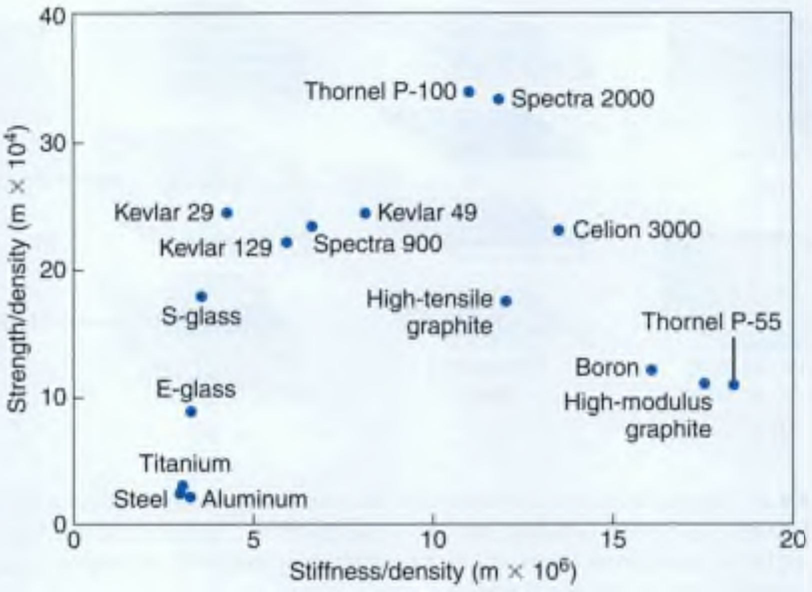

FIGURE 9.3 Specific tensile strength (tensile-strength-to-density ratio) and specific tensile modulus (modulus-of-elasticity-to-density ratio) for various fibers used in reinforced plastics; note the wide range of specific strength and stiffness available.

TABLE 9.2

Typical Properties of Reinforcing Fibers

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)	Relative cost
Boron	3500	380	2380	Highest
Carbon				
High strength	3000	275	1900	Low
High modulus	2000	415	1900	Low
Glass				
E-type	3500	73	2480	Lowest
S-type	4600	85	2540	Lowest
Kevlar				
29	2920	70.5	1440	High
49	3000	112.4	1440	High
129	3200	85	1440	High
Nextel				
312	1700	150	2700	High
610	2770	328	3960	High
Spectra				
900	2270	64	970	High
1000	2670	90	970	High
2000	3240	115	970	High
Alumina (Al_2O_3)	1900	380	3900	High
Silicon carbide	3500	400	3200	High

Note: These properties vary significantly depending on the material and method of preparation.

Glass Fibers. Glass fibers are the most widely used and the least expensive of all fibers. The composite material is called **glass-fiber reinforced plastic** (GFRP), and may contain between 30% and 60% glass fibers. The fibers are made by drawing molten glass through small openings in a platinum die (see Section 18.3.4); they are then elongated, cooled, and wound on a roll. The glass fibers are later treated with silane (a silicon hydride), as described in Section 9.3. The principal types of glass fibers are:

- **E-type:** a calcium aluminoborosilicate glass, the type most commonly used
- **S-type:** a magnesia aluminosilicate glass, offering higher strength and stiffness, but at a higher cost
- **E-CR-type:** a high-performance glass fiber, with higher resistance to elevated temperatures and acid corrosion than does the E-glass

Carbon Fibers. Carbon fibers (Fig. 9.4a), although more expensive than glass fibers, have a combination of low density, high strength, and high stiffness. The composite is called **carbon-fiber reinforced plastic** (CFRP). Although the words are often used interchangeably, the difference between *carbon* and *graphite* depends on the purity of the material and the temperature at which it was processed. Carbon fibers are at least 90% carbon; graphite fibers are usually more than 99% carbon. A typical carbon fiber contains amorphous (noncrystalline) carbon and graphite (crystalline carbon). These fibers are classified by their elastic modulus, which ranges from 35 to 800 GPa, as *low, intermediate, high*, and *very high modulus*. Some trade names for carbon fibers are Celion and Thornel (see Fig. 9.3). Carbon nanotubes also have been used as reinforcement in composite materials, as described in Section 8.6.2.

All carbon fibers are made by **pyrolysis** of organic **precursors**, commonly *polyacrylonitrile* (PAN) because of its low cost. *Rayon* and *pitch* (the residue from catalytic crackers in petroleum refining) also can be used as precursors. Pyrolysis is the process of inducing chemical changes by heat–for instance, by burning a length of yarn and causing the material to carbonize and become black in color. With PAN, the fibers are partially cross-linked at a moderate temperature (in order to prevent melting during subsequent processing steps), and are simultaneously elongated. At this stage, the fibers are *carburized*; they are exposed to elevated temperatures to expel the hydrogen (dehydrogenation) and the nitrogen (denitrogenation) from the PAN. The temperatures for carbonizing range up to about 1500°C; for graphitizing, up to 3000°C.

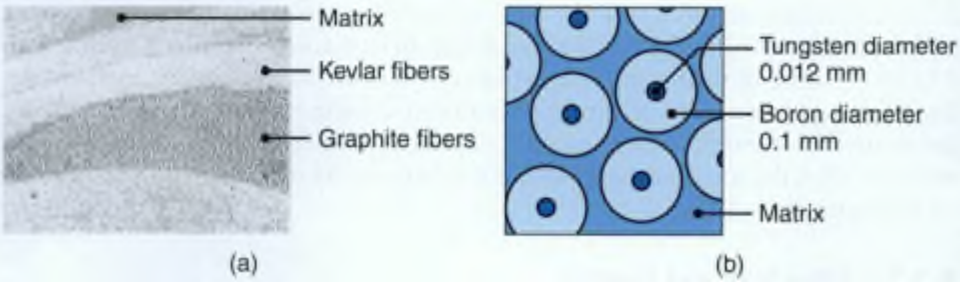

FIGURE 9.4 (a) Cross-section of a tennis racket, showing graphite and aramid (Kevlar) reinforcing fibers. *Source:* Courtesy of F. Garrett, Wilson Sporting Goods Co. (b) Cross-section of boron-fiber reinforced composite material.

Conductive Graphite Fibers. These fibers are produced to make it possible to enhance the electrical and thermal conductivity of reinforced plastic components. The fibers are coated with a metal (usually nickel), using a continuous electroplating process. The coating is typically 0.5-μm thick on a 7-μm-diameter graphite fiber core. Available in chopped or continuous form, the conductive fibers are incorporated directly into injection-molded plastic parts (Section 19.3). Applications include electromagnetic and radio-frequency shielding and lightning-strike protection.

Ceramic Fibers. Ceramic fibers are advantageous for high-temperature applications and in metal-matrix composites (Section 9.5). These fibers have low elongation, low thermal conductivity, and good chemical resistance, in addition to being suitable for high-temperature applications. One family of ceramic fibers is *Nextel*, a trade name; the fibers are oval in cross-section and consist of alumina, silica, and boric oxide. Typical mechanical properties of ceramic are given in Table 9.2.

Polymer Fibers. Polymer fibers may be made of aramids, nylon, rayon, or acrylics; the most common are **aramid fibers**. Aramids (Section 7.6), such as **Kevlar**, are among the toughest fibers, with very high specific strength (Fig. 9.3). Aramids can undergo some plastic deformation prior to fracture and, hence, have higher toughness than brittle fibers. However, aramids absorb moisture (*hygroscopic*), thus degrading their properties.

A high-performance polyethylene fiber is *Spectra* (a trade name); it has ultrahigh molecular weight and high molecular-chain orientation. Spectra, bright white in color, has better abrasion resistance and flexural-fatigue strength than aramid fibers, at a similar cost. In addition, because of its lower density (970 kg/m^3), it has a higher specific strength and specific stiffness than aramid fibers (see Table 9.2). However, a low melting point and poor adhesion characteristics, as compared to other polymers, are its major limitations to applications. (The manufacture of polymer fibers is described in Section 19.2.2.)

Boron Fibers. These fibers consist of tungsten fibers with a layer of boron, deposited by chemical vapor-deposition techniques (Fig. 9.4b); boron also can be deposited onto carbon fibers. Boron fibers have such desirable properties as high strength and stiffness, both in tension and in compression, and resistance to high temperatures. However, because of the high density of tungsten these fibers are heavy, and expensive.

Other Fibers. Among other fibers used in composites are silicon carbide, silicon nitride, aluminum oxide, sapphire, steel, tungsten, molybdenum, boron carbide, boron nitride, and tantalum carbide. **Whiskers** also are used as reinforcing fibers (see Section 22.10). Whiskers are tiny needlelike single crystals that grow to 1–10 μm in diameter, with high aspect ratios (the ratio of fiber length to its diameter), ranging from 100 to 15,000. Because of their small size, whiskers are either free of imperfections or the imperfections they contain do not significantly affect their strength, which approaches the theoretical strength of the material. The elastic moduli of whiskers range between 400 and 700 GPa, and their tensile strength is on the order of 15 to 20 GPa, depending on the material.

9.2.2 Fiber Size and Length

Fibers are very strong and stiff in tension, because (a) the molecules in the fibers are oriented in the longitudinal direction, and (b) their cross-sections are so small, usually less than 0.01 mm in diameter, that the probability is low for any significant defects to exist in the fiber. Glass fibers can have tensile strengths as high as 4600 MPa, whereas the strength of glass in bulk form (Section 8.4.2) is much lower (see Table 2.2).

Fibers generally are classified as **short (discontinuous)** or **long (continuous)**. The designations "short" and "long" are, in general, based on the following distinction: In a given type of fiber, if the mechanical properties improve as a result of increasing average fiber length, it is called a *short fiber*; if there is no such improvement in fiber properties, it is called a *long fiber*. Short fibers typically have aspect ratios between 20 and 60, long fibers between 200 and 500. Reinforcing elements in composites may also be in the form of *chopped fibers, particles, flakes*, or in the form of continuous *roving* (slightly twisted strands) fibers, *woven fabric* (similar to cloth), *yarn* (twisted strands), and *mats* of various combinations.

9.2.3 Matrix Materials

The matrix in reinforced plastics has three principal functions:

1. Support the fibers in place and transfer the stresses to them, so that the fibers can carry most of the load (see Example 9.1)
2. Protect the fibers against physical damage and the environment
3. Slow the propagation of cracks in the composite, by virtue of the higher ductility and toughness of the polymer matrix

Matrix materials usually are *thermoplastics* or *thermosets*, which commonly consist of epoxy, polyester, phenolic, fluorocarbon, polyethersulfone, or silicon. The most commonly used materials are epoxies (in 80% of all reinforced plastics) and polyesters (less expensive than the epoxies). Polyimides, which resist exposure to temperatures in excess of 300°C, are available for use as a matrix with carbon fibers. Some thermoplastics, such as polyetheretherketone (PEEK), also are used as matrix materials. They generally have higher toughness than thermosets, but their resistance to temperature is lower, being limited to 100° to 200°C.

9.3 Properties of Reinforced Plastics

The mechanical and physical properties of reinforced plastics depend on the type, shape, and orientation of the reinforcing material, the length of the fibers, and the volume fraction (percentage) of the reinforcing material. Short fibers are less effective than long fibers (Fig. 9.5), and their properties are strongly influenced by temperature and time under load. Long fibers transmit the load through the matrix better, and are less likely to pull out of the matrix (caused by shear failure of the fiber–matrix interface); thus, they are commonly used in critical applications, particularly at elevated temperatures. The physical properties of reinforced plastics and their resistance to fatigue, creep, and wear depend greatly on the type and amount of reinforcement. Composites can be tailored to impart specific properties (such as permeability and dimensional stability), make processing easier, and reduce production costs.

A critical factor in reinforced plastics is the strength of the bond between the fiber and the polymer matrix, because the load is transmitted through the fiber–matrix interface. Weak interfacial bonding can cause **fiber pullout** and **delamination** of the composite, particularly under adverse environmental conditions. Adhesion at

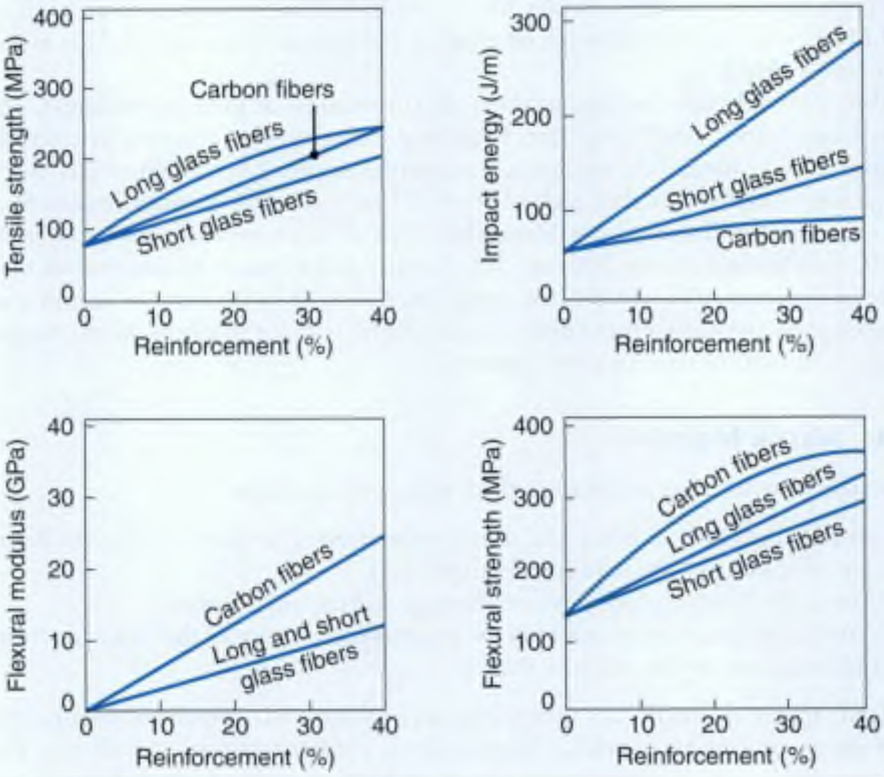

FIGURE 9.5 The effect of the type of fiber on various properties of fiber-reinforced nylon (6,6). *Source:* Courtesy of NASA.

the interface can be improved by special surface treatments, such as coatings and coupling agents. Glass fibers, for example, are treated with **silane** (a silicon hydride) for improved wetting and bonding between the fiber and the matrix. The importance of proper bonding can be appreciated by inspecting the fracture surfaces of reinforced plastics; note in Figs. 9.6a and b, for example, the separation between the fibers and the matrix.

Generally, the highest stiffness and strength in reinforced plastics are obtained when the fibers are aligned in the direction of the tension force. The composite is then highly anisotropic (Fig. 9.7); that is, it has properties, such as strength and stiffness, that depend on direction. As a result, other properties, such as creep resistance, thermal and electrical conductivity, and thermal expansion, also are anisotropic. The transverse properties of such a unidirectionally reinforced structure are much lower than the longitudinal properties. For example, note how strong fiber-reinforced packaging tape is when pulled in tension, yet how easily it can split and tear when pulling it in the width direction.

Because it is an **engineered material**, a part made of reinforced plastic can be given an optimal configuration for a


(a) (b)

FIGURE 9.6 (a) Fracture surface of a glass-fiber reinforced epoxy composite; the fibers are 10 μm in diameter and have random orientation. (b) Fracture surface of a graphite-fiber reinforced epoxy composite; the fibers, 9–11 μm in diameter, are in bundles and are all aligned in the same direction. *Source:* Courtesy of L.J. Broutman.

specific service condition. For example, if the part is to be subjected to stresses in different directions, such as in thin-walled, pressurized vessels, (a) the fibers can be criss-crossed in the matrix or (b) layers of fibers oriented in different directions can be built up into a laminate having improved properties in more than one direction. (See *filament winding*, Section 19.13.3.) For example, a composite flywheel rotor has been produced using a special weaving technique, in which the reinforcing fibers (E-glass) are aligned in the radial direction as well as in the hoop direction. Designed for mechanical-energy storage systems in low-emission electric and hybrid vehicles, the flywheel can operate at speeds up to 50,000 rpm.

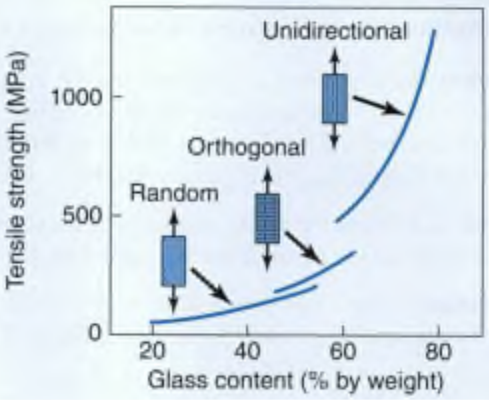

FIGURE 9.7 The tensile strength of glass-reinforced polyester as a function of fiber content and fiber direction in the matrix.

9.3.1 Strength and Elastic Modulus of Reinforced Plastics

The strength and elastic modulus of a reinforced plastic, with unidirectional fibers, can be determined in terms of the (a) strengths and moduli of the fibers and matrix and (b) volume fraction of fibers in the composite. In the following equations, c refers to the composite, f to the fiber, and m to the matrix. The total tensile load, P_c, on the composite is shared by the fiber (P_f) and the matrix (P_m). Thus,

$$P_c = P_f + P_m, \tag{9.1}$$

which can be written as

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m, \tag{9.2}$$

where A_c, A_f, and A_m are the cross-sectional areas of the composite, the fiber, and the matrix, respectively; thus, $A_c = A_f + A_m$. Let's now denote x as the area fraction of the fibers in the composite. (Note that x also represents the volume fraction, because the fibers are uniformly longitudinal in the matrix.) Then Eq. (9.2) can be written as

$$\sigma_c = x\sigma_f + (1-x)\sigma_m. \tag{9.3}$$

The fraction of the total load carried by the fibers can now be calculated. First, note that in the composite under a tensile load, the strains sustained by the fibers and the matrix are the same; that is, $e_c = e_f = e_m$. Next, recall from Section 2.2 that

$$e = \frac{\sigma}{E} = \frac{P}{AE}.$$

Consequently,

$$\frac{P_f}{P_m} = \frac{A_f E_f}{A_m E_m}. \tag{9.4}$$

Since the relevant quantities for a specific situation are known, by using Eq. (9.1), the fraction P_f/P_c can be found. Then, using the foregoing relationships, the elastic modulus, E_c, of the composite can be calculated, by replacing σ in Eq. (9.3) with E. Thus,

$$E_c = xE_f + (1-x)E_m. \tag{9.5}$$

Video Solution 9.1 Design of a Composite Material

EXAMPLE 9.1 **Calculation of Stiffness of a Composite and Load Supported by Fibers**

Given: Assume that a graphite–epoxy reinforced plastic with longitudinal fibers contains 20% graphite fibers. The elastic modulus of the fibers is 300 GPa, and that of the epoxy matrix is 100 GPa.

Find: Calculate the elastic modulus of the composite and the fraction of the load supported by the fibers.

Solution: The data given are $x = 0.2$, $E_f = 300$ GPa, and $E_m = 100$ GPa. Using Eq. (9.5),

$$\begin{aligned} E_c &= 0.2(300) + (1 - 0.2)100 \\ &= 60 + 80 = 140 \text{ GPa}. \end{aligned}$$

From Eq. (9.4), the load fraction P_f/P_m is found to be

$$\frac{P_f}{P_m} = \frac{0.2(300)}{0.8(100)} = 0.75.$$

Because

$$P_c = P_f + P_m \quad \text{and} \quad P_m = \frac{P_f}{0.75},$$

we obtain,

$$P_c = P_f + \frac{P_f}{0.75} = 2.33P_f, \quad \text{or} \quad P_f = 0.43P_c.$$

Thus, the fibers support 43% of the load, even though they occupy only 20% of the cross-sectional area (and hence volume) of the composite.

Video Solution 9.2 Mechanical Properties of Composites

9.4 Applications of Reinforced Plastics

The first engineering application of reinforced plastics was in 1907, for an acid-resistant tank made of a phenolic resin with asbestos fibers. In the 1920s, *Formica* (a trade name) was developed, and used commonly for countertops. Epoxies first were used as a matrix material in the 1930s. Beginning in the 1940s, boats were made with fiberglass, and reinforced plastics were used for aircraft, electrical equipment, and sporting goods. Major developments in composites began in the 1970s, resulting in materials that are now called **advanced composites.** Glass or carbon-fiber reinforced hybrid plastics are available for high-temperature applications, with continuous use ranging up to about 300°C.

Reinforced plastics are typically used in commercial and military aircraft, rocket components, helicopter blades, automobile bodies, leaf springs, drive shafts, pipes, ladders, pressure vessels, sporting goods, helmets, boat hulls, and various other structures and components. About 50% (by weight) of the Boeing 787 Dreamliner is made of composites. By virtue of the resulting weight savings, reinforced plastics have reduced fuel consumption in aircraft by about 2%. The Airbus jumbo jet A380, with a capacity of up to 700 passengers, has horizontal stabilizers, ailerons, wing boxes and leading edges, secondary mounting brackets of the fuselage, and a deck structure made of composites with carbon fibers, thermosetting resins, and thermoplastics. The upper fuselage is made of alternating layers of aluminum and glass-fiber reinforced epoxy prepregs (see Section 19.13).

The contoured frame of the Stealth bomber is made of composites, consisting of carbon and glass fibers, epoxy-resin matrices, high-temperature polyimides, and other advanced materials. Boron-fiber reinforced composites are used in military aircraft, golf-club shafts, tennis rackets, fishing rods, and sailboards (Fig. 9.8). Another example is the development of a small, all-composite ship (twin-hull catamaran design) for the U.S. Navy, capable of speeds of 93 km/h. More recent developments include (a) reinforcing bars for concrete, replacing steel bars, thus

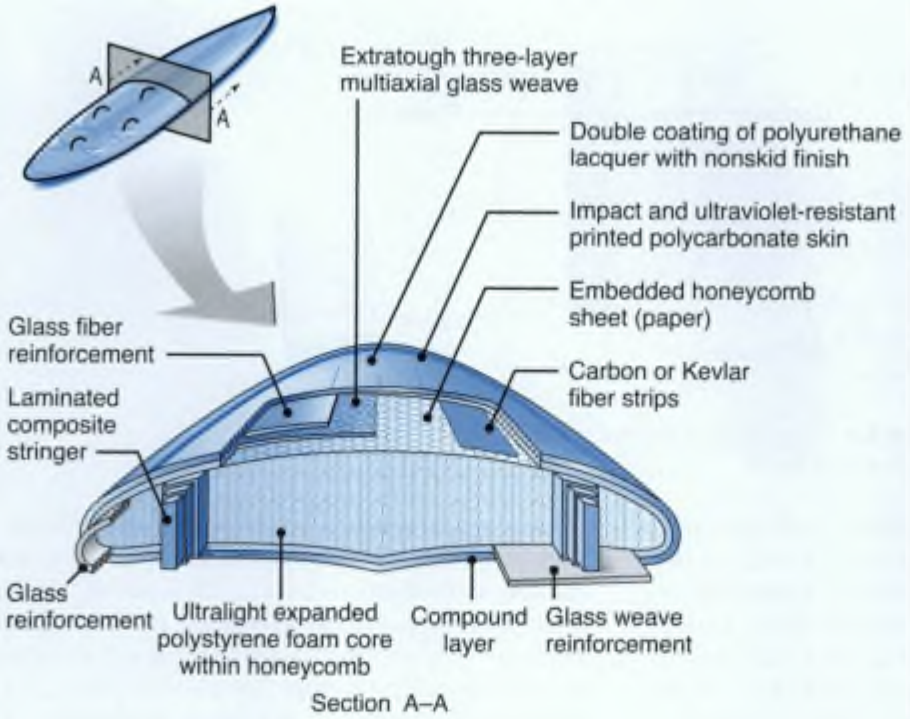

FIGURE 9.8 Cross-section of a composite sailboard, an example of advanced materials construction. *Source:* K. Easterling, *Tomorrow's Materials*, 2nd ed., Institute of Metals, 1990. Courtesy of Maney Publishing. www.maneypublishing.com.

lowering the costs involved due to their corrosion and (b) rollers for papermaking and similar industries, with lower deflections as compared to traditional steel rollers.

CASE STUDY 9.1 Composite Military Helmets and Body Armor

Personal protective equipment, in the form of body armor and composite helmets, have become widespread for military and police use. Body armor relies on high-strength woven fibers to prevent the penetration of projectiles. To stop a bullet, a composite material must first deform or flatten it, a process that occurs when the bullet's tip comes into contact with as many individual fibers of the composite as possible, without the fibers being pushed aside. The momentum associated with projectiles is felt by the user of the armor, but successful designs will contain bullets and shrapnel and thus prevent serious and fatal injuries.

There are two basic types of body armor: (a) *soft armor*, which relies upon several layers of high-strength, woven fibers, and is designed mainly to contain handgun bullets, and (b) *hard armor*, which uses a metal, ceramic, or polymer plate, in addition to the woven fiber, and is intended to provide protection against rifle rounds and shrapnel. A schematic of a body armor is shown in Fig. 9.9.

Several types of fiber meshes have been used in body armor applications. Different suppliers employ different combinations of fiber meshes, and may include additional layers to provide protection against blunt trauma. The first fiber used for flexible body armor was Kevlar 29 (an aramid), which has been improved through a number of versions. Other forms include Kevlar 49, Kevlar 129, and Kevlar Protera, where tensile strength

(*continued*)

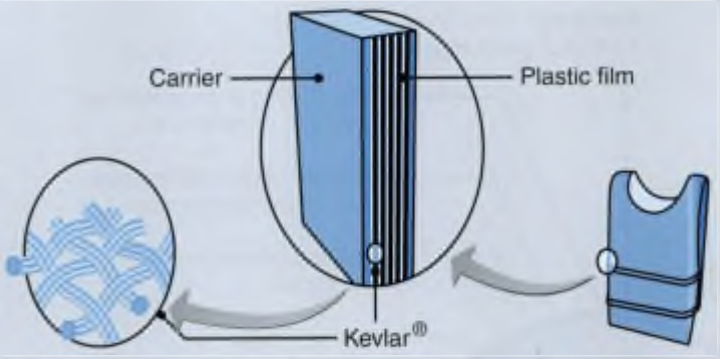

FIGURE 9.9 Schematic illustration of body armor, showing the layers of woven fibers.

and energy-absorbing capabilities have been improved through the development of advanced spinning processes to produce the fibers. Aramid fibers are used very commonly in flexible body armor. Honeywell also produces an aramid-fiber based body armor, but other designs, such as Twaron aramid fiber, use over a thousand finely spun filaments that interact with each other to dissipate the impact energy.

Spectra fiber is used to make a composite for use in body armor. A layer of Spectra Shield composite consists of two unidirectional layers of Spectra fiber, arranged to cross each other at 0° and 90° angles and held in place by a flexible resin. Both the fiber and resin layers are sealed between two thin sheets of polyethylene film, which is similar in appearance to plastic food wrap. Hard armor uses several designs, but typically it consists of steel, ceramic (usually aluminum oxide and silica), or polyethylene plates, strategically located to prevent penetration of ballistic particles to critical areas.

Designs currently being evaluated utilize fluids, with suspended nanoparticles of silica; at low strain rates, these fluids are inviscid and flow readily. At the high strain rates typical of ballistic particles, these fluids are very resistant to deformation and can provide additional protection (see also Section 2.2.7). The fluid is contained by the woven fiber mesh (acting like a sponge holding the fluid in place) and is contained by the outer fabric.

A composite military helmet also has been developed that, although weighing about the same as conventional manganese–steel helmets, covers more of the head and offers twice the ballistic and fragmentation protection. This helmet has a nonwoven fiber construction made with Spectra fibers in a thermosetting polymer matrix, which effectively stops the bullet by flattening it as it strikes the first layer of material.

Source: Courtesy of Pinnacle Armor, Allied Signal Corp., and CGS Gallet SA.

9.5 Metal-matrix Composites

Matrix materials in *metal-matrix composites* (MMC) are usually aluminum, aluminum–lithium alloy (lighter than aluminum), magnesium, copper, titanium, or superalloys (Fig. 9.10). Fiber materials are graphite, aluminum oxide, silicon carbide, boron, molybdenum, or tungsten. The elastic modulus of nonmetallic fibers ranges between 200 and 400 GPa, with tensile strengths in the range from 2000 to 3000 MPa. The advantages of a metal matrix over a polymer matrix are higher elastic modulus, toughness, ductility, and higher resistance to elevated temperatures; the limitations are higher density and a greater difficulty in processing the composite parts. Typical compositions and applications for MMC are given in Table 9.3.

FIGURE 9.10 Examples of metal-matrix composite parts. *Source:* Courtesy of 3M Speciality Materials Division.

TABLE 9.3

Metal-matrix Composite Materials and Applications

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

CASE STUDY 9.2 Aluminum-matrix Composite Brake Calipers

One of the trends in automobile design and manufacture is the increased effort toward lighter-weight designs in order to realize improved performance and/or fuel economy. This trend also can be seen in the development of MMC brake calipers. Traditional brake calipers are made from cast iron, and can weigh around 3 kg each in a small car and up to 14 kg in a truck. The cast-iron caliper could be redesigned completely, using aluminum to achieve weight savings, but that would require a larger volume since the nominal strength of aluminum is lower than the cast iron, and the space available between the wheel and rotor is very constrained.

A new brake caliper was designed, using an aluminum alloy locally reinforced with precast composite inserts using continuous ceramic fiber. The fiber is a nanocrystalline alumina, with a diameter of 10–12 μm and a fiber volume fraction of 65%. The fiber and composite properties are summarized

(*continued*)

in Table 9.4. Finite element analysis confirmed the placement and amount of reinforcement, leading to a design that exceeded minimum design requirements, and matched deflections of cast-iron calipers in a packaging-constrained environment. The new brake caliper is shown in Fig. 9.11. It has a weight savings of 50%, with the additional benefits of corrosion resistance and ease of recyclability.

TABLE 9.4

Summary of Fiber and Composite Properties for an Automotive Brake Caliper

Property	Alumina fiber	Alumina-reinforced composite material
Tensile strength	3.1 GPa	1.5 GPa
Elastic modulus	380 GPa	270 GPa
Density	3.9 g/cm^3	3.48 g/cm^3

FIGURE 9.11 Aluminum-matrix composite brake caliper using nanocrystalline alumina fiber reinforcement. *Source:* Courtesy of 3M Speciality Materials Division.

9.6 Ceramic-matrix Composites

Ceramic-matrix composites (CMC) are characterized by their resistance to high temperatures and corrosive environments. As described in Section 8.3.1, ceramics are strong and stiff; they resist high temperatures, but generally lack toughness. Matrix materials that retain their strength up to 1700°C are silicon carbide, silicon nitride, aluminum oxide, and mullite (a compound of aluminum, silicon, and oxygen). Carbon–carbon-matrix composites retain much of their strength up to 2500°C, although they lack oxidation resistance at high temperatures. Fiber materials are usually carbon and aluminum oxide. Applications of CMC include jet and automotive engine components, deep-sea mining equipment, pressure vessels, structural components, cutting tools, and dies for the extrusion and drawing of metals.

9.7 Other Composites

Composites also may consist of *coatings* of various types, applied on base metals or substrates (Chapter 34). Examples are:

- Plating of aluminum or other metals over plastics, generally for decorative purposes
- Enamels, for wear resistance, hardness, and decorative purposes
- Vitreous (glasslike) coatings on metal surfaces, for various functional or ornamental purposes

Composites are made into cutting tools and dies, such as cemented carbides and cermets. Other composites are grinding wheels, made of aluminum oxide, silicon carbide, diamond, or cubic-boron-nitride abrasive particles, all held together with various organic, inorganic, or metallic binders. A composite, used in machine-tool beds for some precision grinders (see Section 25.3.1), consists of granite particles in an epoxy matrix; it has high strength, good vibration-damping capacity (better than gray cast iron), and good frictional characteristics.

CASE STUDY 9.3 Composites in the Aircraft Industry

High fuel prices have significantly affected the operations of the aircraft industry; any design advantages that lead to increased efficiency or fuel economy continue to be aggressively pursued by aircraft manufacturers. One area where this effect is most dramatic is the increased composite content in commercial aircraft, as shown in Fig. 9.12.

In addition to the amount of composite materials used, there are a number of design innovations in the types and applications of composite materials, including:

- GLARE is a GLAss-REinforced aluminum, consisting of several layers of glass-fiber reinforced

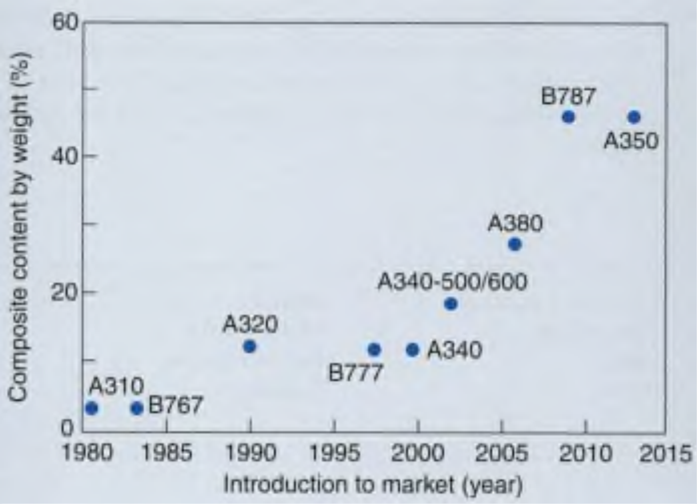

FIGURE 9.12 Composite content in selected commercial aircraft as a function of time (measured by date first introduced into the market). A = Airbus, B = Boeing.

(*continued*)

polymer and sandwiched between thin sheets of aluminum. It is used on the upper fuselage of the Airbus A380 and the leading edges of the tail of the plane, and has been credited with over 500 kg of weight savings, as compared to previously used materials. GLARE also provides improved fatigue strength and corrosion resistance.

- The Boeing 787 Dreamliner has an all-composite fuselage, constructed mainly from CFRP. In addition to weight savings, the fuselage is constructed in one piece and joined end to end, eliminating the need for an estimated 50,000 fasteners. Composites make up around 50% of the weight of the Dreamliner, as compared to 12% on the 777 aircraft, first introduced in 1994.

SUMMARY

- Composites are an important class of engineered materials, with numerous attractive properties. Three major categories are fiber-reinforced plastics, metal-matrix composites, and ceramic-matrix composites. They have a wide range of applications in the aircraft, aerospace, and transportation industries, sporting goods, and for structural components.
- In fiber-reinforced plastics, the fibers are usually glass, graphite, aramids, or boron. Polyester and epoxies commonly are used as the matrix material. These composites have particularly high toughness and high strength-to-weight and stiffness-to-weight ratios.
- In metal-matrix composites, the fibers are typically graphite, boron, aluminum oxide, silicon carbide, molybdenum, or tungsten. Matrix materials generally consist of aluminum, aluminum–lithium alloy, magnesium, copper, titanium, or superalloys.
- In ceramic-matrix composites, the fibers usually are carbon and aluminum oxide, and the matrix materials are silicon carbide, silicon nitride, aluminum oxide, carbon, or mullite (a compound of aluminum, silicon, and oxygen).
- In addition to the type and quality of the materials used, important factors in the structure and properties of composite materials are the size and length of the fibers, their volume percentage compared with that of the matrix, the strength of the bond at the fiber–matrix interface, and the orientation of the fibers in the matrix.

KEY TERMS

Advanced composites
Ceramic matrix
Composite materials
Delamination
Engineered materials
Fiber pullout
Fibers
Hybrid
Matrix
Metal matrix
Polymer matrix
Precursor
Pyrolysis
Reinforced plastics
Silane
Whiskers

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REVIEW QUESTIONS

9.1 Distinguish between composites and metal alloys.

9.2 Describe the functions of the matrix and the reinforcing fibers. What fundamental differences are there in the characteristics of the two materials?

9.3 Name the reinforcing fibers generally used to make composites. Which type of fiber is the strongest? Which type is the weakest?

9.4 What is the range in length and diameter of typical reinforcing fibers?

9.5 List the important factors that determine the properties of reinforced plastics.

9.6 Comment on the advantages and limitations of metal-matrix composites, reinforced plastics, and ceramic-matrix composites, respectively.

9.7 What are the most commonly used matrix materials? Why?

9.8 Describe the advantages of hybrid composites over other composites.

9.9 What material properties are improved by the addition of reinforcing fibers?

9.10 Describe the purpose of the matrix material.

9.11 What are the most common types of glass fibers?

9.12 Explain the difference between a carbon fiber and a graphite fiber.

9.13 How can a graphite fiber be made electrically and thermally conductive?

9.14 What is a whisker? What is the difference between a whisker and a fiber?

9.15 Describe the composition of boron fibers. Why are they heavy?

9.16 Give a succinct definition of fiber, yarn, and fabric, respectively.

QUALITATIVE PROBLEMS

9.17 How do you think the use of straw mixed with clay originally came about in making brick for dwellings?

9.18 What products have you personally seen that are made of reinforced plastics? How can you tell?

9.19 Describe applications that are not well suited for composite materials. Explain.

9.20 Is there a difference between a composite material and a coated material? Explain.

9.21 Identify metals and alloys that have strengths comparable to those of reinforced plastics.

9.22 What limitations or disadvantages do composite materials have? What suggestions would you make to overcome the limitations?

9.23 Give examples of composite materials other than those described in this chapter.

9.24 Explain why the behavior of the materials depicted in Fig. 9.5 is as shown.

9.25 Explain why fibers are so capable of supporting a major portion of the tensile load in composite materials.

9.26 Do metal-matrix composites have any advantages over reinforced plastics? Explain.

9.27 Give reasons for the development of ceramic-matrix composites. Name some applications, and explain why they should be effective.

9.28 Explain how you would go about determining the hardness of reinforced plastics and of composite materials. Are hardness measurements on these types of materials meaningful? Does the size of the indentation make any difference? Explain.

9.29 How would you go about trying to determine the strength of a fiber?

9.30 Glass fibers are said to be much stronger than bulk glass. Why is this so?

9.31 Describe situations in which a glass could be used as a matrix material.

9.32 When the American Plains states were settled, no trees existed for the construction of housing. Pioneers cut bricks from sod—basically, prairie soil as a matrix and grass and its root system as reinforcement. Explain why this approach was successful.

9.33 By incorporating small amounts of a blowing agent, it is possible to manufacture hollow polymer fibers with gas cores. List possible applications for such fibers.

9.34 Referring to Fig. 9.2c, would there be an advantage in using layers of cloth (woven fibers) instead of continuous fiber stacks without weaving? Explain.

9.35 Is it possible to design a composite material that has a Poisson's ratio of zero in a desired direction? Explain. Can a composite material be designed that has a thermal conductivity of zero in a desired direction? Explain.

QUANTITATIVE PROBLEMS

9.36 Calculate the average increase in the properties of the plastics given in Table 7.1 as a result of their reinforcement, and describe your observations.

9.37 In Example 9.1, what would be the percentage of the load supported by the fibers if their strength were 1000 MPa and the matrix strength were 200 MPa? What would be the answer if the fiber stiffness were doubled and the matrix stiffness were halved?

9.38 Calculate the percent increase in the mechanical properties of reinforced nylon from the data shown in Fig. 9.5.

9.39 Plot E/ρ and $E/\rho^{0.5}$ for the composite materials listed in Table 9.1, and compare your results with the properties of the materials described in Chapters 4 through 8. (See also Table 9.2.)

9.40 Calculate the stress in the fibers and in the matrix in Example 9.1. Assume that the cross-sectional area is 150 mm^2 and $P_c = 220$ kg.

9.41 Repeat the calculations in Example 9.1 if (a) Nextel 610 fiber is used and (b) Spectra 2000 is used.

9.42 Refer to the properties listed in Table 7.1. If acetal is reinforced with E-type glass fibers, what is the range of fiber content in glass-reinforced acetal?

9.43 Plot the elastic modulus and strength of an aluminum metal-matrix composite with high-modulus carbon fibers, as a function of fiber content.

9.44 For the data in Example 9.1, what should be the fiber content so that the fibers and the matrix fail simultaneously? Use an allowable fiber stress of 200 MPa and a matrix strength of 30 MPa.

9.45 It is desired to obtain a composite material with a target stiffness of 10 GPa. If a high strength carbon fiber is to be used, determine the required fiber volume if the matrix is (a) nylon, (b) polyester, (c) acetal, and (d) polyethylene.

9.46 A rectangular cantilever beam, 100 mm high, 20 mm wide, and 1 m long, is subjected to a concentrated load of 50 kg at its end. (a) Consider a polymer reinforced with high modulus carbon fibers, with a fiber volume ratio of $x = 10\%$. What is the maximum deflection of the beam if the matrix material is polyester? (b) Obtain the deflection of the beam if aluminum or steel was used, for the same beam dimensions. (c) What fiber volume ratio is needed to produce the same deflection as the aluminum or steel beams? (d) Determine the weight of the beams considered in parts (b) and (c), and compare them.

SYNTHESIS, DESIGN, AND PROJECTS

9.47 What applications for composite materials can you think of in addition to those given in Section 9.4? Why do you think your applications would be suitable for these materials?

9.48 Using the information given in this chapter, develop special designs and shapes for possible new applications of composite materials.

9.49 Would a composite material with a strong and stiff matrix and a soft and flexible reinforcement have any practical uses? Explain.

9.50 Make a list of products for which the use of composite materials could be advantageous because of their anisotropic properties.

9.51 Inspect Fig. 9.1 and explain what other components of an aircraft, including the cabin, could be made of composites.

9.52 Name applications in which both specific strength and specific stiffness are important.

9.53 What applications for composite materials can you think of in which high thermal conductivity would be desirable? Explain.

9.54 As with other materials, the mechanical properties of composites are obtained by preparing appropriate specimens and then testing them. Explain what problems you might encounter in preparing such specimens for testing in tension. Suggest methods for making appropriate specimens, including their shape and how they would be clamped into the jaws of testing machines.

9.55 Developments are taking place in techniques for three-dimensional reinforcement of composites. Describe (a) applications in which strength in the thickness direction of the composite is important and (b) your ideas on how to achieve this strength. Include simple sketches of the structure utilizing such reinforced plastics.

9.56 Design and describe a test method to determine the mechanical properties of reinforced plastics in their thickness direction. (Note, for example, that plywood is weak in its thickness direction.)

9.57 As described in this chapter, reinforced plastics can be adversely affected by the environment—in particular, moisture, chemicals, and temperature variations. Design and describe test methods to determine the mechanical properties of composite materials subjected to these environmental conditions.

9.58 Comment on your observations on the design of the sailboard illustrated in Fig. 9.8.

9.59 Make a survey of various sports equipment and identify the components made of composite materials. Explain the reasons for and the advantages of using composites in these specific applications.

9.60 Several material combinations and structures were described in this chapter. In relative terms, identify those that would be suitable for applications involving each of the following: (a) very low temperatures, (b) very high temperatures, (c) vibrations, and (d) high humidity.

9.61 Obtain a textbook on composite materials, and investigate the effective stiffness of a continuous fiber-reinforced polymer. Plot the stiffness of such a composite as a function of orientation with respect to the fiber direction.

9.62 It is possible to make fibers or whiskers with a varying cross-section, or a "wavy" fiber. What advantages would such fibers have?

9.63 Describe how you can produce some simple composite materials using raw materials that are available around a home. Explain.

9.64 *Gel spinning* is a specialized process used in making fibers with high strength or special properties. Search the technical literature, and write a brief paper on this subject.

9.65 Figure P9.65 shows a section of a three-dimensional weave that uses a binder yarn to tie layers of fibers together. Conduct a literature search, and determine the advantages and limitations of using three-dimensional weaves as reinforcements in composite materials.

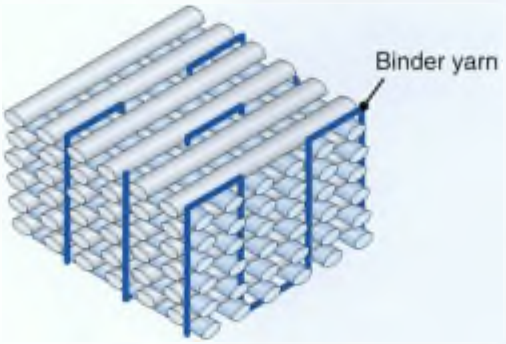

FIGURE P9.65

Metal-casting Processes and Equipment

PART II

As described throughout the rest of this book, several methods are available to shape metals into products. One of the oldest processes is **casting**, which basically involves pouring molten metal into a mold cavity. Upon solidification, the metal takes the shape of the cavity; two examples of cast parts are shown in Fig. II.1. Casting was first used around 4000 B.C. to make ornaments, arrowheads, and various other objects. A wide variety of products can be cast, and the process is capable of producing intricate shapes in one piece, including those with internal cavities, such as engine blocks. Figure II.2 shows cast components in a typical automobile, a product that was used in the introduction to Part I to illustrate the selection and use of a variety of materials. The common casting processes, developed over the years, are shown in Fig. II.3.

As in all manufacturing operations, each casting process has its own characteristics, applications, advantages, limitations, and costs involved. Casting is most often selected over other manufacturing methods because:

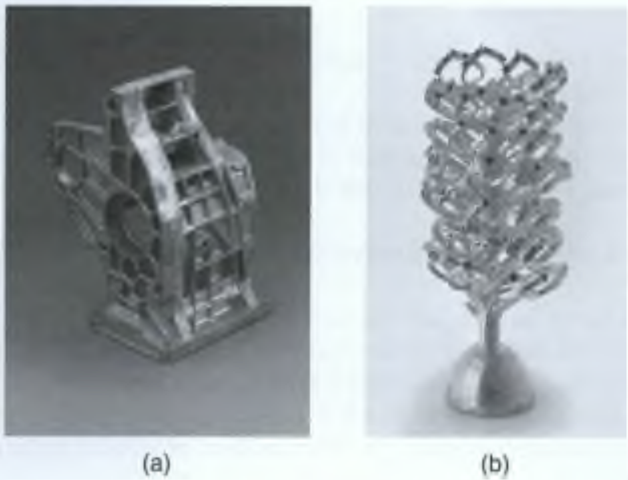

FIGURE II.1 Examples of cast parts. (a) A die-cast aluminum transmission housing. (b) A tree of rings produced through investment casting. *Source:* (b) Courtesy of Romanoff, Inc.

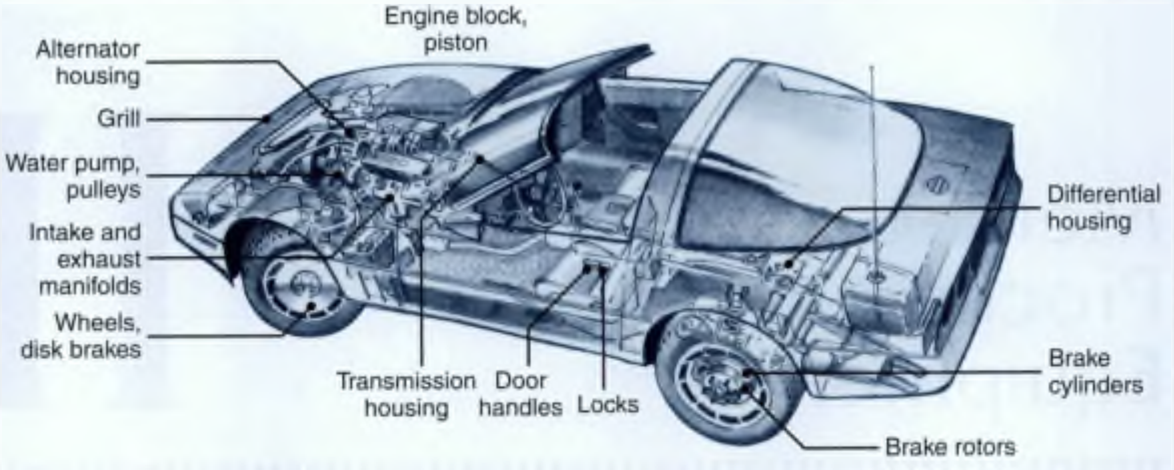

FIGURE II.2 Cast parts in a typical automobile.

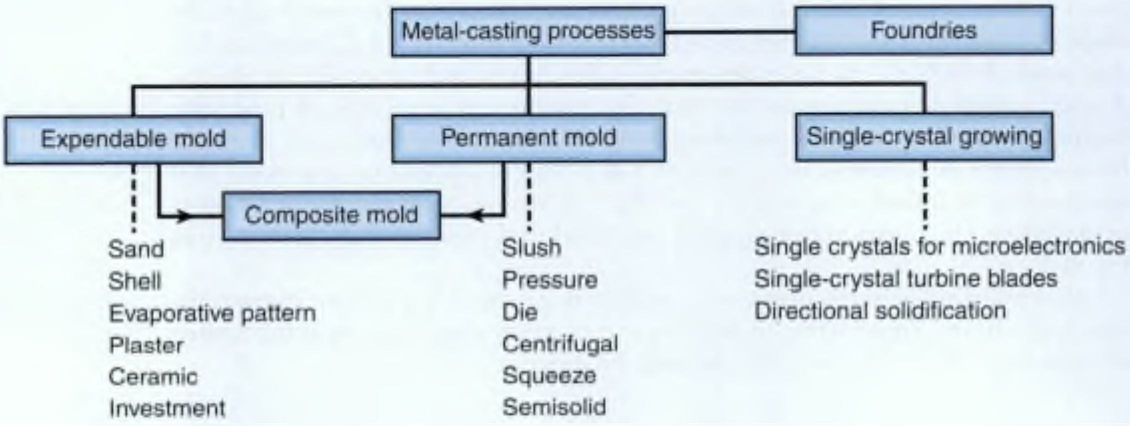

FIGURE II.3 Outline of metal-casting processes described in Part II.

- Casting can produce complex shapes and can incorporate internal cavities or hollow sections
- Very large parts can be produced in one piece
- Casting can utilize materials that are difficult or uneconomical to process by other means, such as hard metals that are difficult to machine or plastically deform
- The casting process can be competitive with other manufacturing processes

Almost all metals can be cast in, or nearly in, the final shape desired, often requiring only minor finishing operations. This capability places casting among the most important *net-shape manufacturing* technologies, along with net-shape forging (Chapter 14), stamping of sheet metal (Chapter 16), and powder metallurgy and metal-injection molding (Chapter 17). With modern processing techniques and control of chemical composition, mechanical properties of castings can equal those made by other processes.

Fundamentals of Metal Casting

CHAPTER 10

- First used about 6000 years ago, casting continues to be an important manufacturing process for producing very small, as well as very large and complex, parts.
- The first topic described is solidification of molten metals, including the differences between solidification of pure metals and alloys.
- Fluid flow in casting is then described, with Bernoulli's and the continuity equations being applied to establish a framework for analyzing molten metal flow through the cavities of a mold.
- The importance of turbulence versus laminar flow is introduced.
- Heat transfer and shrinkage of castings are also discussed, including Chvorinov's rule for solidification time.
- The chapter ends with a description of the causes of porosity in castings and common methods of reducing them to improve cast-metal properties.

EXAMPLE:

10.1 Introduction

The **casting** process basically involves (a) pouring molten metal into a mold, patterned after the part to be cast, (b) allowing it to solidify, and (c) removing the part from the mold. As with all other manufacturing processes, an understanding of the underlying science is essential for the production of good quality and economical parts, and for establishing proper techniques for mold design and casting practice.

Important considerations in casting operations are:

- Flow of the molten metal into the mold cavity, and design of gating systems or pathways for molten metal to fill the cavity
- Solidification and cooling of the metal in the mold
- Influence of the mold material

This chapter describes relationships among the many factors involved in casting. The flow of molten metal into the mold cavity is first described, in terms of mold design and fluid-flow characteristics. Solidification and cooling of metals in the mold are affected by several factors, including the metallurgical and thermal properties of the metal. The type of mold also has an important influence, because it affects the rate of cooling. The chapter concludes with a description of the factors influencing defect formation in castings.

Metal-casting processes, design considerations, and casting materials are described in Chapters 11 and 12. The casting of ceramics and plastics, which involves methods and procedures somewhat similar to those for metal, are described in Chapters 18 and 19, respectively.

10.2 Solidification of Metals

After molten metal is poured into a **mold**, a sequence of events takes place during solidification and cooling of the metal to ambient temperature. These events greatly influence the size, shape, uniformity, and chemical composition of the grains formed throughout the casting, which, in turn, influence the overall properties of the casting. The significant factors affecting these events are the type of metal cast, the thermal properties of both the metal and the mold, the geometric relationship between volume and surface area of the casting, and the shape of the mold.

10.2.1 Pure Metals

Because a pure metal has a clearly defined melting, or freezing, point, it solidifies at a constant temperature, as shown in Fig. 10.1. Pure aluminum, for example, solidifies at 660°C, iron at 1537°C, and tungsten at 3410°C. (See also Table 3.1.) After the temperature of the molten metal drops to its freezing point, its temperature remains constant while the *latent heat of fusion* is given off. The *solidification front* (the solid–liquid interface) moves through the molten metal from the mold walls in toward the center. The solidified metal, called the *casting*, is then removed from the mold and allowed to cool to ambient temperature.

As shown in Fig. 10.1b and described in greater detail in Section 10.5.2, metals shrink while cooling and, generally, also shrink when they solidify. This is an

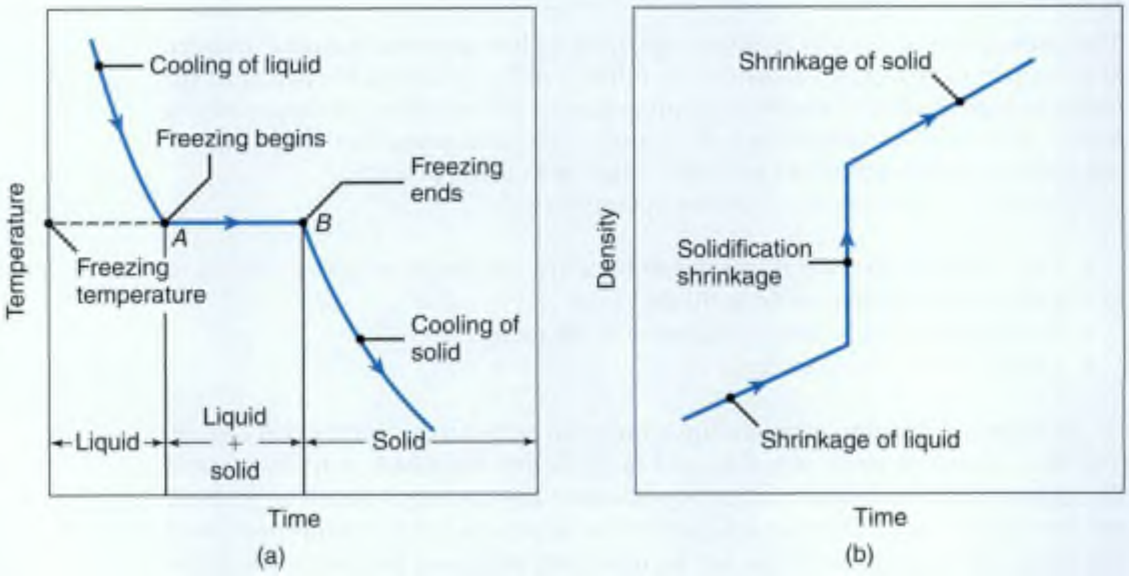

FIGURE 10.1 (a) Temperature as a function of time for the solidification of pure metals; note that freezing takes place at a constant temperature. (b) Density as a function of time.

important consideration, because shrinkage can lead to microcracking and the associated porosity, which can adversely affect the mechanical properties of the casting.

As an example of the grain structure that develops in a casting, Fig. 10.2a shows a cross-section of a box-shaped mold. At the mold walls, which are at ambient temperature at first, or typically are much cooler than the molten metal, the metal cools rapidly, producing a solidified **skin**, or *shell*, of fine equiaxed grains. The grains generally grow in a direction opposite to that of the heat transfer out through the mold.

Those grains that have favorable orientation grow preferentially, and are called **columnar grains** (Fig. 10.3). Those grains that have substantially different orientations are blocked from further growth. As the driving force of the heat transfer decreases away from the mold walls, the grains become equiaxed and coarse. This sequence of grain development is known as **homogenous nucleation**, meaning that the grains (crystals) grow upon themselves, starting at the mold wall.

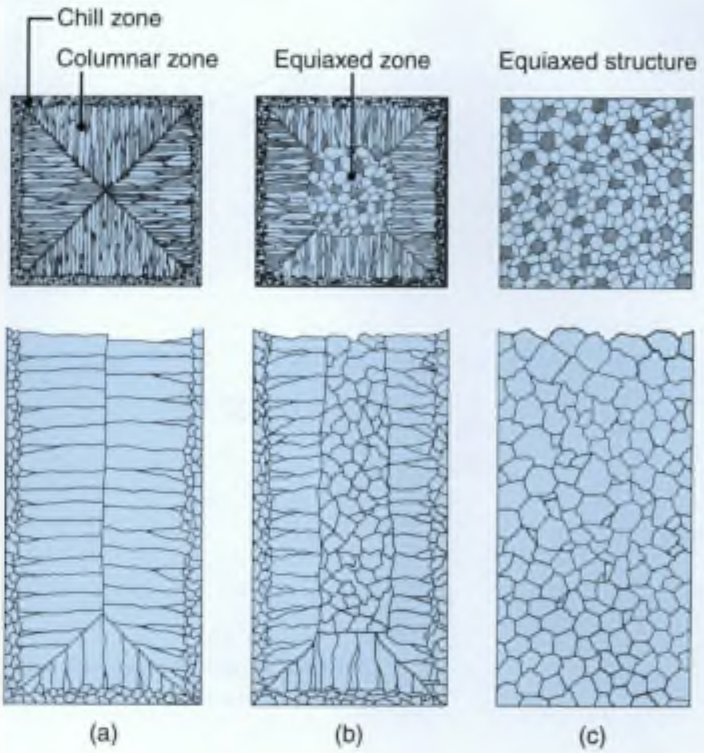

FIGURE 10.2 Schematic illustration of three cast structures of metals solidified in a square mold: (a) pure metals; (b) solid–solution alloys; and (c) structure obtained by using nucleating agents. *Source:* After G.W. Form, J.F. Wallace, J.L. Walker, and A. Cibula.

10.2.2 Alloys

Solidification in alloys begins when the temperature drops below the *liquidus*, T_L, and is complete when it reaches the *solidus*, T_S (Fig. 10.4). Within this temperature range, the alloy is in a *mushy* or *pasty* state, consisting of **columnar dendrites** (from the Greek *dendron*, meaning "akin to," and *drys*, meaning "tree"). Note the presence of liquid metal between the dendrite *arms*.

Dendrites have three-dimensional arms and branches (*secondary arms*), which eventually interlock, as can be seen in Fig. 10.5. The study of dendritic structures, although complex, is important, because such structures can contribute to detrimental factors, such as compositional variations, segregation, and microporosity within a cast part.

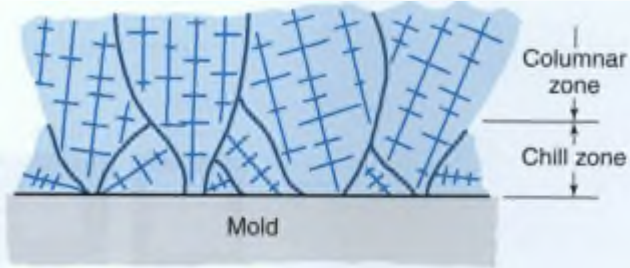

FIGURE 10.3 Development of a preferred texture at a cool mold wall; note that only favorably oriented grains grow away from the surface of the mold surface.

The width of the **mushy zone**, where both liquid and solid phases are present, is an important factor during solidification. This zone is described in terms of a temperature difference, known as the **freezing range**, as

$$\text{Freezing range} = T_L - T_S. \qquad (10.1)$$

It can be seen in Fig. 10.4 that pure metals have a freezing range that approaches zero, and that the solidification front moves as a plane without developing a mushy zone. Eutectics (Section 4.3) solidify in a similar manner, with an essentially plane

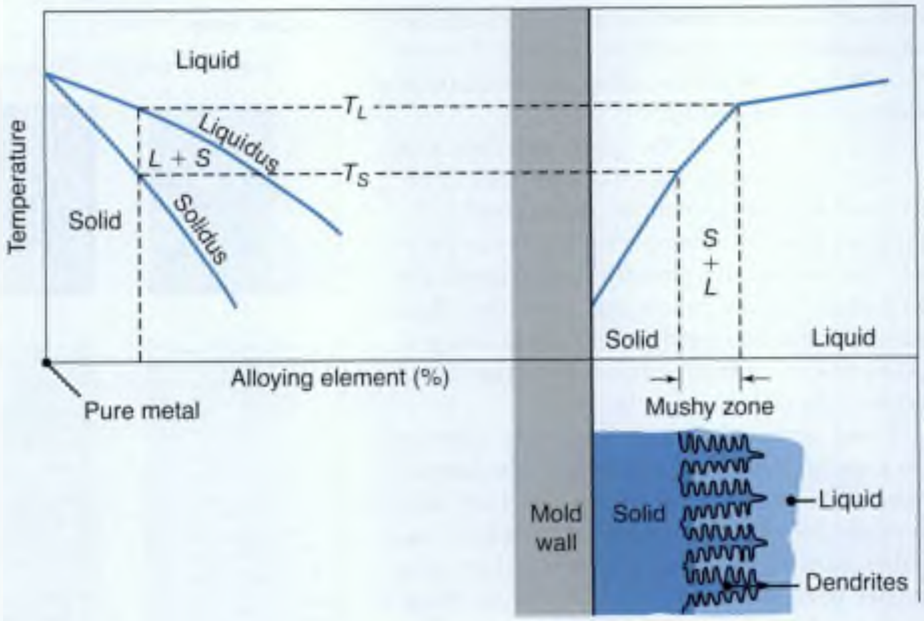

FIGURE 10.4 Schematic illustration of alloy solidification and temperature distribution in the solidifying metal; note the formation of dendrites in the mushy zone.

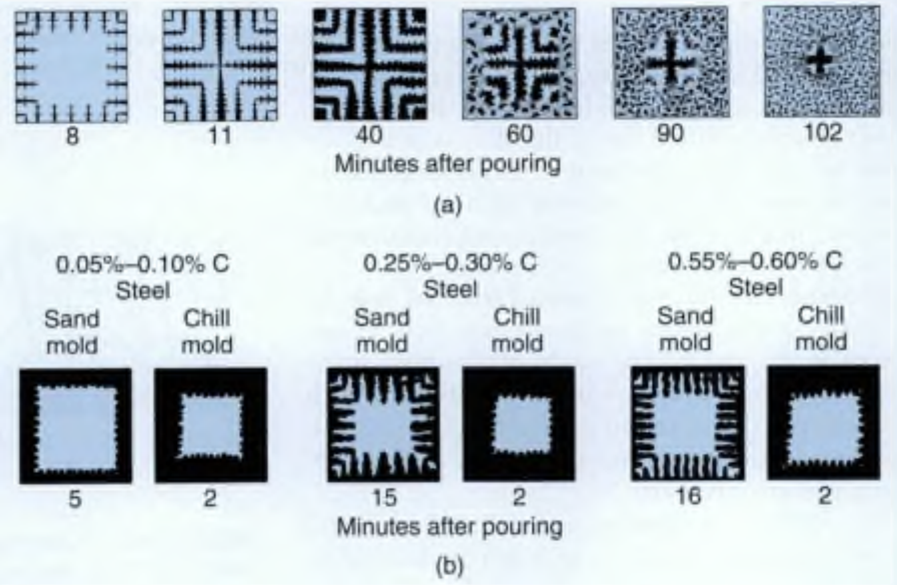

FIGURE 10.5 (a) Solidification patterns for gray cast iron in a 180-mm square casting. Note that after 11 min of cooling, dendrites reach each other, but the casting is still mushy throughout; it takes about 2 h for this casting to solidify completely. (b) Solidification of carbon steels in sand and chill (metal) molds; note the difference in solidification patterns as the carbon content increases. *Source:* After H.F. Bishop and W.S. Pellini.

front. The structure developed upon solidification depends on the composition of the eutectic. In alloys with a nearly symmetrical phase diagram (see Fig. 4.4), the structure is generally lamellar, with two or more solid phases present, depending on the alloy system. When the volume fraction of the minor phase of the alloy is less than about 25%, the structure generally becomes fibrous. These conditions are particularly significant for cast irons.

For alloys, a *short freezing range* generally involves a temperature difference of less than 50°C, and for a *long freezing range*, more than 110°C. Ferrous castings generally have narrow mushy zones, whereas aluminum and magnesium alloys have wide mushy zones. Consequently, these alloys are in a mushy state throughout most of their solidification process.

Effects of Cooling Rates. Slow cooling rates, on the order of 10^2 K/s, or long local solidification times, result in *coarse* dendritic structures, with large spacing between dendrite arms. For higher cooling rates, on the order of 10^4 K/s, or for short local solidification times, the structure becomes *finer*, with smaller dendrite arm spacing. For still higher cooling rates, on the order of from 10^6 to 10^8, the structures developed are *amorphous*, as described in Section 6.14.

The structures developed and the resulting grain size have an influence on the properties of the casting. As grain size decreases, the strength and ductility of the cast alloy increase, microporosity (*interdendritic shrinkage voids*) in the casting decreases, and the tendency for the casting to crack (*hot tearing*, see Fig. 10.12) during solidification decreases. Lack of uniformity in grain size and grain distribution result in castings that have *anisotropic properties*.

A criterion describing the kinetics of the liquid–solid interface is the ratio G/R, where G is the *thermal gradient* and R is the *rate* at which the interface moves. Typical values for G range from 10^2 to 10^3 K/m, and for R the range is from 10^{-3} to 10^{-4} m/s. Dendritic-type structures (Figs. 10.6a and b) typically have a G/R ratio in the range from 10^5 to 10^7, whereas ratios of 10^{10} to 10^{12} produce a plane front, nondendritic liquid–solid interface (Fig. 10.7).

10.2.3 Structure–property Relationships

Because all castings are expected to possess certain properties to meet design and service requirements, the relationships between properties and the structures developed

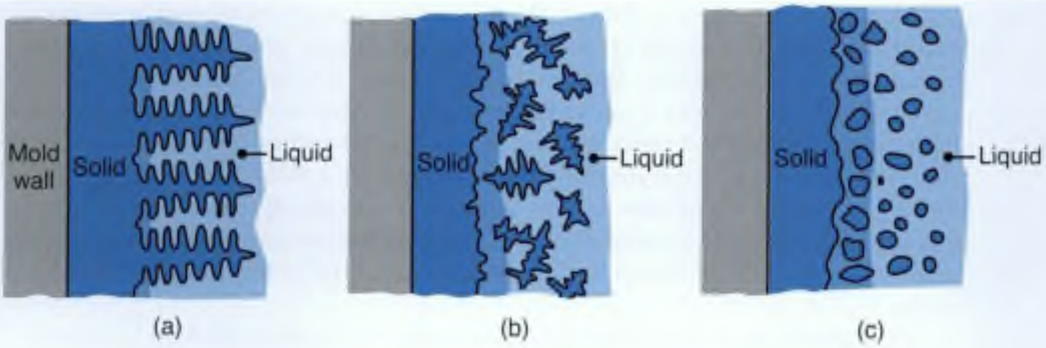

FIGURE 10.6 Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. *Source:* Courtesy of D. Apelian.

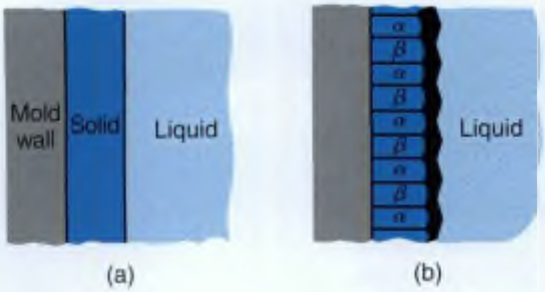

FIGURE 10.7 Schematic illustration of cast structures in (a) plane front, single phase, and (b) plane front, two phase. *Source:* Courtesy of D. Apelian.

during solidification are important aspects of casting. This section describes these relationships in terms of dendrite morphology and the concentration of alloying elements in various regions within the casting.

The compositions of dendrites and the liquid metal are given by the *phase diagram* of the particular alloy. When the alloy is cooled very slowly, each dendrite develops a uniform composition. However, under the normally higher cooling rates encountered in practice, **cored dendrites** are formed. These dendrites have a surface composition different from that at their centers, a difference referred to as *concentration gradient.* The surface of the dendrite has a higher concentration of alloying elements than at its core, due to solute rejection from the core toward the surface during solidification of the dendrite (**microsegregation**). The darker shading in the interdendritic liquid near the dendrite roots shown in Fig. 10.6 indicates that these regions have a higher solute concentration. Microsegregation in these regions is much more pronounced than in others.

There are several types of **segregation.** In contrast to microsegregation, **macrosegregation** involves differences in composition throughout the casting itself. In situations where the solidification front moves away from the surface of a casting as a plane (Fig. 10.7), lower melting-point constituents in the solidifying alloy are driven toward the center (**normal segregation**). Consequently, such a casting has a higher concentration of alloying elements at its center than at its surfaces. In dendritic structures, such as those found in solid–solution alloys (Fig. 10.2b), the opposite occurs; that is, the center of the casting has a lower concentration of alloying elements (**inverse segregation**) than does at its surface. The reason is that the liquid metal (having a higher concentration of alloying elements) enters the cavities developed from solidification shrinkage in the dendrite arms, which have solidified sooner.

Another form of segregation is due to gravity. **Gravity segregation** involves a process whereby higher-density inclusions or compounds sink while lighter elements (such as antimony in an antimony–lead alloy) float to the surface.

A typical cast structure of a solid–solution alloy, with an inner zone of equiaxed grains, is shown in Fig. 10.2b. This inner zone can be extended throughout the casting, as shown in Fig. 10.2c, by adding an **inoculant** (*nucleating agent*) to the alloy. The inoculant induces nucleation of the grains throughout the liquid metal (**heterogeneous nucleation**).

Because of the presence of *thermal gradients* in a solidifying mass of liquid metal, and due to gravity and the resultant density differences, *convection* has a strong influence on the structures developed. Convection involves heat transfer by the movement of matter, and in a casting it usually is associated with the flow of the liquid metal. Convection promotes the formation of an outer chill zone, refines grain size, and accelerates the transition from columnar to equiaxed grains. The structure shown in Fig. 10.6b also can be obtained by increasing convection within the liquid metal, whereby dendrite arms separate (**dendrite multiplication**). Conversely, reducing or eliminating convection results in coarser and longer columnar dendritic grains.

The dendrite arms are not particularly strong and can be broken up by agitation or mechanical vibration in the early stages of solidification (as in **semisolid metal forming** and **rheocasting,** described in Section 11.4.7). This process results in finer grain size, with equiaxed nondendritic grains distributed more uniformly throughout the casting (Fig. 10.6c). A side benefit is the *thixotropic* behavior of alloys (that is, the viscosity decreases when the liquid metal is agitated), leading to improved castability of the metal. Another form of semisolid metal forming is **thixotropic casting**, where a solid billet is first heated to a semisolid state and then injected into a die-casting mold (Section 11.4.5).

10.3 Fluid Flow

To emphasize the importance of fluid flow in casting, consider a basic gravity casting system, as shown in Fig. 10.8. The molten metal is poured through a **pouring basin** or **cup**; it then flows through the **gating system** (consisting of sprue, runners, and gates) into the mold cavity. As also illustrated in Fig. 11.3, the **sprue** is a tapered vertical channel through which the molten metal flows downward in the mold. **Runners** are the channels that carry the molten metal from the sprue into the mold cavity or connect the sprue to the **gate** (that portion of the runner through which the molten metal enters the mold cavity). **Risers**, also called **feeders**, serve as reservoirs of molten metal to supply any molten metal necessary to prevent porosity due to shrinkage during solidification.

Although such a gating system appears to be relatively simple, successful casting requires proper design and control of the solidification process to ensure adequate fluid flow in the system. For example, an important function of the gating system in sand casting is to trap contaminants (such as oxides and other inclusions) and remove them from the molten metal, by having the contaminants adhere to the walls of the gating system, thereby preventing them from reaching the mold cavity. Furthermore, a properly designed gating system helps avoid or minimize such problems as premature cooling, turbulence, and gas entrapment. Even before it reaches the mold cavity, the molten metal must be handled carefully to avoid the formation of oxides on molten-metal surfaces from exposure to the environment or the introduction of impurities into the molten metal.

Two basic principles of fluid flow are relevant to gating design: Bernoulli's theorem and the law of mass continuity.

Bernoulli's Theorem. This theorem is based on the principle of the conservation of energy, and relates pressure, velocity, the elevation of the fluid at any location in the system, and the frictional losses in a system that is full of liquid. The Bernoulli equation is

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant}, \tag{10.2}$$

where h is the elevation above a certain reference level, p is the pressure at that elevation, v is the velocity of the liquid at that elevation, ρ is the density of the fluid (assuming that it is incompressible), and g is the gravitational constant.

Conservation of energy requires that, at a particular location in the system, the following relationship be satisfied:

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f, \tag{10.3}$$

where the subscripts 1 and 2 represent two different locations in the system and f represents the frictional loss in the liquid as it travels through the system. The frictional loss includes

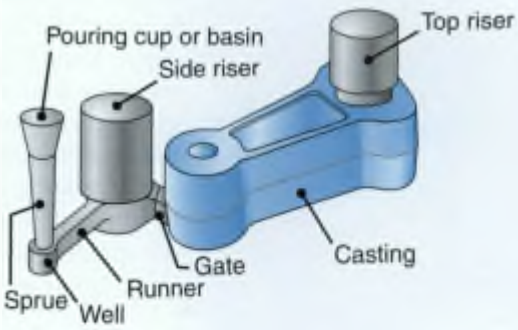

FIGURE 10.8 Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification.

such factors as energy loss at the liquid–mold wall interfaces and turbulence in the liquid.

Mass Continuity. The law of mass continuity states that, for incompressible liquids and in a system with impermeable walls, the rate of flow is constant. Thus,

$$Q = A_1 v_1 = A_2 v_2, \tag{10.4}$$

where Q is the volume rate of flow (such as m^3/s), A is the cross-sectional area of the liquid stream, and v is the average velocity of the liquid in that cross-section. The subscripts 1 and 2 refer to two different locations in the system. According to this law, the flow rate must be maintained everywhere in the system. The wall permeability is important, because otherwise some liquid will escape through the walls (as occurs in sand molds); thus, the flow rate will decrease as the liquid moves through the system. Coatings often are used to inhibit such behavior in sand molds. A small amount of permeability is useful to allow escape of gases and can aid in heat transfer.

Sprue Design. An application of the Bernoulli and mass continuity equations is the traditional tapered design of sprues shown in Fig. 10.8. Note that in a free-falling liquid (such as water from a faucet), the cross-sectional area of the stream decreases as the liquid gains velocity downward. Thus, if a sprue has a constant cross-sectional area and molten metal is poured into it, regions can develop where the liquid loses contact with the sprue walls. As a result, **aspiration** (a process whereby air is drawn in or entrapped in the liquid) may take place.

One of two basic alternatives is used to prevent aspiration: (a) A tapered sprue is used to prevent molten metal separation from the sprue wall or (b) straight-sided sprues are supplied with a **choking** mechanism at the bottom, consisting of either a choke core or a runner choke, as shown in Fig. 11.3. The choke slows the flow sufficiently to prevent aspiration in the sprue.

Video Solution 10.1 Design of a Sprue

The specific shape of a tapered sprue that prevents aspiration can be determined from Eqs. (10.3) and (10.4). Assuming that the pressure at the top of the sprue is equal to the pressure at the bottom, and that there are no frictional losses, the relationship between height and cross-sectional area at any point in the sprue is given by the parabolic relationship

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}, \tag{10.5}$$

where, for example, the subscript 1 denotes the top of the sprue and 2 denotes the bottom. The distances h_1 and h_2 are measured from the liquid level in the pouring cup or basin (Fig. 10.8), so that h_2 is larger than h_1. Moving downward from the top, the cross-sectional area of the sprue must therefore decrease. The area at the bottom of the sprue, A_2, is selected to allow for desired flow rates, as discussed below, and the profile produced is according to Eq. (10.5).

Depending on the assumptions made, expressions other than Eq. (10.5) also can be obtained. For example, assume a certain molten-metal velocity, V_1, at the top of the sprue; then, using Eqs. (10.3) and (10.4), an expression can be obtained for the ratio A_1/A_2 as a function of h_1, h_2, and V_1.

Modeling. Another application of the foregoing equations is in the *modeling of mold filling*. For example, consider the situation shown in Fig. 10.8 where molten metal is poured into a pouring cup or basin; it flows through a sprue to a runner and a gate, and fills the mold cavity. If the pouring basin has a much larger cross-sectional area than the sprue bottom, then the velocity of the molten metal at the top of the pouring basin is very low and can be taken to be zero. If frictional losses are due to a viscous dissipation of energy, then f in Eq. (10.3) can be taken to be a function of the vertical distance, and is often approximated as a linear function. The velocity of the molten metal leaving the gate is obtained from Eq. (10.3) as

$$v = c\sqrt{2gh},$$

where h is the distance from the sprue base to the liquid metal height and c is a friction factor. For frictionless flow, c equals unity, and for flows with friction, c is always between 0 and 1. The magnitude of c varies with mold material, runner layout, and channel size, and can include energy losses due to turbulence, as well as viscous effects.

If the liquid level has reached a height of x at the gate, then the gate velocity is

$$v = c\sqrt{2g}\sqrt{h-x}.$$

The flow rate through the gate will then be the product of this velocity and the gate area, according to Eq. (10.4). The shape of the casting will determine the height as a function of time. Integrating Eq. (10.4) gives the mean fill time and flow rate, and dividing the casting volume by this mean flow rate gives the mold fill time.

Simulation of mold filling assists designers in the specification of the runner diameter, as well as the size and number of sprues and pouring basins. To ensure that the runners stay open, the fill time must be a small fraction of the solidification time, but the velocity should not be so high as to erode the mold material (referred to as *mold wash*) or to result in too high of a **Reynolds number** (see below); otherwise, turbulence and associated air entrainment results. Several computational tools are now available to evaluate gating designs and assist in the sizing of components, such as Magmasoft, ProCast, Quikcast, SolidCast, Star-cast, SutCast, and PASSAGE/Powercast.

Flow Characteristics. An important consideration of fluid flow in gating systems is the presence of **turbulence**, as opposed to the *laminar flow* of fluids. Turbulence is flow that is highly chaotic; in casting systems such flow can lead to aspiration. The **Reynolds number**, Re, is used to quantify this aspect of fluid flow; it represents the ratio of the *inertia* to the *viscous* forces in fluid flow, and is defined as

$$\mathrm{Re} = \frac{vD\rho}{\eta}, \tag{10.6}$$

where v is the velocity of the liquid, D is the diameter of the channel, and ρ and η are the density and viscosity of the liquid, respectively.

The higher the Reynolds number, the greater the tendency for turbulent flow to occur. In gating systems, Re typically ranges from 2000 to 20,000, where a value of up to 2000 represents laminar flow. Between 2000 and 20,000, it represents a mixture of laminar and turbulent flow; such a mixture generally is regarded as harmless in gating systems. However, Re values in excess of 20,000 represent severe turbulence, resulting in significant air entrainment and the formation of *dross* (the scum that forms on the surface of molten metal), from the reaction of the liquid metal with air and other gases. Techniques for minimizing turbulence generally involve avoidance of sudden changes in local flow direction and in the geometry of channel cross-sections in gating system design.

Dross or slag can be eliminated only by *vacuum casting* (Section 11.4.2). Conventional atmospheric casting mitigates dross or slag by (a) skimming, (b) using properly

Video Solution 10.2 Reynolds Number in Gating Systems designed pouring basins and runner systems, or (c) using filters, which also can eliminate turbulent flow in the runner system. Filters usually are made of ceramics, mica, or fiberglass; their proper location and placement are important for effective filtering of dross and slag.

10.4 Fluidity of Molten Metal

The capability of molten metal to fill mold cavities is called *fluidity*, which consists of two basic factors: (1) characteristics of the molten metal and (2) casting parameters. Although complex, the term **castability** generally is used to describe the ease with which a metal can be cast to produce a part with good quality. Castability includes not only fluidity, but the nature of casting practices as well.

The following characteristics of molten metal influence fluidity:

1. Viscosity. As viscosity and its sensitivity to temperature increase, fluidity decreases.

2. Surface Tension. A high surface tension of the liquid metal reduces fluidity. Because of this, oxide films on the surface of the molten metal have a significant adverse effect on fluidity; for example, an oxide film on the surface of pure molten aluminum triples the surface tension.

3. Inclusions. Because they are insoluble, inclusions can have a significant adverse effect on fluidity. This effect can be verified by observing the viscosity of a liquid (such as oil) with and without sand particles in it; the liquid with sand in it has a higher viscosity and, hence, lower fluidity.

4. Solidification Pattern of the Alloy. The manner in which solidification takes place (Section 10.2) can influence fluidity. Moreover, fluidity is inversely proportional to the freezing range: The shorter the range (as in pure metals and eutectics), the higher the fluidity. Conversely, alloys with long freezing ranges (such as solid–solution alloys) have lower fluidity.

The following casting parameters influence fluidity and also influence the fluid flow and thermal characteristics of the system:

1. Mold Design. The design and dimensions of the sprue, runners, and risers all influence fluidity.

2. Mold Material and Its Surface Characteristics. The higher the thermal conductivity of the mold and the rougher its surfaces, the lower the fluidity of the molten metal. Although heating the mold improves fluidity, it slows down solidification of the metal; thus, the casting develops coarse grains and hence has lower strength.

3. Degree of Superheat. *Superheat* (defined as the increment of temperature of an alloy above its melting point) improves fluidity by delaying solidification. The **pouring temperature** often is specified instead of the degree of superheat, because it can be specified more easily.

4. Rate of Pouring. The slower the rate of pouring molten metal into the mold, the lower the fluidity, because of the higher rate of cooling when poured slowly.

5. Heat Transfer. This factor directly affects the viscosity of the liquid metal (see below).

10.4.1 Tests for Fluidity

Several tests have been developed to quantify fluidity, although none is accepted universally. In one such common test, the molten metal is made to flow along a channel that is at room temperature (Fig. 10.9); the distance the metal flows before it solidifies and stops flowing is a measure of its fluidity. Obviously, this length is a function of the thermal properties of the metal and the mold, as well as of the design of the channel. Still, such fluidity tests are useful and simulate casting situations to a reasonable degree.

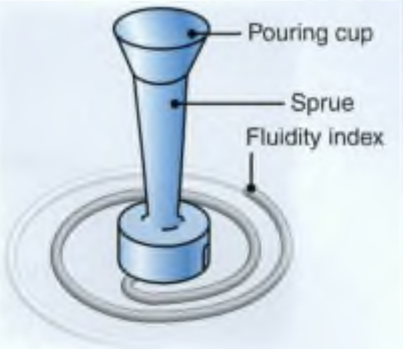

FIGURE 10.9 A test method for fluidity using a spiral mold. The fluidity index is the length of the solidified metal in the spiral passage; the greater the length of the solidified metal, the greater is the metal's fluidity.

10.5 Heat Transfer

The heat transfer during the complete cycle (from pouring, to solidification, and to cooling to room temperature) is another important consideration in metal casting. Heat flow at different locations in the system is a complex phenomenon and depends on several factors relating to the material cast, the mold, and process parameters. For instance, in casting thin sections, the metal flow rates must be high enough to avoid premature chilling and solidification. On the other hand, the flow rate must not be so high as to cause excessive turbulence—with its detrimental effects on the casting process.

A typical temperature distribution at the mold liquid–metal interface is shown in Fig. 10.10. Heat from the liquid metal is given off through the mold wall and to the surrounding air. The temperature drop at the air–mold and mold–metal interfaces is caused by the presence of boundary layers and imperfect contact at these interfaces. The shape of the curve depends on the thermal properties of the molten metal and the mold.

10.5.1 Solidification Time

During the early stages of solidification, a thin skin begins to form at the relatively cool mold walls, and as time passes, the thickness of the skin increases (Fig. 10.11). With flat mold walls, the thickness is proportional to the square root of time; thus, doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker.

The **solidification time** is a function of the volume of a casting and its surface area (*Chvorinov's rule*):

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n, \qquad (10.7)$$

where C is a constant that reflects (a) the mold material, (b) the metal properties (including latent heat), and (c) the temperature. The parameter n has a value between 1.5 and 2, but usually is taken as 2. Thus, a large solid sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller solid sphere. The reason for this is that the volume of a sphere is proportional to the cube of its diameter, whereas the surface area is proportional to the square of its diameter.

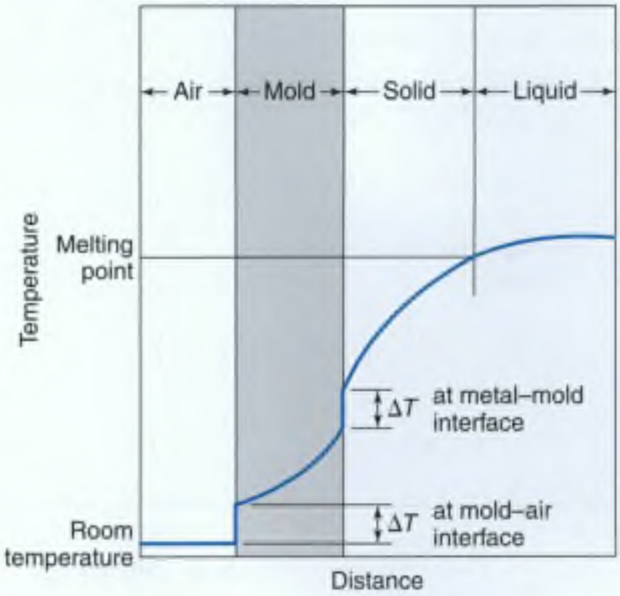

FIGURE 10.10 Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting.

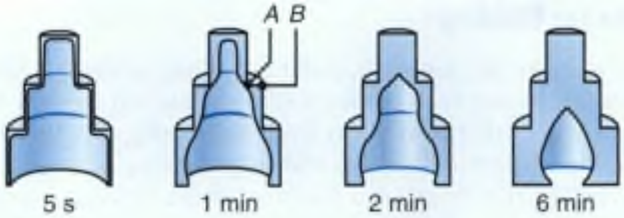

FIGURE 10.11 Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called *slush casting*, which is based on this principle. *Source:* After H.F. Taylor, J. Wulff, and M.C. Flemings.

Video Solution 10.3 Application of Chvorinov's Rule

Similarly, it can be shown that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume (see Example 10.1).

The effects of mold geometry and elapsed time on skin thickness and shape are shown in Fig. 10.11. As illustrated, the unsolidified molten metal has been poured from the mold at time intervals ranging from 5 s to 6 min. Note that (as expected) the skin thickness increases with elapsed time, and that the skin is thinner at internal angles (location *A* in the figure) than at external angles (location *B*). The latter condition is caused by slower cooling at internal angles than at external angles.

EXAMPLE 10.1 **Solidification Times for Various Shapes**

Given: Three metal pieces being cast have the same volume, but different shapes: One is a sphere, one a cube, and the other a cylinder with its height equal to its diameter. Assume that $n = 2$.

Find: Which piece will solidify the fastest, and which one the slowest?

Solution: The volume of the piece is taken as unity. Thus from Eq. (10.7),

$$\text{Solidification time} \propto \frac{1}{(\text{Surface area})^2}.$$

The respective surface areas are:

Sphere:

$$V = \left(\frac{4}{3}\right)\pi r^3, \quad r = \left(\frac{3}{4\pi}\right)^{1/3},$$

$$A = 4\pi r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.84.$$

Cube:

$$V = a^3, \quad a = 1, \quad \text{and} \quad A = 6a^2 = 6.$$

Cylinder:

$$V = \pi r^2 h = 2\pi r^3, \qquad r = \left(\frac{1}{2\pi}\right)^{1/3},$$

$$A = 2\pi r^2 + 2\pi r h$$

$$= 6\pi r^2 = 6\pi\left(\frac{1}{2\pi}\right)^{2/3} = 5.54.$$

The respective solidification times are

$$t_{\text{sphere}} = 0.043C, \quad t_{\text{cube}} = 0.028C,$$
$$t_{\text{cylinder}} = 0.033C.$$

Hence, the cube-shaped piece will solidify the fastest, and the spherical piece will solidify the slowest.

10.5.2 Shrinkage

Because of their thermal expansion characteristics, metals usually shrink (contract) during solidification and while cooling to room temperature. *Shrinkage*, which causes dimensional changes and sometimes warping and cracking, is the result of the following three sequential events:

1. Contraction of the molten metal as it cools prior to its solidification
2. Contraction of the metal during phase change from liquid to solid
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature

The largest shrinkage occurs during the phase change of the material from liquid to solid, but this can be reduced or eliminated through the use of risers or pressure-feeding of molten metal. The amount of contraction during the solidification of various metals is shown in Table 10.1; note that some metals (such as gray cast iron) expand. The reason is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal. Shrinkage, especially that due to thermal contraction, is further discussed in Section 12.2.1 in connection with design considerations in casting.

TABLE 10.1

Volumetric Solidification Contraction or Expansion for Various Cast Metals

Contraction (%)		Expansion (%)	
Aluminum	7.1	Bismuth	3.3
Zinc	6.5	Silicon	2.9
Al–4.5% Cu	6.3	Gray iron	2.5
Gold	5.5		
White iron	4–5.5		
Copper	4.9		
Brass (70–30)	4.5		
Magnesium	4.2		
90% Cu–10% Al	4		
Carbon steels	2.5–4		
Al–12% Si	3.8		
Lead	3.2		

10.6 Defects

Various defects can develop during manufacturing, depending on such factors as the quality of raw materials, casting design, and control of processing parameters. While some defects affect only the appearance, others can have major adverse effects on the structural integrity of the parts made.

Several defects can develop in castings, as illustrated in Figs. 10.12 and 10.13. Because different terms have been used in the past to describe the same defect, the International Committee of Foundry Technical Associations has developed a standardized nomenclature, consisting of seven basic categories of casting defects, identified with boldface capital letters:

A—Metallic projections, consisting of fins, flash, or projections, such as swells and rough surfaces.

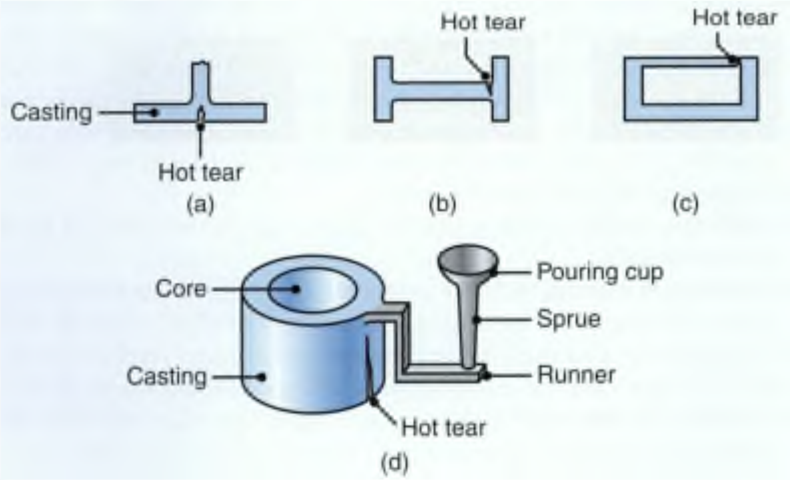

FIGURE 10.12 Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat-producing) compounds may be used (as exothermic padding) to control cooling at critical sections to avoid hot tearing.

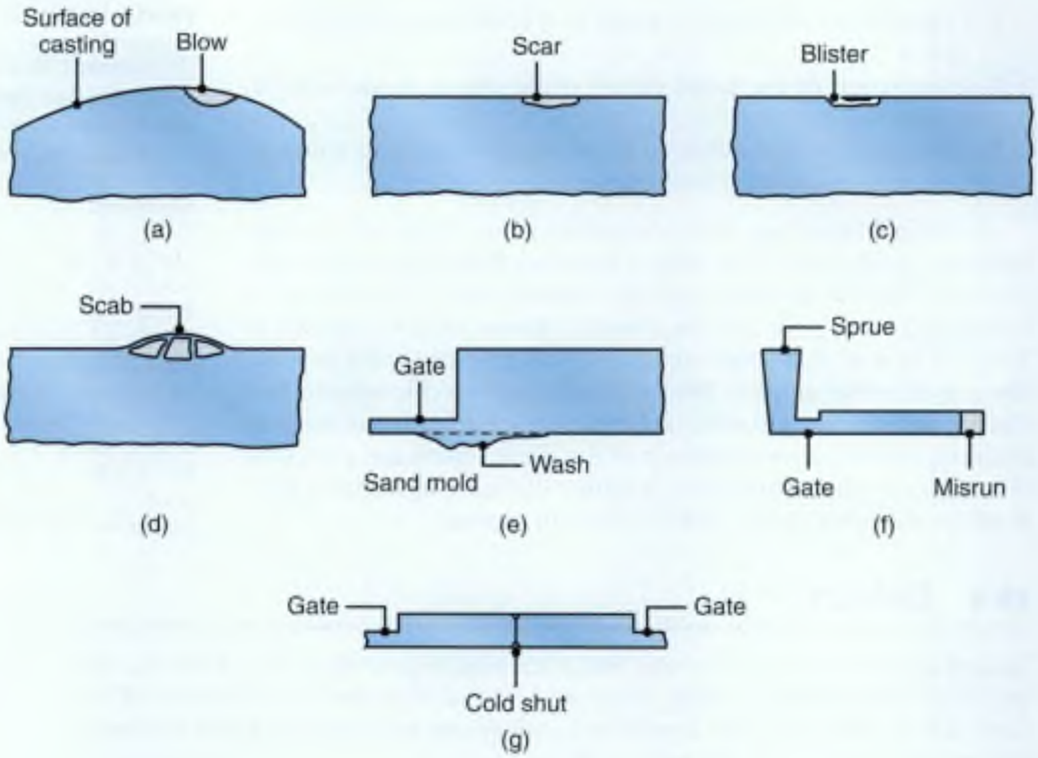

FIGURE 10.13 Examples of common defects in castings; these defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedures. *Source:* After J. Datsko.

B—Cavities, consisting of rounded or rough internal or exposed cavities, including blowholes, pinholes, and shrinkage cavities (see *porosity*, Section 10.6.1).

C—Discontinuities, such as cracks, cold or hot tearing, and cold shuts. If the solidifying metal is constrained from shrinking freely, cracking and tearing may occur. Although several factors are involved in tearing, coarse grain size and the presence of low-melting-point segregates along the grain boundaries of the metal increase the tendency for hot tearing. *Cold shut* is an interface in a casting that lacks complete fusion, because of the meeting of two streams of liquid metal from different gates.

D—Defective surface, such as surface folds, laps, scars, adhering sand layers, and oxide scale.

E—Incomplete casting, such as *misruns* (due to premature solidification), insufficient volume of the metal poured, and *runout* (due to loss of metal from the mold after pouring). Incomplete castings also can result from the molten metal being at too low a temperature or from pouring the metal too slowly.

F—Incorrect dimensions or shape, due to such factors as improper shrinkage allowance, pattern mounting error, irregular contraction, deformed pattern, or warped casting.

G—Inclusions, which form during melting, solidification, and molding. Generally nonmetallic, they are regarded as harmful, because they act as stress raisers, and thus reduce the strength of the casting. Inclusions may form during melting when the molten metal reacts with the environment (usually oxygen), with the crucible or the mold material. Chemical reactions among components in the molten metal itself may produce inclusions. Slags and other foreign material entrapped in the molten metal also become inclusions, although filtering the molten metal can remove particles as small as 30 μm. Finally, spalling of the mold and core surfaces can produce inclusions, thus indicating the importance of the quality of molds and their maintenance.

10.6.1 Porosity

Porosity in a casting may be caused by *shrinkage*, entrained or dissolved *gases*, or both. Porous regions can develop in castings because of **shrinkage** of the solidified metal. Thin sections in a casting solidify sooner than thicker regions; as a result, molten metal flows into the thicker regions that have not yet solidified. Porous regions may develop at their centers because of contraction as the surfaces of the thicker region begin to solidify first. *Microporosity* also can develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches.

Porosity is detrimental to the strength and ductility of a casting and its surface finish, potentially making the casting permeable, thus affecting the pressure tightness of a cast pressure vessel.

Porosity caused by shrinkage can be reduced or eliminated by various means, including the following:

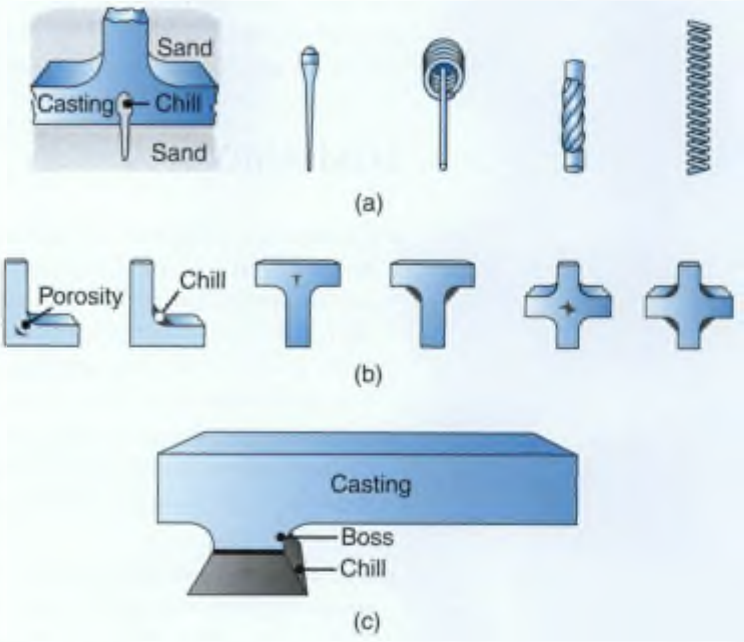

FIGURE 10.14 Various types of (a) internal and (b) external chills (dark areas at corners) used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

- Adequate liquid metal should be provided to prevent cavities caused by shrinkage.
- Internal or external chills, as those used in sand casting (Fig. 10.14), also are an effective means of reducing shrinkage porosity. The function of chills is to increase the rate of solidification in critical regions. Internal chills are usually made from the same material as the casting itself, and are left in the casting. However, problems may arise that involve proper fusion of the internal chills with the casting; thus, foundries generally avoid the use of internal chills. External chills may be made from the same material as the casting or may be made of iron, copper, or graphite.
- With alloys, porosity can be reduced or eliminated by high temperature gradients, that is, by increasing the cooling rate; for example, mold materials with higher thermal conductivity may be used.
- Subjecting the casting to hot isostatic pressing is another method of reducing porosity (see Section 17.3.2).

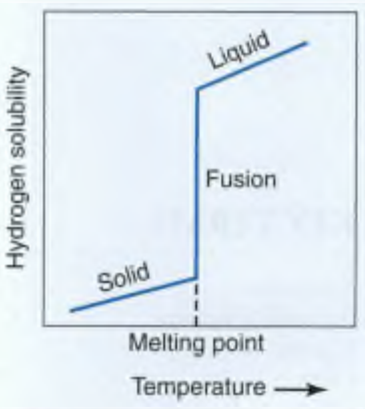

FIGURE 10.15 Solubility of hydrogen in aluminum; note the sharp decrease in solubility as the molten metal begins to solidify.

Because *gases* are more soluble in liquid metals than in solid metals (Fig. 10.15), when a metal begins to solidify, the dissolved gases are expelled from the solution; gases also may be due to reactions of the molten metal with the mold materials. Gases either accumulate in regions of existing porosity (such as in interdendritic regions) or cause microporosity in the casting, particularly in cast iron, aluminum, and copper. Dissolved gases may be removed from the molten metal by *flushing* or *purging* with an inert gas or by melting and pouring the metal in a vacuum. If the dissolved gas is oxygen, the molten metal can be *deoxidized*. Steel usually is deoxidized with aluminum, silicon, copper-based alloys with phosphorus, copper, titanium, or zirconium-bearing materials.

Whether microporosity is a result of shrinkage or is caused by gases may be difficult to determine. If the porosity is spherical and has smooth walls (similar to the shiny holes in Swiss cheese), it is generally from gases. If the walls are rough and angular, porosity is likely from shrinkage between dendrites. Gross porosity is from shrinkage and usually is called a **shrinkage cavity**.

SUMMARY

- Casting is a solidification process in which molten metal is poured into a mold and allowed to cool. The metal may flow through a variety of passages (pouring basins, sprues, runners, risers, and gating systems) before reaching the mold cavity. Bernoulli's theorem, the continuity law, and the Reynolds number are the analytical tools used in designing castings, with the goals of achieving an appropriate flow rate and eliminating defects associated with fluid flow.
- Solidification of pure metals takes place at a constant temperature, whereas solidification of alloys occurs over a range of temperatures. Phase diagrams are important tools for identifying the solidification point or points for technologically important metals.
- The composition and cooling rates of the molten metal both affect the size and shape of the grains and the dendrites in the solidifying alloy; in turn, the size and structure of grains and dendrites influence properties of the solidified casting. Solidification time is a function of the volume and surface area of a casting (Chvorinov's rule).
- The grain structure of castings can be controlled by various means to obtain desired properties. Because most metals contract during solidification and cooling, cavities can form in the casting. Porosity caused by gases evolved during solidification can be a significant problem, particularly because of its adverse effect on the properties of castings. Various defects also can develop in castings from lack of control of material and process variables.
- Dimensional changes and cracking (hot tearing) are difficulties that can arise during solidification and cooling. Several basic categories of casting defects have been identified.

KEY TERMS

Aspiration
Bernoulli's theorem
Casting
Chills
Columnar dendrite
Columnar grain
Cored dendrite
Dendrite
Fluidity
Freezing range
Gate
Gating system
Heterogeneous nucleation
Homogenous nucleation
Inoculant
Macrosegregation
Microsegregation
Mold
Mushy zone
Normal segregation
Porosity
Pouring basin
Reynolds number
Rheocasting
Riser
Runner
Segregation
Shrinkage
Skin
Solidification
Sprue
Turbulence

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REVIEW QUESTIONS

10.1 Explain why casting is an important manufacturing process.

10.2 Why do most metals shrink when they are cast?

10.3 What are the differences between the solidification of pure metals and metal alloys?

10.4 What are dendrites? Why are they called so?

10.5 Describe the difference between short and long freezing ranges.

10.6 What is superheat? Is it important? What are the consequences of excessive superheat?

10.7 Define shrinkage and porosity. How can you tell whether cavities in a casting are due to porosity or to shrinkage?

10.8 What is the function of chills? What are they made of?

10.9 Why is the Reynolds number important in casting?

10.10 What is a sprue? What shape should a sprue have if a mold has no other choking means?

10.11 How is fluidity defined? Why is it important?

10.12 Explain the reasons for hot tearing in castings.

10.13 Why is it important to remove dross or slag during the pouring of molten metal into the mold? What methods are used to remove them?

10.14 Why is Bernoulli's equation important in casting?

10.15 Describe thixocasting and rheocasting.

10.16 What is Chvorinov's Rule?

10.17 How is a blister related to a scab?

QUALITATIVE PROBLEMS

10.18 Is there porosity in a chocolate bar? In an ice cube? Explain.

10.19 Describe the stages involved in the contraction of metals during casting.

10.20 Explain the effects of mold materials on fluid flow and heat transfer in casting operations.

10.21 It is known that pouring metal at a high rate into a mold can have certain disadvantages. Are there any disadvantages to pouring it very slowly?

10.22 Describe the events depicted in Fig. 10.5.

10.23 Would you be concerned about the fact that portions of internal chills are left within the casting? Explain.

10.24 Review Fig. 10.8 and make a summary, explaining the purpose of each feature shown and the consequences of omitting the feature from the mold design.

10.25 Make a sketch of volume vs. temperature for a metal that shrinks when it cools from the liquid state to room temperature. On the graph, mark the area where shrinkage is compensated by risers.

10.26 What practical demonstrations can you suggest to indicate the relationship of the solidification time to the volume and surface area of a casting?

10.27 Explain why a casting may have to be subjected to various heat treatments.

10.28 List and explain the reasons why porosity can develop in a casting.

10.29 Why does porosity have detrimental effects on the mechanical properties of castings? Would physical properties, such as thermal and electrical conductivity, also be adversely affected by porosity? Explain.

10.30 A spoked handwheel is to be cast in gray iron. In order to prevent hot tearing of the spokes, would you insulate the spokes or chill them? Explain.

10.31 Which of the following considerations are important for a riser to function properly? Must it: (a) have a surface area larger than the part being cast, (b) be kept open to atmospheric pressure, and/or (c) solidify first? Explain.

10.32 Explain why the constant C in Eq. (10.7) depends on mold material, metal properties, and temperature.

10.33 Are external chills as effective as internal chills? Explain.

10.34 Explain why, as shown in Table 10.1, gray cast iron undergoes expansion rather than contraction during solidification.

10.35 Referring to Fig. 10.11, explain why internal corners, such as *A*, develop a thinner skin than external corners, such as *B*, during solidification.

10.36 Note the shape of the two risers shown in Fig. 10.8, and discuss your observations with respect to Eq. (10.7).

10.37 Is there any difference in the tendency for shrinkage void formation in metals with short and long freezing ranges, respectively? Explain.

10.38 What is the influence of the cross-sectional area of the spiral channel, shown in Fig. 10.9, on fluidity test results? What is the effect of sprue height? If this test is run with the entire test setup heated to elevated temperatures, would the results be more useful? Explain.

10.39 It has long been observed that (a) low pouring temperatures (i.e., low superheat) promote the formation of equiaxed grains over columnar grains and (b) equiaxed grains become finer as the pouring temperature decreases. Explain these two phenomena.

10.40 In casting metal alloys, what would you expect to occur if the mold were agitated (vibrated) aggressively after the molten metal had been in the mold for a sufficient period of time to form a skin?

10.41 If you inspect a typical cube of ice, you are likely to see air pockets and cracks in the cube. Some ice cubes, however, are tubular in shape and do not have noticeable air pockets or cracks in their structure. Explain this phenomenon.

10.42 How can you tell whether cavities in a casting are due to shrinkage or entrained air bubbles?

10.43 Describe the drawbacks to having a riser that is (a) too large and (b) too small.

10.44 Reproduce Fig. 10.2 for a casting that is spherical in shape.

10.45 List the process variables that affect the fluidity index shown in Fig. 10.9.

10.46 Assume that you have a method of measuring porosity in a casting. Could you use this information to accurately predict the strength of the casting? Explain.

QUANTITATIVE PROBLEMS

10.47 A round casting is 0.2 m in diameter and 0.75 m in length. Another casting of the same metal is elliptical in cross-section, with a major-to-minor axis ratio of 2, and has the same length and cross-sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?

10.48 A cylinder with a diameter of 50 mm and a height of 75 mm solidifies in three minutes in a sand casting operation. What is the solidification time if the cylinder height is doubled? What is the time if the diameter is doubled?

10.49 The constant C in Chvorinov's rule is given as 2.5 s/mm^2, and is used to produce a cylindrical casting with a diameter of 50 mm and height of 125 mm. Estimate the time for the casting to fully solidify. The mold can be broken safely when the solidified shell is at least 20 mm. Assuming that the cylinder cools evenly, how much time must transpire after pouring the molten metal before the mold can be broken?

10.50 Pure copper is poured into a sand mold. The metal level in the pouring basin is 250 mm above the metal level in the mold, and the runner is circular with a 10 mm diameter. What are the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar?

10.51 For the sprue described in Problem 10.58, what runner diameter is needed to ensure a Reynolds number of 2000? How long will a 250 mL casting take to fill with such a runner?

10.52 Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers to them.

10.53 When designing patterns for casting, pattern makers use special rulers that automatically incorporate solid shrinkage allowances into their designs; therefore, a 100-mm patternmaker's ruler is longer than 100 mm. How long should a patternmaker's ruler be for (1) aluminum castings, (2) malleable cast iron, and (3) high manganese steel?

SYNTHESIS, DESIGN, AND PROJECTS

10.54 Can you devise fluidity tests other than that shown in Fig. 10.9? Explain the features of your test methods.

10.55 Figure P10.55 indicates various defects and discontinuities in cast products. Review each defect and offer solutions to prevent it.

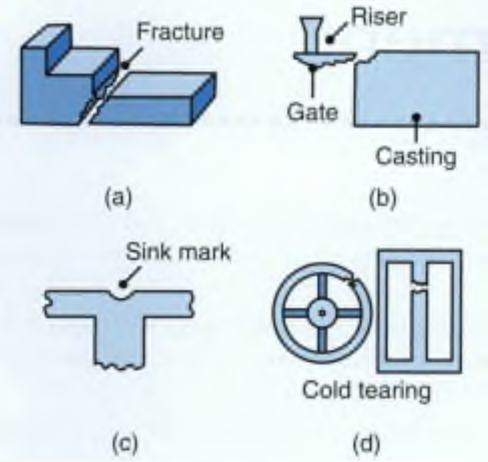


FIGURE P10.55

10.56 The fluidity test shown in Fig. 10.9 illustrates only the principle of this test. Design a setup for such a test, showing the type of materials and the equipment to be used. Explain the method by which you would determine the length of the solidified metal in the spiral passage.

10.57 Utilizing the equipment and materials available in a typical kitchen, design an experiment to reproduce results similar to those shown in Fig. 10.11. Comment on your observations.

10.58 One method of relieving stress concentrations in a part is to apply a small, uniform plastic deformation to it. Make a list of your concerns and recommendations if such an approach is suggested for a casting.

10.59 Describe the effects on mold design, including the required change in the size of the risers, runners, chokes, and sprues, for a casting of a given shape that is to be doubled in volume.

10.60 Small amounts of slag often persist after skimming and are introduced into the molten-metal flow in casting. Recognizing that the slag is much less dense than the metal, design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

10.61 Figure II.2 shows a variety of components in a typical automobile that are produced by casting. Think of other products, such as power tools and small appliances, and prepare an illustration similar to the figure.

10.62 Design an experiment to measure the constants C and n in Chvorinov's rule, Eq. (10.7). Describe the features of your design, and comment on any difficulties that might be encountered in running such an experiment.

CHAPTER

11

Metal-casting Processes and Equipment

CASE STUDIES:

- Building upon the fundamentals of solidification, fluid flow, and heat transfer described in the preceding chapter, this chapter describes the industrial casting processes.
- Casting processes are generally categorized as permanent-mold and expendable-mold processes; expendable-mold processes are further categorized as permanent-mold and expendable-pattern processes.
- The characteristics of each process are described, together with typical applications, advantages, and limitations.
- Special casting processes that produce single-crystal components as well as amorphous alloys are then described.
- The chapter ends with a description of inspection techniques for castings.

Typical products made by casting: Engine blocks, crankshafts, power tool housings, turbine blades, plumbing parts, zipper teeth, dies and molds, gears, railroad wheels, propellers, office equipment, and statues. Casting is extremely versatile and suitable for a wide variety of products.

Alternative processes: Forging, powder metallurgy, machining, rapid prototyping, and fabrication.

11.1 Introduction

The first metal castings were made during the period from 4000 to 3000 B.C., using stone or metal molds for casting copper. Various casting processes have been developed over time, each with its own characteristics and applications (see also Fig. I.5a), to meet specific design requirements (Table 11.1). A very wide variety of parts and components are made by casting (Fig. 11.1), such as engine blocks, crankshafts, automotive components and powertrains, agricultural and railroad equipment, pipes and plumbing fixtures, power-tool housings, gun barrels, frying pans, jewelry, orthopedic implants, and very large components for hydraulic turbines.

Two trends have had a major impact on the casting industry. The first is the mechanization and automation of casting operations, which has led to significant changes in the use of equipment and labor. Advanced machinery and automated process-control systems have replaced traditional methods of casting. The second major trend has been the increasing demand for high-quality castings with close dimensional tolerances.

This chapter is organized around the major classifications of casting practices (given in Fig. II.3 in the Introduction to Part II). These classifications are related to

TABLE 11.1

Summary of Casting Processes

Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to part size, shape, or weight; low tooling cost	Some finishing required; relatively coarse surface finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment
Evaporative pattern	Most metals can be cast, with no limit to size; complex part shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate part shapes; good dimensional accuracy and surface finish; low porosity	Limited to nonferrous metals; limited part size and volume of production; mold-making time relatively long
Ceramic mold	Intricate part shapes; close-tolerance parts; good surface finish; low cooling rate	Limited part size
Investment	Intricate part shapes; excellent surface finish and accuracy; almost any metal can be cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited part shape and complexity; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	High die cost; limited part size; generally limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical or tubular parts with good quality; high production rate	Expensive equipment; limited part shape

mold materials, pattern production, molding processes, and methods of feeding the mold with molten metal. The major categories are:

1. **Expendable molds,** typically made of sand, plaster, ceramics, and similar materials, and generally mixed with various binders (*bonding agents*) for improved properties. A typical sand mold consists of 90% sand, 7% clay, and 3% water. As described in Chapter 8, these materials are *refractories* (i.e., they are capable of withstanding the high temperatures of molten metals). After the casting has solidified, the mold is broken up to remove the casting, hence the word *expendable*.

   The mold is produced from a pattern; in some processes, and although the mold is expendable, the pattern is reused to produce several molds. Such processes are referred to as *expendable-mold, permanent-pattern casting processes*. On the other hand, investment casting requires a pattern for each mold produced, and is an example of an *expendable-mold, expendable-pattern process*.
2. **Permanent molds,** made of metals that maintain their strength at high temperatures. As the name implies, the molds are used repeatedly, and are designed in such a way that the casting can be removed easily and the mold used for the next casting. Metal molds are better heat conductors than expendable nonmetallic molds (see Table 3.1), hence the solidifying casting is subjected to a higher rate of cooling, which in turn affects the microstructure and grain size within the casting.
3. **Composite molds,** made of two or more different materials (such as sand, graphite, and metal), combining the advantages of each material. These molds have a permanent and an expendable portion, and are used in various casting processes to improve mold strength, control the cooling rate, and optimize the overall economics of the casting operation.

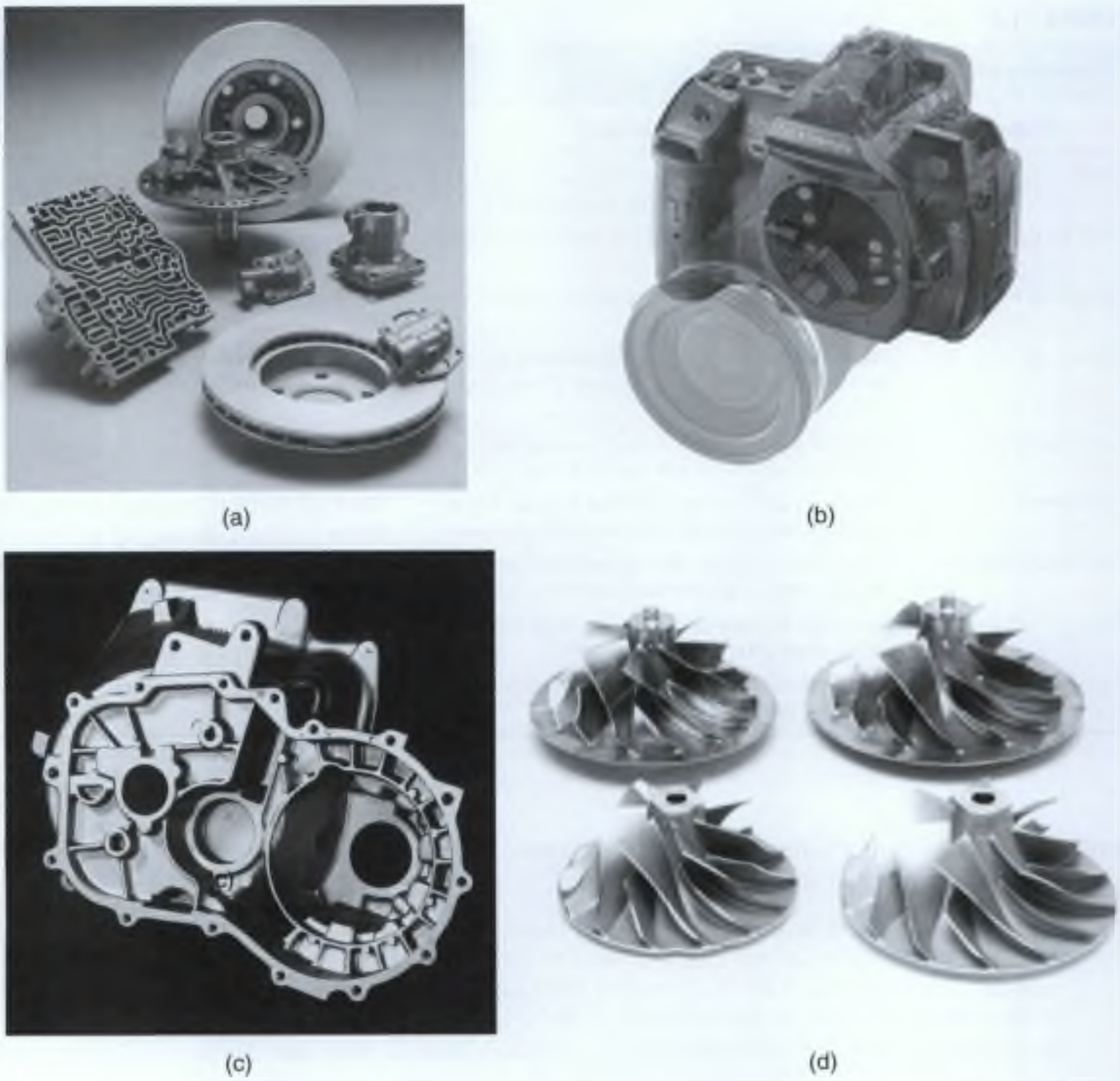


FIGURE 11.1 (a) Typical gray-iron castings used in automobiles, including the transmission valve body (left) and the hub rotor with disk-brake cylinder (front). *Source:* Courtesy of Central Foundry Division of General Motors Corporation. (b) Die-cast magnesium housing for the Olympus E-3 camera; *Source:* Courtesy of Olympus Inc. (c) A cast transmission housing. (d) Cast aluminum impellers for automotive turbochargers. *Source:* (c) and (d) Courtesy of American Foundry Society.

The general characteristics of sand casting and other casting processes are summarized in Table 11.2. As it can be seen, almost all commercial metals can be cast. The surface finish obtained is largely a function of the mold material, and can be very good, although, as expected, sand castings generally have rough, grainy surfaces. Dimensional tolerances generally are not as good as those in machining and other net-shape processes; however, intricate shapes, such as engine blocks and very large propellers for ocean liners, can be made by casting.

Because of their unique characteristics and applications, particularly in manufacturing microelectronic devices (described in Part V), basic crystal-growing techniques also are included in this chapter, which concludes with a brief overview of modern foundries.

TABLE 11.2

General Characteristics of Casting Processes

	Sand	Shell	Evaporative pattern	Plaster	Investment	Permanent mold	Die	Centrifugal
Typical materials cast	All	All	All	Nonferrous (Al, Mg, Zn, Cu)	All	All	Nonferrous (Al, Mg, Zn, Cu)	All
Weight (kg):								
Minimum	0.01	0.01	0.01	0.01	0.001	0.1	<0.01	0.01
Maximum	No limit	100+	100+	50+	100+	300	50	5000+
Typical surface finish (R_a in μm)	5–25	1–3	5–25	1–2	0.3–2	2–6	1–2	2–10
Porosity[1]	3–5	4–5	3–5	4–5	5	2–3	1–3	1–2
Shape complexity[1]	1–2	2–3	1–2	1–2	1	2–3	3–4	3–4
Dimensional accuracy[1]	3	2	3	2	1	1	1	3
Section thickness (mm):								
Minimum	3	2	2	1	1	2	0.5	2
Maximum	No limit	—	—	—	75	50	12	100
Typical dimensional tolerance (mm)	1.6–4 mm (0.25 mm for small parts)	±0.003		±0.005–0.010	±0.005	±0.015	± 0.001–0.005	0.015
Equipment	3–5	3	2–3	3–5	3–5	2	1	1
Pattern/die	3–5	2–3	2–3	3–5	2–3	2	1	1
Labor	1–3	3	3	1–2	1–2	3	5	5
Typical lead time[2]	Days	Weeks	Weeks	Days	Weeks	Weeks	Weeks to months	Months
Typical production rate[2] (parts/mold-hour)	1–20	5–50	1–20	1–10	1–1000	5–50	2–200	1–1000
Minimum quantity[2]	1	100	500	10	10	1000	10,000	10–10,000

Notes: 1. Relative rating, from 1 (best) to 5 (worst). For example, die casting has relatively low porosity, mid to low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are only general; significant variations can occur, depending on the manufacturing methods used.
2. Approximate values without the use of rapid-prototyping technologies; minimum quantity is 1 when applying rapid prototyping.
Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3rd ed., McGraw-Hill, 2000.

11.2 Expendable-mold, Permanent-pattern Casting Processes

The major categories of expendable-mold, permanent-pattern casting processes are sand, shell mold, plaster mold, ceramic mold, and vacuum casting.

11.2.1 Sand Casting

The traditional method of casting metals is in sand molds and has been used for millennia. Sand casting is still the most prevalent form of casting; in the United States alone, about 15 million metric tons of metal are cast by this method each year. Typical applications of sand casting include machine bases, large turbine impellers, propellers, plumbing fixtures, and a wide variety of other products and components. The capabilities of sand casting are given in Table 11.2.

Sand casting basically consists of (a) placing a pattern, having the shape of the part to be cast, in sand to make an imprint, (b) incorporating a gating system, (c) removing the pattern and filling the mold cavity with molten metal, (d) allowing the metal to cool until it solidifies, (e) breaking away the sand mold, and (f) removing the casting (Fig. 11.2).

Sands. Most sand-casting operations use silica sand (SiO_2) as the mold material. Sand is inexpensive and is suitable as a mold material because of its high-temperature characteristics and high melting point. There are two general types of sand: **naturally bonded** (*bank sand*) and **synthetic** (*lake sand*). Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries.

Several factors are important in the selection of sand for molds, and certain tradeoffs with respect to properties have to be considered. Sand having fine, round grains can be packed closely and thus forms a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold *permeability* (where fluids and gases can pass through pores). Good permeability of molds and cores allows gases and steam evolved during the casting process to escape easily. The mold also

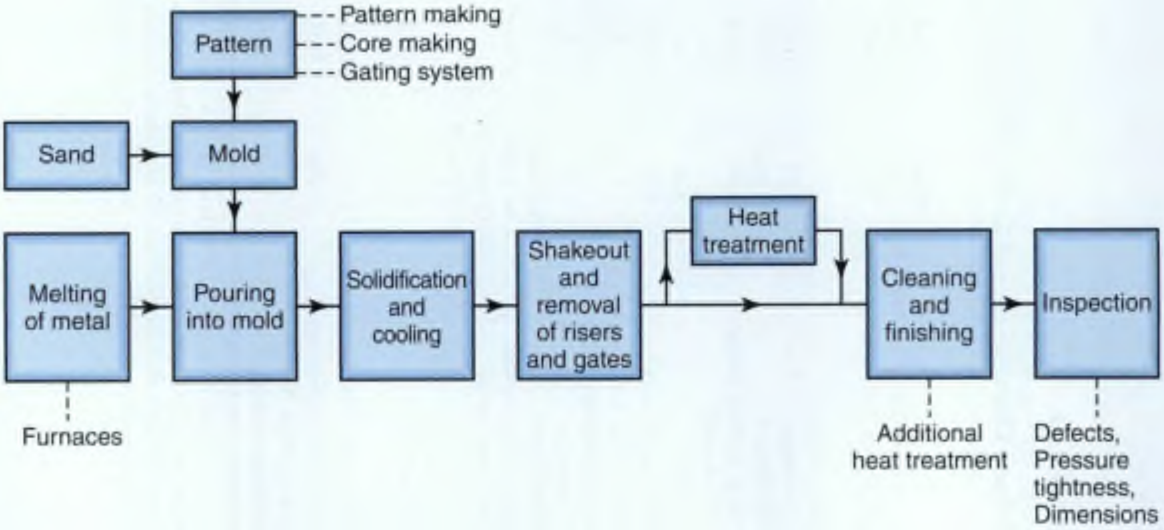


FIGURE 11.2 Outline of production steps in a typical sand-casting operation.

should have good *collapsibility*, in order to allow the casting to shrink while it is cooling, and thus prevent defects in the casting, such as hot tearing and cracking shown in Fig. 10.12.

Types of Sand Molds. Sand molds (Fig. 11.3) are characterized by the types of sand that comprise them and by the methods used to produce them. There are three basic types of sand molds: (a) green-sand, (b) cold-box, and (c) no-bake molds. The most common mold material is **green molding sand,** a mixture of sand, clay, and water. The term "green" refers to the fact that the sand in the mold is moist or damp while the metal is poured into it.

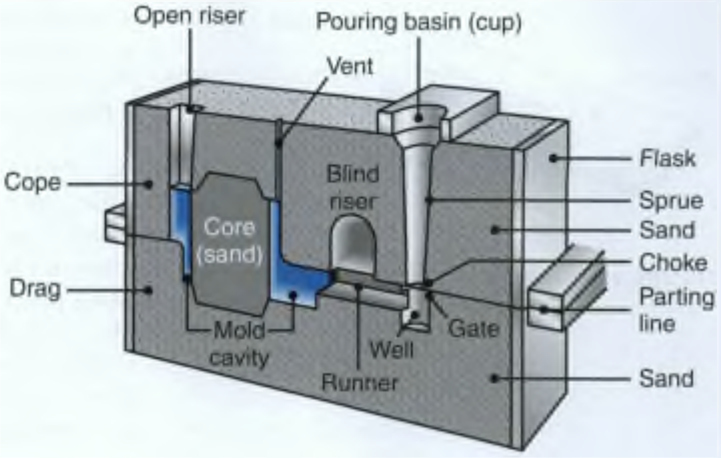


FIGURE 11.3 Schematic illustration of a sand mold, showing various features.

Green-sand molding is the least expensive method of making molds, and the sand is recycled easily for subsequent reuse. In the *skin-dried* method, the mold surfaces are dried, either by storing the mold in air or by drying it with torches. Because of their higher strength, these molds are generally used for large castings.

In the **cold-box mold** process, various organic and inorganic *binders* are blended into the sand to bond the grains chemically for greater strength. These molds are more dimensionally accurate than green-sand molds, but are more expensive to make. In the no-bake mold process, a synthetic liquid resin is mixed with the sand, and the mixture hardens at room temperature. Because the bonding of the mold in this and in the cold-box process takes place without heat, they are called **cold-setting processes.**

Sand molds can be oven dried (*baked*) prior to pouring the molten metal; they then become stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, this method has drawbacks in that (a) distortion of the mold is greater; (b) the castings are more susceptible to hot tearing, because of the lower collapsibility of the mold; and (c) the production rate is lower, because of the considerable drying time required.

The major features of molds in sand casting are:

1. The **flask,** which supports the mold itself. Two-piece molds consist of a **cope** on top and a **drag** on the bottom; the seam between them is the *parting line.* When more than two pieces are used in a sand mold, the additional parts are called *cheeks.*
2. A **pouring basin** or **pouring cup,** into which the molten metal is poured.
3. A **sprue,** through which the molten metal flows downward.
4. The **runner system,** which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlets into the mold cavity.
5. **Risers,** which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers—a *blind riser* and an *open riser*—are shown in Fig. 11.3.
6. **Cores,** which are inserts made from sand; they are placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to form features, such as lettering or numbering.

QR Code 11.1 Sand core production. (*Source:* Courtesy of Alcast Technologies, Ltd.)

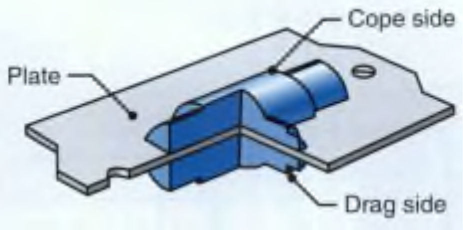


FIGURE 11.4 A typical metal match-plate pattern used in sand casting.

7. **Vents,** which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and the core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold.

Patterns. *Patterns* are used to mold the sand mixture into the shape of the casting, and may be made of wood, plastic, or metal. The selection of a pattern material depends on the size and shape of the casting, the dimensional accuracy and the quantity of castings required, and the molding process. Because patterns are used repeatedly to make molds, the strength and durability of the material selected for a pattern must reflect the number of castings that the mold will produce. Patterns may also be made of a combination of materials to reduce wear in critical regions; they usually are coated with a **parting agent** to facilitate the removal of the pattern from the molds.

Patterns can be designed with a variety of features for specific applications and economic requirements. **One-piece patterns,** also called *loose* or *solid patterns,* are generally used for simpler shapes and low-quantity production; they generally are made of wood and are inexpensive. **Split patterns** are two-piece patterns, made such that each part forms a portion of the cavity for the casting; in this way, castings with complicated shapes can be produced. **Match-plate patterns** are a common type of mounted pattern in which two-piece patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate (Fig. 11.4). In such constructions, the gating system can be mounted on the drag side of the pattern. This type of pattern is used most often in conjunction with molding machines and for large production runs to produce smaller castings.

An important development in mold and pattern making is the application of **rapid prototyping** (Chapter 20). In sand casting, for example, a pattern can be fabricated in a rapid-prototyping machine, and fastened to a backing plate at a fraction of the time and the cost of machining a pattern. There are several rapid-prototyping techniques with which these tools can be produced quickly. These technologies are best suited for small production runs.

Pattern design is a critical aspect of the total casting operation. The design should provide for **metal shrinkage,** permit proper metal flow in the mold cavity, and allow the pattern to be easily removed from the sand mold, by means of a taper or draft (Fig. 11.5) or some other geometric feature. (These topics are described in greater detail in Chapter 12.)

QR Code 11.2 Sand casting using manual molding methods. (*Source:* Courtesy of Alcast Technologies, Ltd.)

Cores. For castings with internal cavities or passages, such as those found in automotive engine blocks or valve bodies, *cores* are utilized. Cores are placed in the mold cavity to form the interior surfaces of the casting, and are removed from the finished part during shakeout and further processing. Like molds, cores must possess strength, permeability, collapsibility, and the ability to withstand heat; hence cores are made of sand aggregates.

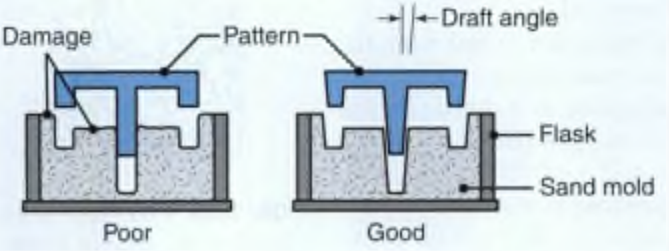


FIGURE 11.5 Taper on patterns for ease of removal from the sand mold.

The core is anchored by **core prints,** which are geometric features added to the pattern to locate and support the core and to provide vents for the escape of gases (Fig. 11.6a). A common problem with cores is that, for some casting requirements, as in the case where a recess is required, they may

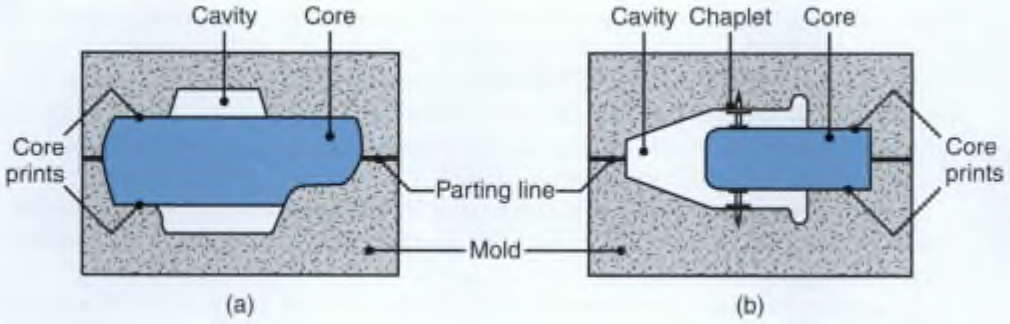


FIGURE 11.6 Examples of sand cores, showing core prints and chaplets to support the cores.

lack sufficient structural support in the cavity. To keep the core from shifting, metal supports (**chaplets**) may be used to anchor the core in place (Fig. 11.6b).

Cores are generally made in a manner similar to that used in sand moldmaking; the majority are made with shell (see Section 11.2.2), no-bake, or cold-box processes. Cores are shaped in *core boxes*, which are used in much the same way that patterns are used to form sand molds.

Sand-molding Machines. The oldest known method of molding, which is still used for simple castings and for small production runs, is to compact the sand by hand hammering (tamping) or ramming it around the pattern. For most operations, however, the sand mixture is compacted around the pattern by *molding machines*. These machines eliminate arduous labor, manipulate the mold in a controlled manner, offer high-quality casting by improving the application and distribution of forces, and increase production rate.

In **vertical flaskless molding**, the pattern halves form a vertical chamber wall against which sand is blown and compacted (Fig. 11.7). Then, the mold halves are packed horizontally with the parting line oriented vertically, and moved along a pouring conveyor. This is a simple operation and eliminates the need to handle

QR Code 11.3 Sand casting using automated molding methods. (*Source:* Courtesy of Alcast Technologies, Ltd.)

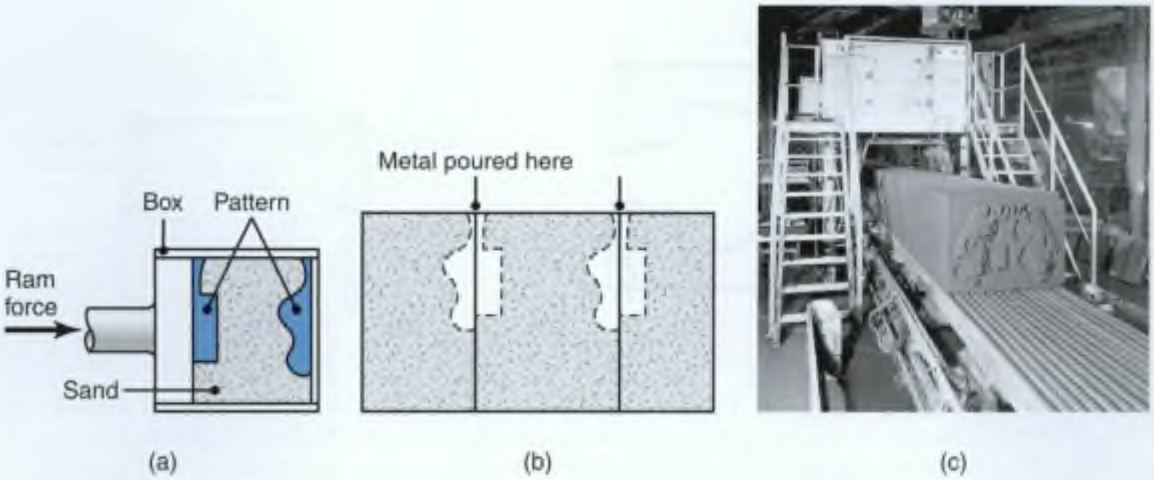


FIGURE 11.7 Vertical flaskless molding. (a) Sand is squeezed between two halves of the pattern. (b) Assembled molds pass along an assembly line for pouring. (c) A photograph of a vertical flaskless molding line. *Source:* Courtesy of American Foundry Society.

flasks, allowing for very high production rates, particularly when other aspects of the operation (such as coring and pouring) are automated.

Sandslingers fill the flask uniformly with sand under a high-pressure stream; they are used to fill large flasks and are often automated. An impeller in the machine throws sand from its blades or cups at such high speeds that the machine not only places the sand, but also rams it appropriately.

In **impact molding**, the sand is compacted by a controlled explosion or instantaneous release of compressed gases. This method produces molds with uniform strength and good permeability.

In **vacuum molding** (also known as the *V process*), shown in Fig. 11.8, the pattern is covered tightly with a thin sheet of plastic. A flask is placed over the covered pattern and is filled with dry, binderless sand. A second sheet of plastic then is placed on top of the sand, and a vacuum action compacts the sand; the pattern can then be removed. Both halves of the mold are made in this manner and subsequently assembled. During pouring of the molten metal, the mold remains under vacuum, but the casting cavity does not. When the metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting.

As shown in Fig. 11.8, vacuum molding does not require a draft in the part, and can be very economical because of the low tooling costs, long pattern life, and absence of binders in the sand (which also simplifies sand recovery and reuse). Vacuum molding produces castings with high-quality surface detail and dimensional accuracy; it is suited especially well for large, relatively flat (plane) castings.

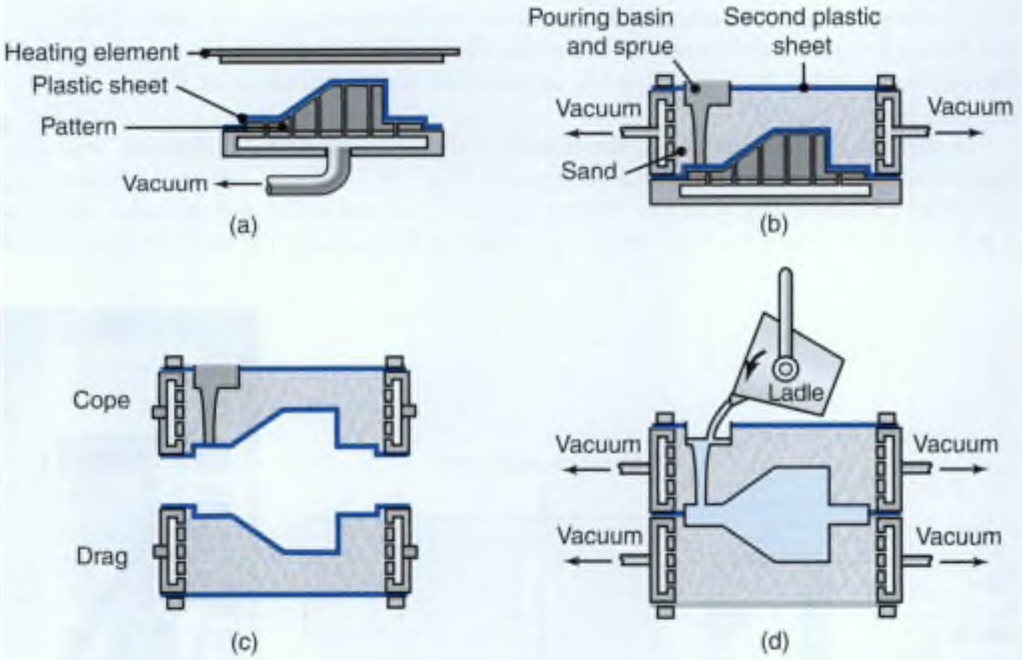
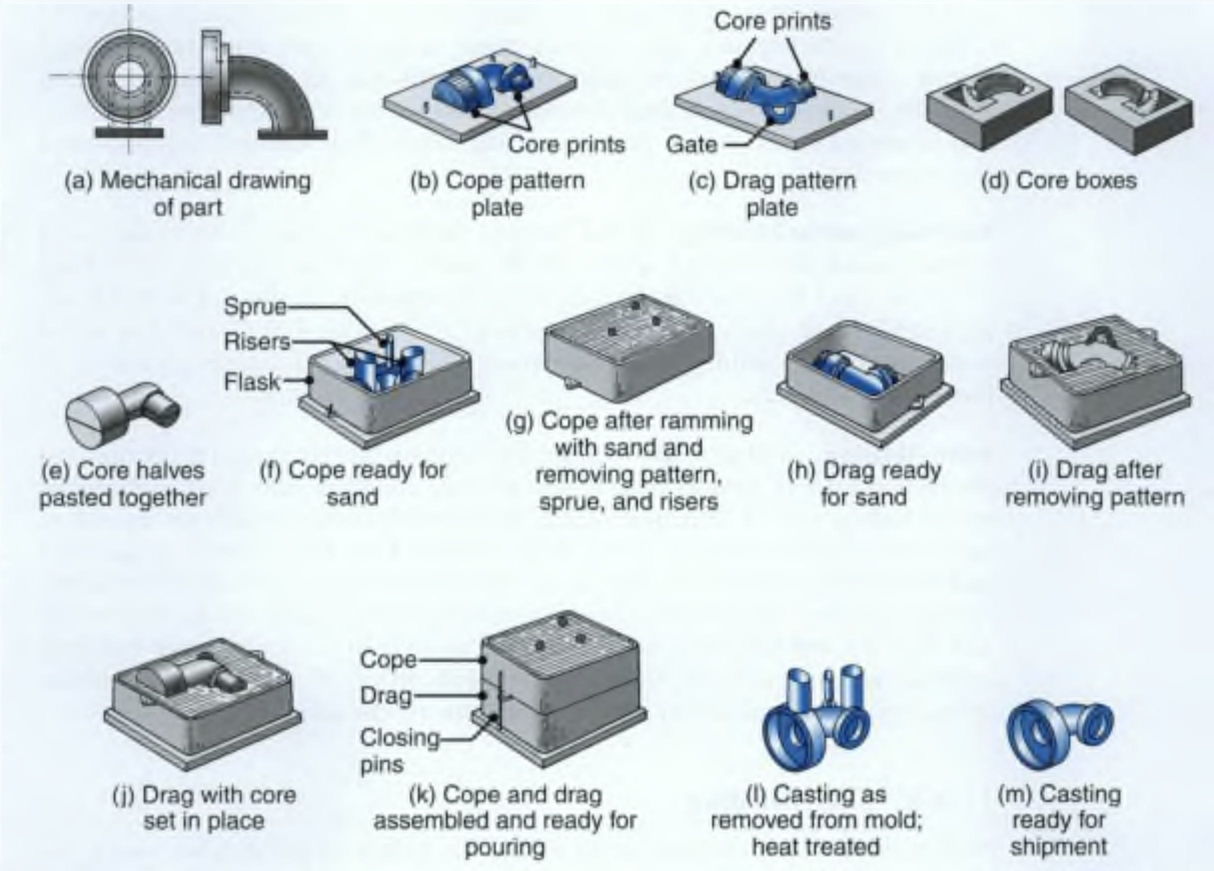


FIGURE 11.8 The vacuum molding process. (a) A plastic sheet is thermoformed (see Section 19.6) over a pattern; (b) a vacuum flask is placed over the pattern, a pouring basin/sprue insert is located, and the flask is filled with sand. A second sheet is located on the top of the sand mold, and vacuum is applied to tightly compact the sand against the pattern. (c) A drag is also produced, along with cheeks, cores, etc., as in conventional sand casting; the cope and drag can be carefully transported without vacuum applied. (d) After the mold halves are joined, vacuum is applied to ensure mold strength, and molten metal is poured into the mold.

The Sand-casting Operation. After the mold has been shaped and the cores have been placed in position, the two mold halves (cope and drag) are closed, clamped, and weighted down, to prevent the separation of the mold sections under the pressure exerted when the molten metal is poured into the mold cavity. A complete sequence of operations in sand casting is shown in Fig. 11.9.



(a) Mechanical drawing of part
(b) Cope pattern plate
(c) Drag pattern plate
(d) Core boxes
(e) Core halves pasted together
(f) Cope ready for sand
(g) Cope after ramming with sand and removing pattern, sprue, and risers
(h) Drag ready for sand
(i) Drag after removing pattern
(j) Drag with core set in place
(k) Cope and drag assembled and ready for pouring
(l) Casting as removed from mold; heat treated
(m) Casting ready for shipment

FIGURE 11.9 Schematic illustration of the sequence of operations for sand casting. (a) A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be built into the drawing. (b) and (c) Patterns have been mounted on plates equipped with pins for alignment; note the presence of core prints designed to hold the core in place. (d) and (e) Core boxes produce core halves, which are pasted together; the cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching inserts to form the sprue and risers. (g) The flask is rammed with sand, and the plate and inserts are removed. (h) The drag half is produced in a similar manner with the pattern inserted; a bottom board is placed below the drag and aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins; the flasks are then subjected to pressure to counteract buoyant forces in the liquid, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (when necessary). *Source:* Courtesy of Steel Founders' Society of America.

After it solidifies, the casting is shaken out of its mold, and the sand and oxide layers adhering to the casting are removed (by vibration, using a shaker, or by sand blasting). Castings are also cleaned by blasting with steel shot or grit (*shot blasting*; Section 26.8). The risers and gates are cut off by oxyfuel-gas cutting, sawing, shearing, or abrasive wheels; or they are trimmed in dies. Gates and risers on steel castings also may be removed with air carbon-arc cutting (Section 30.8) or torches. Castings may be cleaned further by electrochemical means or by pickling with chemicals to remove surface oxides.

The casting subsequently may be *heat treated* to improve certain properties required for its intended use; heat treatment is particularly important for steel castings. *Finishing operations* may involve machining, straightening, or forging with dies (sizing) to obtain final dimensions. *Inspection* is an important final step, and is carried out to ensure that the casting meets all design and quality-control requirements.

Rammed-graphite Molding. In this process, rammed graphite (Section 8.6) is used to make molds for casting reactive metals, such as titanium and zirconium. Sand cannot be used because these metals react vigorously with silica. The molds are packed like sand molds, air dried, baked at 175°C, fired at 870°C, and then stored under controlled humidity and temperature. The casting procedures are similar to those for sand molds.

Mold Ablation. Ablation has been used to improve the mechanical properties and production rates in sand casting. In this process, a sand mold is filled with molten metal, and the mold is then immediately sprayed with a liquid and/or gas solvent, to progressively erode the sand. As the mold is removed, the liquid stream causes rapid and directional solidification of the metal. With proper risers, mold ablation results in significantly lower porosity than conventional sand casting, leading to higher strength and ductility, and has therefore been applied to normally difficult-to-cast materials or metal-matrix composites. Since ablation speeds up solidification and also removes cores, significant productivity improvements can also be achieved.

11.2.2 Shell Molding

Shell molding, first developed in the 1940s, has grown significantly because it can produce many types of castings, with close dimensional tolerances and good surface finish, and at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process is also used widely in producing high-precision molding cores. The capabilities of shell-mold casting are given in Table 11.2.

In this process, a mounted pattern, made of a ferrous metal or aluminum, is (a) heated to a range of 175°–370°C, (b) coated with a parting agent (such as silicone), and (c) clamped to a box or chamber. The box contains fine sand, mixed with 2.5–4% of a thermosetting resin binder (such as phenol-formaldehyde), which coats the sand particles. Either the box is rotated upside down (Fig. 11.10) or the sand mixture is blown over the pattern, allowing it to form a coating.

The assembly is then placed in an oven for a short period of time to complete the curing of the resin. In most shell-molding machines, the oven consists of a metal box, with gas-fired burners that swing over the shell mold to cure it. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

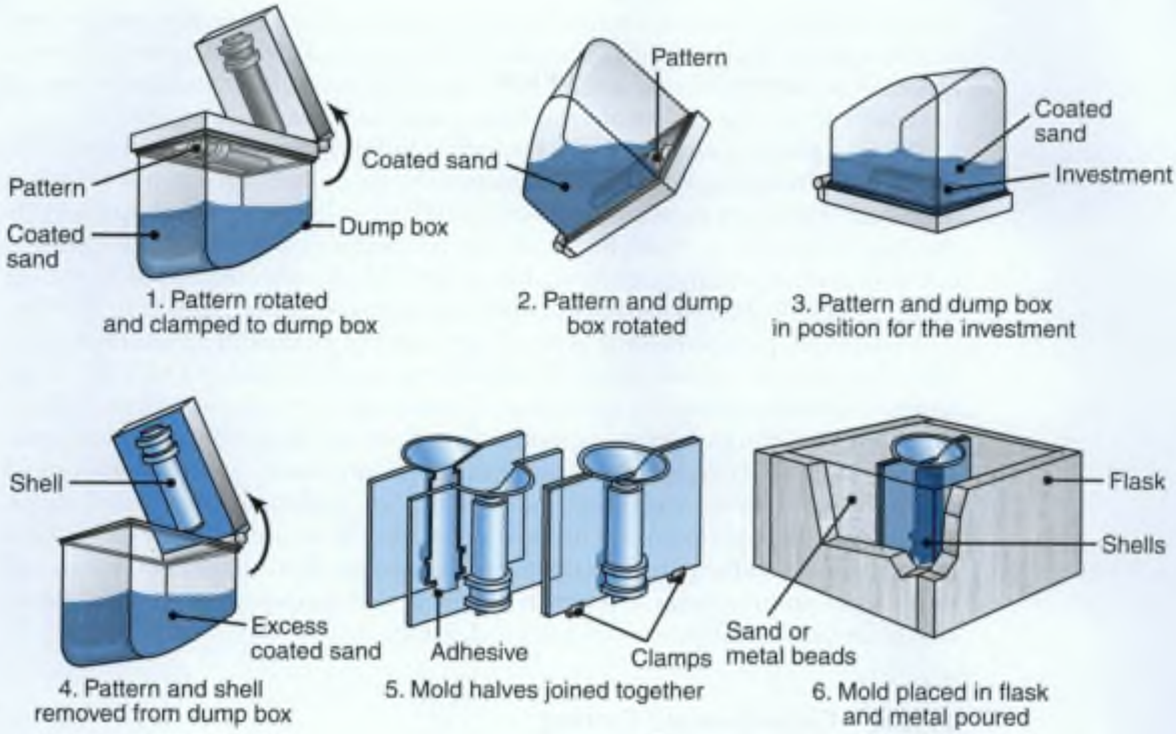


FIGURE 11.10 The shell-molding process, also called the dump-box technique.

The thickness of the shell can be determined accurately by controlling the time that the pattern is in contact with the mold. In this way, the shell can be formed with the required strength and rigidity, in order to hold the weight of the molten liquid. The shells are light and thin—usually 5 to 10 mm—and, consequently, their thermal characteristics are different from those for thicker molds.

Shell sand has a much smaller grain size, and therefore a lower permeability than the sand used for green-sand molding. The decomposition of the shell-sand binder also produces a high volume of gas. Thus, unless the molds are vented properly, trapped air and gas can result in defects in the shell molding of ferrous castings. The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

11.2.3 Plaster-mold Casting

This process, and the ceramic-mold and investment casting processes described in Sections 11.2.4 and 11.3.2, are known as **precision casting**, because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments. The castings are typically in the range of 125–250 g, although parts as light as 1 g (0.035 oz) have been made. The capabilities of plaster-mold casting are given in Table 11.2.

In the *plaster-molding process*, the mold is made of plaster of paris (gypsum or calcium sulfate), with the addition of talc and silica powder to improve strength and to control the time required for the plaster to set. These components are mixed with water, and the resulting slurry is poured over the pattern. After the plaster sets (usually within 15 min), it is removed and the mold is dried at a temperature range of 120°–260°C; higher drying temperatures may be used, depending on the type of plaster. The mold halves are assembled to form the mold cavity and are preheated to about 120°C. The molten metal is then poured into the mold.

Because plaster molds have very low permeability, gases evolved during solidification of the metal cannot escape; consequently, the molten metal is poured either in a vacuum or under pressure. Mold permeability can be increased substantially by the *Antioch process*, in which the molds are dehydrated in an autoclave (pressurized oven) for 6–12 h, and then rehydrated in air for 14 h. Another method of increasing the permeability of the mold is to use foamed plaster, containing trapped air bubbles.

Patterns for plaster molding generally are made of aluminum alloys, thermosetting plastics, brass, or zinc alloys. Wood patterns are not suitable for making a large number of molds, because they are repeatedly in contact with the water-based plaster slurry and thus warp or degrade quickly. Since there is a limit to the maximum temperature that the plaster mold can withstand (generally about 1200°C), plaster-mold casting is used only for aluminum, magnesium, zinc, and some copperbased alloys. The castings have good surface finish with fine details. Because plaster molds have lower thermal conductivity than other mold materials, the castings cool slowly, and thus a more uniform grain structure is obtained, with less warpage. The wall thickness of the cast parts can be as thin as 1 to 2.5 mm.

11.2.4 Ceramic-mold Casting

The *ceramic-mold casting* process (also called *cope-and-drag investment casting*) is similar to the plaster-mold process, except that it uses refractory mold materials suitable for high-temperature exposure. Typical parts made are impellers, cutters for machining operations, dies for metalworking, and molds for making plastic and rubber components. Parts weighing as much as 700 kg have been cast by this process. The slurry is a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern (Fig. 11.11) which has been placed in a flask.

The pattern may be made of wood or metal. After setting, the molds (ceramic facings) are removed, dried, ignited to burn off volatile matter, and baked. The molds are clamped firmly and used as all-ceramic molds. In the *Shaw process*, the ceramic facings are backed by fireclay (which resists high temperatures) to give strength to the mold. The facings are then assembled into a complete mold, ready to be poured.

The high-temperature resistance of the refractory molding materials allows these molds to be used for casting ferrous and other high-temperature alloys, stainless

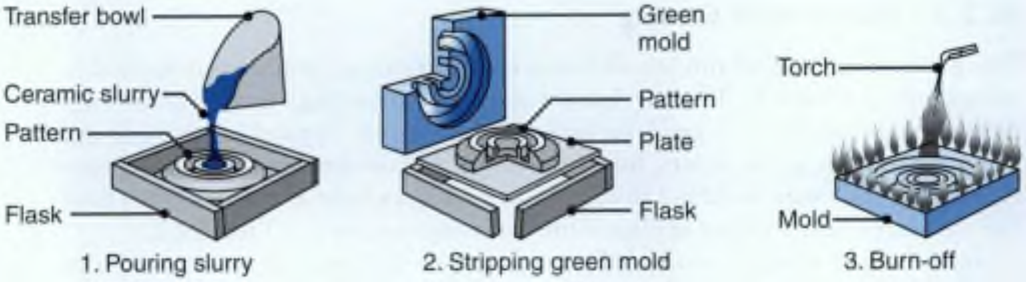


FIGURE 11.11 Sequence of operations in making a ceramic mold. *Source: Metals Handbook*, Vol. 5, 8th ed., ASM International, 1970.

steels, and tool steels. Although the process is somewhat expensive, the castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes.

11.3 Expendable-mold, Expendable-pattern Casting Processes

Evaporative-pattern and investment casting also are referred to as *expendable-pattern* casting processes or *expendable mold–expendable pattern* processes. They are unique in that a mold and a pattern must be produced for each casting, whereas the patterns in the processes described in the preceding section are reusable. Typical applications are cylinder heads, engine blocks, crankshafts, brake components, manifolds, and machine bases.

11.3.1 Evaporative-pattern Casting (Lost-foam Process)

The *evaporative-pattern casting* (EPC) process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting; this process is also known as *lost-foam casting*, or *full-mold casting* (FMC) process. It has become one of the more important casting processes for ferrous and nonferrous metals, particularly for the automotive industry.

In this process, polystyrene beads, containing 5–8% pentane (a volatile hydrocarbon), are placed in a preheated die, usually made of aluminum. Complex patterns may be made by bonding various individual pattern sections using hot-melt adhesive (Section 32.4.1). Polymethylmethacrylate (PMMA) and polyalkylene carbonate also may be used as pattern materials for ferrous castings.

The polystyrene expands and takes the shape of the die cavity; additional heat is applied to fuse and bond the beads together. The die is then cooled and opened, and the polystyrene pattern is removed. The pattern is then coated with a water-based refractory slurry, dried, and placed in a flask. The flask is filled with loose, fine sand, which surrounds and supports the pattern (Fig. 11.12), and may be dried or mixed with bonding agents to give it additional strength. The sand is compacted periodically, without removing the polystyrene pattern; then the molten metal is poured into the mold. The molten metal vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene. Any degradation products from the polystyrene are vented into the surrounding sand.

Because the polymer requires considerable energy to degrade, large thermal gradients are present at the metal–polymer interface; in other words, the molten metal cools faster than it would if it were poured directly into an empty cavity. Consequently, fluidity is less than in sand casting. This has important effects on the microstructure throughout the casting, and also leads to directional solidification of the metal.

The evaporative-pattern process has several advantages over other casting methods:

- The process is relatively simple, because there are no parting lines, cores, or riser systems.
- Inexpensive flasks are used for the process.
- Polystyrene is inexpensive, and can be processed easily into patterns having complex shapes, various sizes, and fine surface detail.
- The casting requires minimal finishing and cleaning operations.

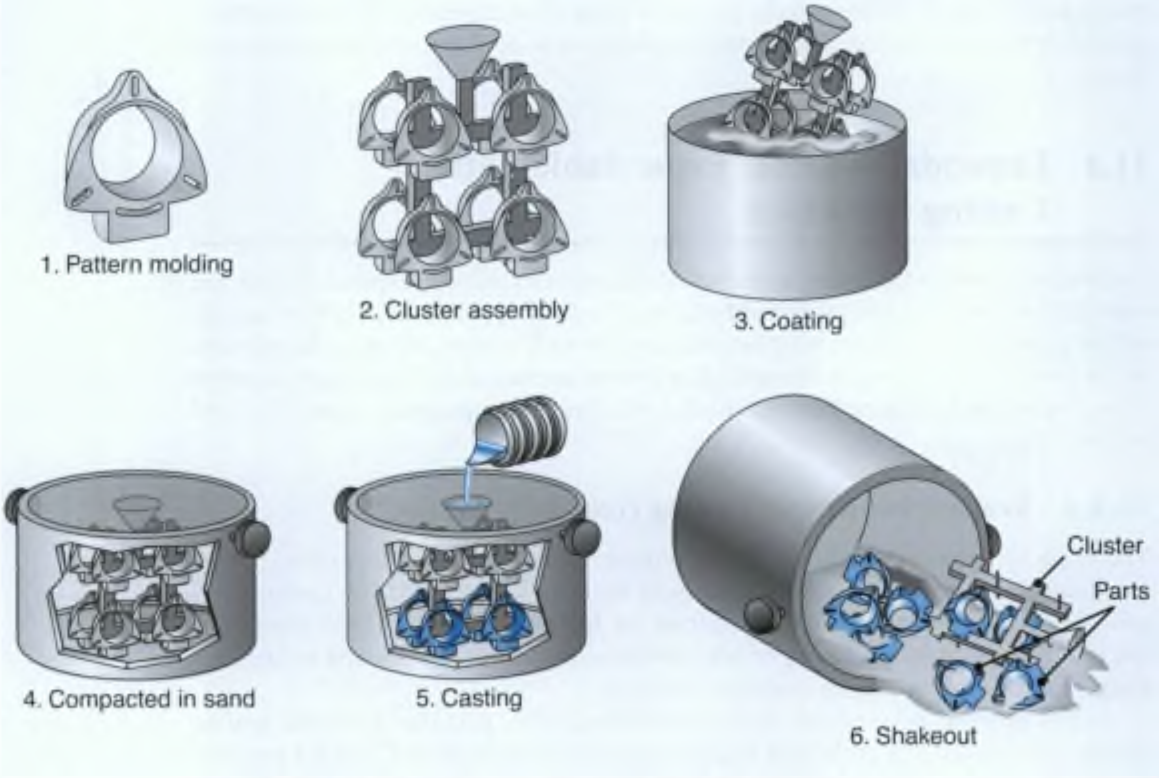


FIGURE 11.12 Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

- The process can be automated and is economical for long production runs; however, the cost to produce the die and the need for two sets of tooling are significant factors.

In a modification of the evaporative-pattern process, called the *Replicast® C-S process*, a polystyrene pattern is surrounded by a ceramic shell; then the pattern is burned out prior to pouring the molten metal into the mold. Its principal advantage over investment casting (which uses wax patterns, Section 11.3.2) is that carbon pickup into the metal is avoided entirely. Further developments in EPC include the production of metal-matrix composites (Sections 9.5 and 19.14). During molding of the polymer pattern, fibers or particles are embedded throughout, which then become an integral part of the casting. Other techniques include the modification and grain refinement of the casting by using grain refiners and modifier master alloys.

CASE STUDY 11.1 Lost-foam Casting of Engine Blocks

One of the most important components in an internal combustion engine is the engine block. Industry trends have focused upon high-quality, low-cost, and lightweight designs. Economic benefits can be attained through casting more complex geometries and by incorporating multiple components into one part. Recognizing that evaporative-pattern casting can simultaneously satisfy all of these requirements, Mercury Castings built a lost-foam casting line to produce aluminum engine blocks and cylinder heads.

One example of a part produced through lostfoam casting is a 45-kW, three-cylinder engine block used for marine applications, such as an outboard motor on a small boat illustrated in Fig. 11.13. Previously manufactured as eight separate die castings, the block was converted to a single 10-kg casting, with a weight and cost savings of 1 kg and $25, respectively, on each block. Lost-foam casting also allowed consolidation of the engine's cylinder head and the exhaust and cooling systems into the block, thus eliminating the associated machining operations and fasteners required in sand-cast or die-cast designs. In addition, since the pattern contained holes, which could be cast without the use of cores, numerous drilling operations were eliminated.

Mercury Marine also was in the midst of developing a new V6 engine, utilizing a new corrosion-resistant aluminum alloy with increased wear resistance. This engine design also required a cylinder block and head integration, featuring hollow sections for water jacket cooling that could not be cored out in die casting or semipermanent mold processes (which were used for its other V6 blocks). Based on the success the foundry had with the three-cylinder lost-foam block, engineers applied this process for casting the V6 die block (Fig. 11.13b). The new engine block involves only one casting, and is lighter and less expensive than the previous designs. Produced with an integrated cylinder head and exhaust and cooling system, this component is cast hollow to develop more efficient water jacket cooling of the engine during its operation.

The company also has developed a pressurized lost-foam process. First, a foam pattern is made, placed in a flask, and surrounded by sand. Then the flask is inserted into a pressure vessel, where a robot pours molten aluminum onto the polystyrene pattern. A lid on the pressure vessel is closed, and a pressure of 1 MPa is applied to the casting until it solidifies, in about 15 min. The result is a casting with better dimensional accuracy, lower porosity, and improved strength, as compared to conventional lost-foam casting.

Source: Courtesy of Mercury Marine.

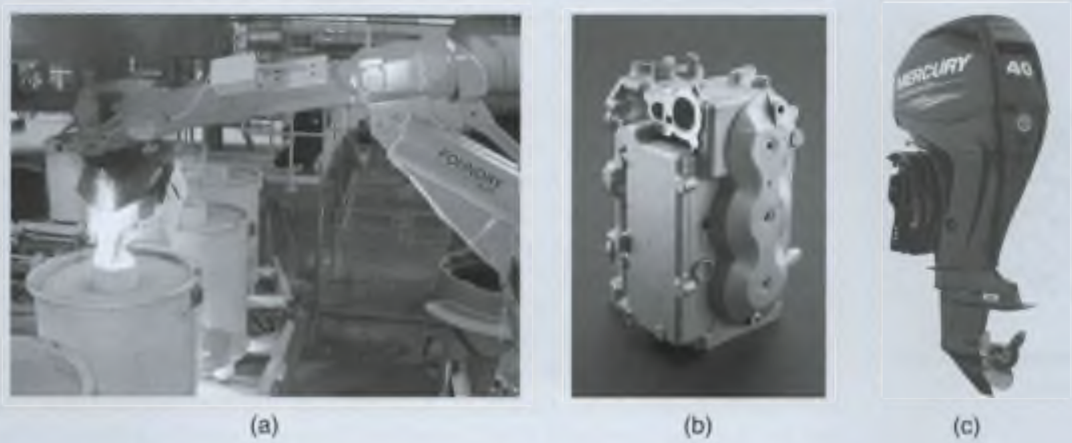


FIGURE 11.13 (a) Metal is poured into a mold for lost-foam casting of a 40-hp, three-cylinder marine engine; (b) finished engine block; and (c) completed outboard motor. *Source:* Mercury Marine.

11.3.2 Investment Casting

The *investment-casting* process, also called the **lost-wax process**, was first used during the period from 4000 to 3000 B.C. Typical parts made are components for office equipment and mechanical components, such as gears, cams, valves, and ratchets. Parts up to 1.5 m in diameter and weighing as much as 1140 kg have been cast successfully by this process. The capabilities of investment casting are given in Table 11.2.

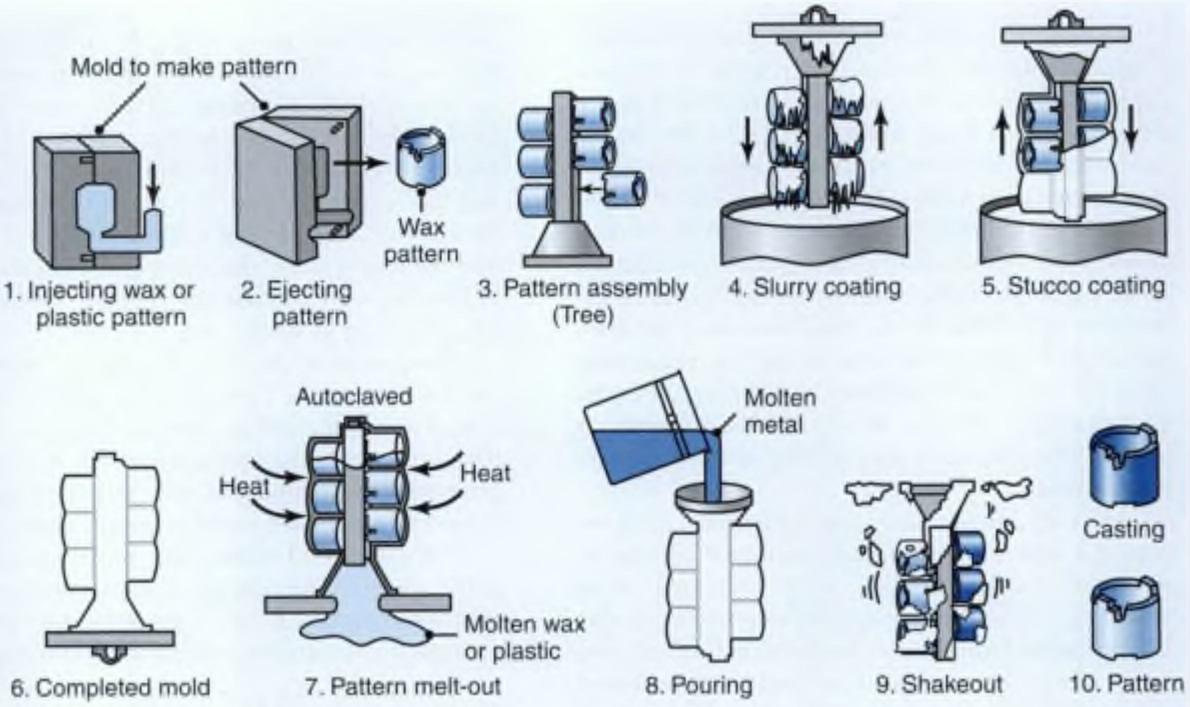


FIGURE 11.14 Schematic illustration of the investment-casting (lost-wax) process. Castings produced by this method can be made with very fine detail and from a variety of metals. *Source:* Courtesy of Steel Founders' Society of America.

Video Solution 11.1 Cast-in- place Gems

QR Code 11.4 Investment casting of sculptures. (*Source:* Courtesy of the National Sculpture Society)

The sequence involved in investment casting is shown in Fig. 11.14. The pattern is made of wax, or of a plastic such as polystyrene, by molding or rapid-prototyping techniques (Chapter 20). It is then dipped into a slurry of refractory material such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness, for higher strength. Note that smaller particles can be used for the initial coating to develop a better surface finish in the casting; subsequent layers use larger particles and are intended to increase the coating thickness quickly.

The term *investment* derives from the fact that the pattern is invested (surrounded) with the refractory material. Wax patterns require careful handling, because they are not strong enough to withstand the forces encountered during mold making; unlike plastic patterns, however, wax can be recovered and reused.

The one-piece mold is dried in air and heated to a temperature of 90°–175°C; it is held in an inverted position for a few hours to melt out the wax. The mold is then fired to 650°–1050°C for about four hours (depending on the metal to be cast), to drive off the water of crystallization (chemically combined water) and to burn off any residual wax. After the metal has been poured and has solidified, the mold is broken up and the casting is removed.

A number of patterns can be joined to make one mold, called a **tree** (Fig. 11.14), significantly increasing the production rate. For small parts, the tree can be inserted into a permeable flask and filled with a liquid slurry investment. The investment is then placed into a chamber and evacuated (to remove the air bubbles in it) until the mold solidifies. The flask is usually placed in a vacuum-casting machine, so that the molten metal is drawn into the permeable mold producing fine detail.

Although the mold materials and labor involved make the lost-wax process costly, it is suitable for casting high-melting-point alloys, with good surface finish and close dimensional tolerances. Few or no finishing operations are required, which otherwise would add significantly to cost of the casting. The process is capable of producing intricate shapes from a wide variety of ferrous and nonferrous metals and alloys, with parts weighing from 1 g to 35 kg. Advances include the casting of titanium aircraft-engine and structural airframe components, with wall thicknesses on the order of 1.5 mm, thus competing with previously used sheet-metal structures.

FIGURE 11.15 Investment casting of an integrally cast rotor for a gas turbine. (a) Wax pattern assembly. (b) Ceramic shell around wax pattern. (c) Wax is melted out and the mold is filled, under a vacuum, with molten superalloy. (d) The cast rotor, produced to net or near-net shape. *Source:* Courtesy of Howmet Corporation.

Ceramic-shell Investment Casting. A variation of the investment-casting process is *ceramic-shell casting*. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed (see Section 4.12) of fine-grained fused silica or zircon powder. The pattern is then dipped into coarser grained silica, to build up additional coatings and develop a proper thickness so that the pattern can withstand the thermal shock during pouring. The rest of the procedure is similar to investment casting. The process is economical and is used extensively for the precision casting of steels and high-temperature alloys.

The sequence of operations involved in making a turbine disk by this method is shown in Fig. 11.15. If ceramic cores are used in the casting, they are removed by leaching using caustic solutions under high pressure and temperature. The molten metal may be poured in a vacuum to extract evolved gases and reduce oxidation, thus improving the casting quality. To further reduce microporosity, the castings made by this, as well as other processes, are subjected to hot isostatic pressing.

CASE STUDY 11.2 Investment-cast Superalloy Components for Gas Turbines

Investment-cast superalloys have been replacing wrought counterparts in high-performance gas turbines since the 1960s. The microstructure of an integrally investment-cast gas-turbine rotor is shown in the upper half of Fig. 11.16; note the fine, uniform equiaxed grains throughout the rotor cross-section. Casting procedures include the use of a nucleant addition to the molten metal, as well as close control of its superheat, pouring techniques, and the cooling rate of the casting (see Section 10.2).

In contrast, note the coarse-grained structure in the lower half of the figure, showing the same type of rotor cast conventionally; this rotor has inferior properties as compared with the fine-grained rotor. Due to further developments in these processes, the proportion of cast parts to other parts in aircraft engines has increased from 20% to about 45% by weight.

(*continued*)

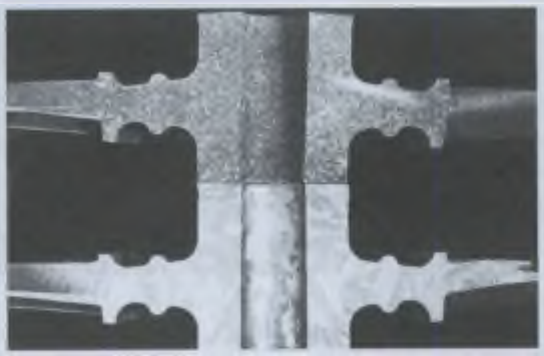


FIGURE 11.16 Cross-section and microstructure of two rotors: (top) investment cast; (bottom) conventionally cast. *Source:* Courtesy of ASM International.

CASE STUDY 11.3 Investment Casting of Total Knee Replacements

With major advances in medical care in the past few decades, life expectancies have increased significantly, but so have expectations for the quality of life in later years to remain high. One of the reasons for improvements in the past 40 years has been the great success of orthopedic implants. Hip, knee, shoulder, spine, and other implants have resulted in increased activity and reduced pain for millions worldwide.

An example of an orthopedic implant that has greatly improved quality of life is the *total knee replacement* (TKR), as shown in Fig. 11.17a. TKRs are very popular and reliable for the relief of osteoarthritis, a chronic and painful degenerative condition of the knee joint, that typically sets in after middle age. TKRs consist of multiple parts, including femoral, tibial, and patellar components. Typical materials used include cobalt alloys, titanium alloys, and ultrahigh-molecular-weight polyethylene (UHMWPE; Section 7.6). Each material is chosen for specific properties that are important in the application of the implant.

This case study describes the investment casting of femoral components of TKRs, which are produced from cobalt–chrome alloy (Section 6.6). The manufacturing process begins with injection molding of the patterns, which are then hand assembled onto trees, as shown in Fig. 11.17b. The patterns are spaced properly on a central wax sprue, and then are welded in place by dipping them into molten wax and pressing them against the sprue, until the patterns are held in place. The final assembled tree, shown in Fig. 11.18a, contains 12 knee implants arranged into four rows.

The completed trees are then placed in a rack, where they form a queue and are then taken in order by an industrial robot (Section 37.6). The robot follows a set sequence in building up the mold. It first dips the pattern into a dilute slurry, and then rotates it under a sifting of fine particles. Next, the robot moves the tree beneath a blower to quickly dry the ceramic coating, and then it repeats the cycle. After a few cycles of such exposure to dilute slurry and fine particles, the details of the patterns are well produced, and good surface finish is ensured. The robot then dips the pattern into a thicker slurry, that quickly builds up the mold thickness (Fig. 11.18c). The trees are then dried and placed into a furnace to melt out and burn the wax. They are placed into another furnace to preheat them in preparation for the casting process.

A mold, ready for investment casting, is placed into a casting machine. The mold is placed upside down on the machine, directly over a measured volume of molten cobalt chrome. The machine then rotates so that the metal flows into the mold, as shown in Fig. 11.17d. The tree is then allowed to cool and the mold is removed. The cast parts are machined from the tree and are further machined and polished to the required dimensional tolerance and surface finish. Figure 11.18 shows the progression of investment casting, from tree, to investment, to casting. The parts are then removed from the tree and subjected to finishing operations.

Source: Courtesy of M. Hawkins, Zimmer, Inc.

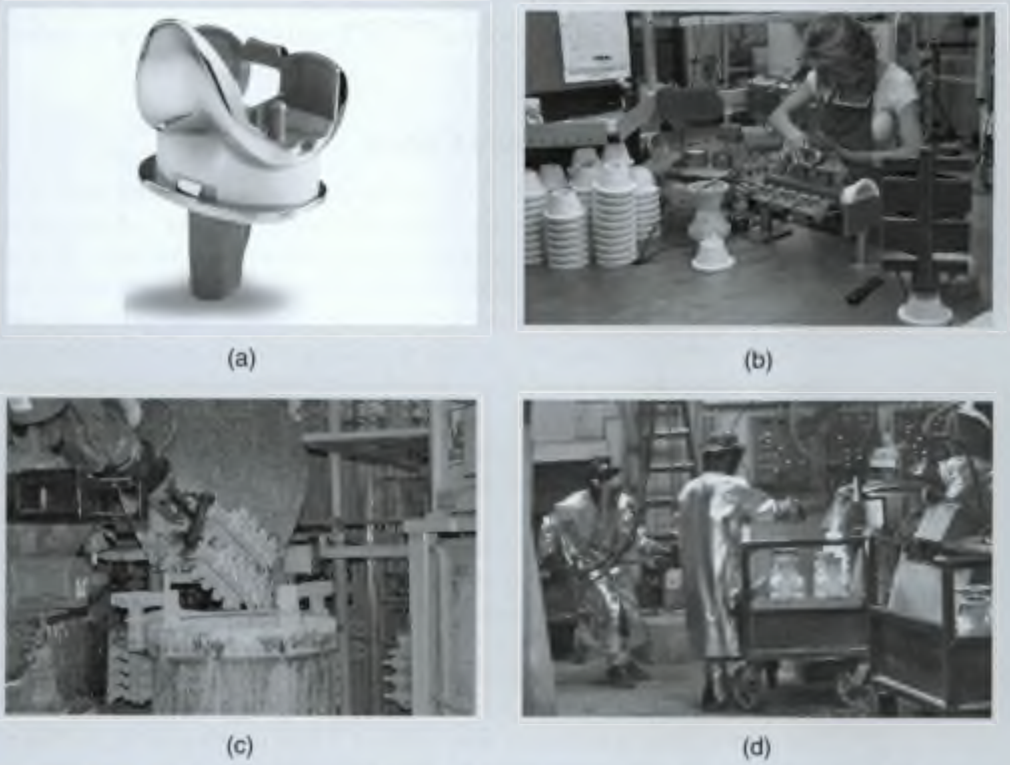

(a) (b) (c) (d)

FIGURE 11.17 Manufacture of total knee replacements. (a) The Zimmer NexGen mobile-bearing knee (MBK); the femoral portion of the total knee replacement is the subject of this case study. (b) Assembly of patterns onto a central tree. (c) Dipping of the tree into slurry to develop a mold from investment. (d) Pouring of metal into a mold. *Source:* Courtesy of M. Hawkins, Zimmer, Inc.

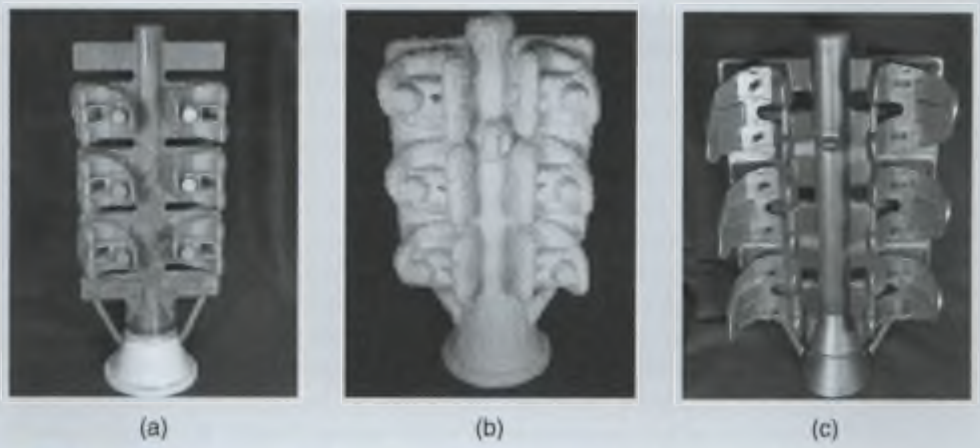

(a) (b) (c)

FIGURE 11.18 Progression of the tree. (a) After assembly of blanks onto the tree; (b) after coating with investment; (c) after removal from the mold. *Source:* Courtesy of M. Hawkins, Zimmer, Inc.

11.4 Permanent-mold Casting Processes

Permanent-mold casting processes have certain advantages over other casting processes, as described in this section.

11.4.1 Permanent-mold Casting

In *permanent-mold casting* (also called *hard-mold casting*), two halves of a mold are made from materials with high resistance to erosion and thermal fatigue, such as cast iron, steel, bronze, graphite, or refractory metal alloys. Typical parts made are automobile pistons, cylinder heads, connecting rods, gear blanks for appliances, and kitchenware. Parts that can be made economically generally weigh less than 25 kg, although special castings, weighing a few hundred kilograms, have been made using this process. The capabilities of permanent-mold casting are given in Table 11.2.

The mold cavity and gating system are machined into the mold and thus become an integral part of it. To produce castings with internal cavities, cores made of metal or sand aggregate are placed in the mold prior to casting. Typical core materials are oil-bonded or resin-bonded sand, plaster, graphite, gray iron, low-carbon steel, and hot-work die steel. Gray iron is used most commonly, particularly for large molds used for aluminum and magnesium casting. Inserts also are used in various locations of the mold.

In order to increase the life of permanent molds, the surfaces of the mold cavity are usually coated with a refractory slurry, such as sodium silicate and clay, or are sprayed with graphite every few castings. These coatings also serve as parting agents and as thermal barriers, thus controlling the rate of cooling of the casting. Mechanical ejectors (such as pins located in various parts of the mold) may be required for the removal of complex castings. Ejectors usually leave small round impressions, which generally are not significant.

The molds are clamped together by mechanical means, and heated to about 150°–200°C to facilitate metal flow and reduce thermal damage to the dies. Molten metal is then poured through the gating system. After solidification, the molds are opened and the casting is removed. The mold often incorporates special cooling features, such as a means for pumping cooling water through the channels located in the mold and the use of cooling fins. Although the permanent-mold casting operation can be performed manually, it is often automated for large production runs.

The process is used mostly for aluminum, magnesium, and copper alloys, as well as for gray iron because of their generally lower melting points, although steels also can be cast using graphite or heat-resistant metal molds. Permanent-mold casting produces castings with good surface finish, close dimensional tolerances, uniform and good mechanical properties, and at high production rates.

Although equipment costs can be high, because of high die costs, labor costs are kept low through automation. The process is not economical for small production runs and is not suitable for intricate shapes, because of the difficulty in removing the casting from the mold. However, easily collapsible sand cores can be used (in a process called **semipermanent mold casting**), which are then removed from castings, leaving intricate internal cavities.

11.4.2 Vacuum Casting

A schematic illustration of the *vacuum-casting* process, also called *countergravity low-pressure* (CL) *process* (not to be confused with the vacuum-molding process

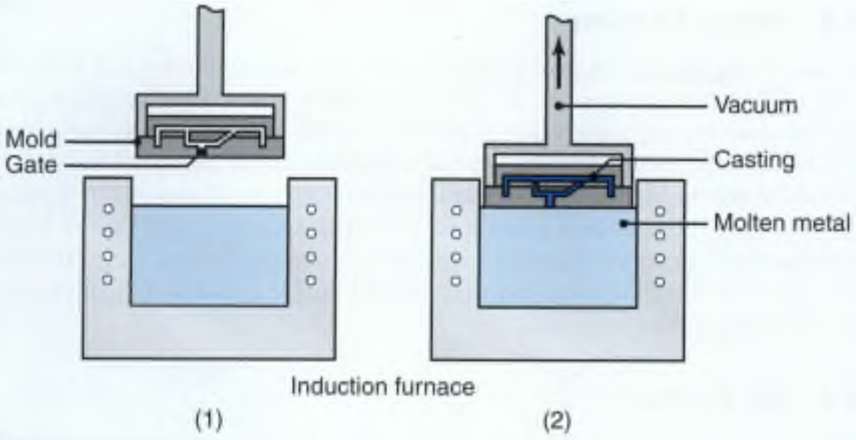


FIGURE 11.19 Schematic illustration of the vacuum-casting process; note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source:* After R. Blackburn.

described in Section 11.2.1), is shown in Fig. 11.19. Vacuum casting is an alternative to investment, shell-mold, and green-sand casting, and is suitable particularly for thin-walled complex shapes, with uniform properties. Typical parts made are superalloy gas-turbine components with walls as thin as 0.5 mm.

In this process, a mixture of fine sand and urethane is molded over metal dies, and cured with amine vapor. The mold is then held with a robot arm and immersed partially into molten metal held in an induction furnace. The metal may be melted in air (*CLA process*) or in a vacuum (*CLV process*). The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold. The metal in the furnace is usually at a temperature of 55°C above the liquidus temperature of the alloy; consequently, it begins to solidify within a very short time.

The process can be automated, with production costs that are similar to those for green-sand casting. Carbon, low- and high-alloy steel, and stainless steel parts, weighing as much as 70 kg, have been vacuum cast by this method. CLA castings are made easily at high volume and relatively low cost, and CLV parts usually involve reactive metals, such as aluminum, titanium, zirconium, and hafnium.

11.4.3 Slush Casting

It was noted in Fig. 10.11 that a solidified skin develops in a casting, which becomes thicker with time. Thin-walled hollow castings can be made by permanent-mold casting using this principle, in a process called *slush casting*. The molten metal is poured into the metal mold. After the desired thickness of solidified skin is obtained, the mold is inverted (or slung) and the remaining liquid metal is poured out. The mold halves are then opened and the casting is removed. Note that this operation is similar to making hollow chocolate shapes, eggs, and other confectionaries. Slush casting is suitable for small production runs, and is generally used for making ornamental and decorative objects (such as lamp bases and stems) and toys from low-melting-point metals such as zinc, tin, and lead alloys.

11.4.4 Pressure Casting

In the two permanent-mold processes described previously, the molten metal flows into the mold cavity by gravity. In *pressure casting* (also called *pressure pouring* or *low-pressure casting*), the molten metal is forced upward by gas pressure into a graphite or metal mold. The pressure is maintained until the metal has solidified completely in the mold. The molten metal also may be forced upward by a vacuum, which also removes dissolved gases and produces a casting with lower porosity. Pressure casting is generally used for high-quality castings, such as steel railroad-car wheels, although these wheels also may be cast in sand molds or semipermanent molds made of graphite and sand.

11.4.5 Die Casting

The *die-casting* process, developed in the early 1900s, is a further example of permanent-mold casting. The European term for this process is *pressure die casting*, and should not be confused with pressure casting, described above. Typical parts made by die casting are housings for transmissions, business-machine and appliance components, hand-tool components, and toys. The weight of most castings generally ranges from less than 90 g to about 25 kg. Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low, because the process is semi- or fully automated. Die casting is economical for large production runs. The capabilities of die casting are given in Table 11.2.

In the die-casting process, molten metal is forced into the die cavity at pressures ranging from 0.7 to 700 MPa. There are two basic types of die-casting machines: *hot-* and *cold-chamber*.

The **hot-chamber process** (Fig. 11.20) involves the use of a piston, which forces a specific volume of molten metal into the die cavity through a gooseneck and nozzle. Pressures range up to 35 MPa, with an average of about 15 MPa. The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling (thereby reducing cycle time), dies are usually cooled by circulating water or oil, through various passageways in the die block. Low-melting-point alloys (such as zinc, magnesium, tin, and lead) commonly are cast using this process. Cycle times usually range from 200 to 300 shots (individual injections) per hour, for zinc, although very small components, such as zipper teeth, can be cast at rates of 18,000 shots per hour.

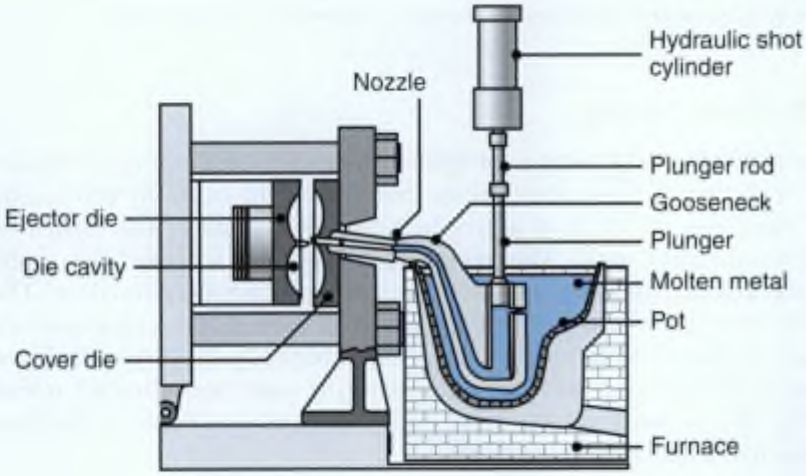


FIGURE 11.20 Schematic illustration of the hot-chamber die-casting process.

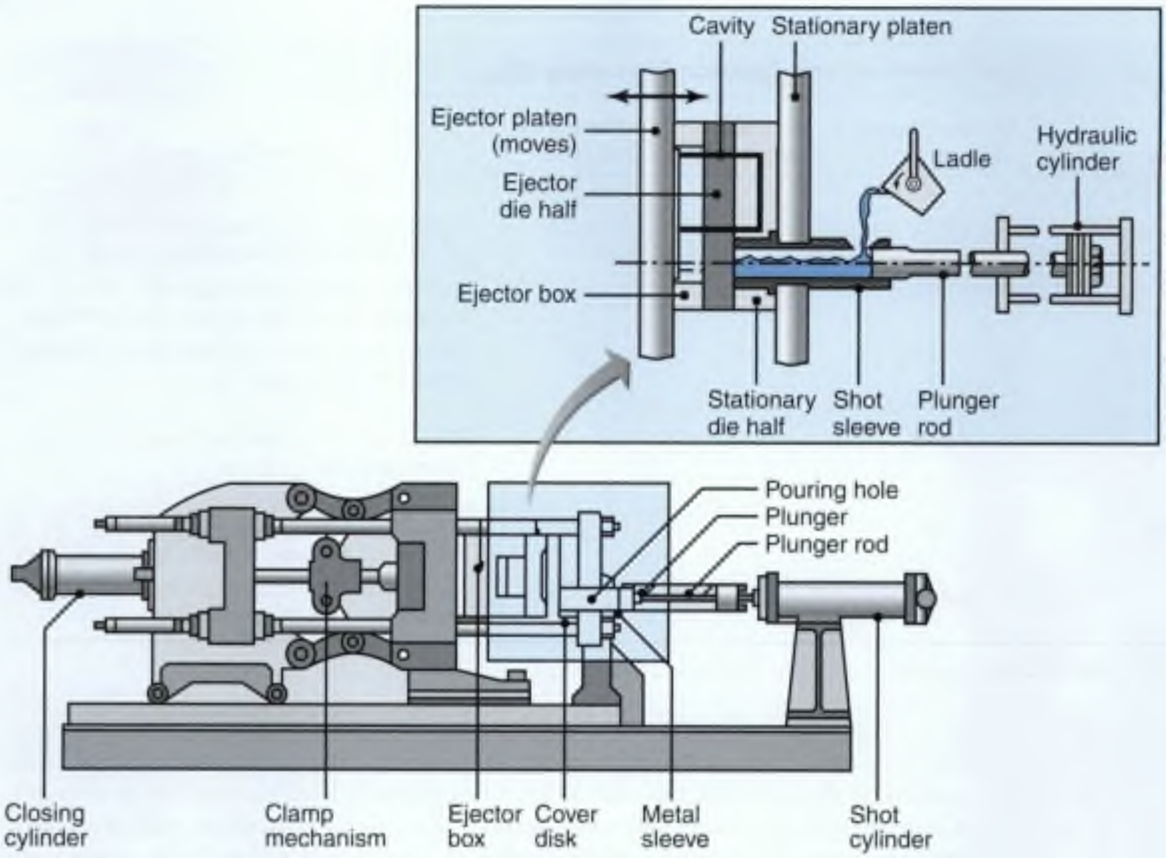


FIGURE 11.21 Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure during casting.

In the **cold-chamber process** (Fig. 11.21), molten metal is poured into the injection cylinder (*shot chamber*). The chamber is not heated, hence the term *cold chamber*. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa although they may be as high as 150 MPa.

The machines may be horizontal (as shown in the figure), or vertical, in which case the shot chamber is vertical. High-melting-point alloys of aluminum, magnesium, and copper normally are cast using this method, although ferrous and other metals also can be cast. Molten-metal temperatures begin at about 600°C for aluminum and some magnesium alloys, and increase considerably for copper-based and ironbased alloys.

Process Capabilities and Machine Selection. Die casting has the capability for rapid production of high-quality parts with complex shapes, especially with aluminum, brass, magnesium, and zinc (Table 11.3). It also produces good dimensional accuracy and surface details, so that parts require little or no subsequent machining or finishing operations (net-shape forming). Because of the high pressures involved, walls as thin as 0.38 mm are produced, which are thinner than those obtained by other casting methods. However, ejector marks remain on part surfaces, as may small amounts of flash (thin material squeezed out between the dies) at the die parting line.

A typical part made by die casting is the aluminum impeller shown in Fig. 11.1d; note the intricate shape and fine surface detail. For certain parts, die casting can compete favorably with other manufacturing methods (such as sheet-metal stamping

TABLE 11.3

Properties and Typical Applications of Some Common Die-casting Alloys

Alloy	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Aluminum				
380 (3.5 Cu–8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium				
AZ91 B (9 Al–0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc				
No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
No. 5 (4 Al–1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: Images provided by: North American Die Casting Association, Wheeling, Illinois.

and forging) or other casting processes. In addition, because the molten metal chills rapidly at the die walls, the casting has a fine-grained, hard skin with high strength. Consequently, the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. With good surface finish and dimensional accuracy, die casting can produce smooth surfaces for bearings that otherwise would normally have to be machined.

Components such as pins, shafts, and threaded fasteners can be die cast integrally; called **insert molding**, this process is similar to placing wooden sticks in popsicles prior to freezing (see also Section 19.3). For good interfacial strength, insert surfaces may be knurled (see Fig. 23.11), grooved, or splined. Steel, brass, and bronze inserts are commonly used in die-casting alloys. In selecting insert materials, the possibility of galvanic corrosion should be taken into account; to avoid this potential problem, the insert can be insulated, plated, or surface treated.

Because of the high pressures involved, dies for die casting have a tendency to separate unless clamped together tightly (see Fig. 11.21). Die-casting machines are thus rated according to the clamping force that can be exerted, to keep the dies closed during casting. The capacities of commercially available machines range from about 23 to 2700 metric tons. Other factors involved in the selection of die-casting machines are die size, piston stroke, shot pressure, and cost.

Die-casting dies (Fig. 11.22) may be *single cavity, multiple cavity* (several identical cavities), *combination cavity* (several different cavities), or *unit dies* (simple, small dies that can be combined in two or more units in a master holding die). Typically, the ratio of die weight to part weight is 1000 to 1. Thus, for example, the die for a casting weighing 2 kg would weigh about 2000 kg. The dies are usually made of hot-work die steels or mold steels (see Section 5.7). Die wear increases with the temperature of the molten metal. **Heat checking** of dies (surface cracking from repeated heating and cooling of the die, described in Section 3.6) can be a problem. When the materials are selected and maintained properly, however, dies can last more than a half million shots before any significant die wear takes place.

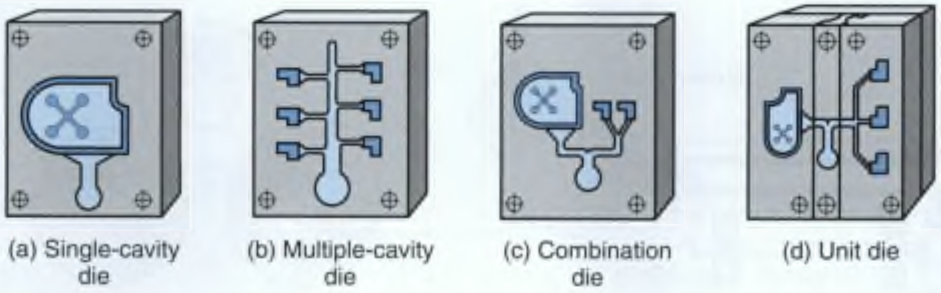


FIGURE 11.22 Various types of cavities in a die-casting die. *Source:* Images provided by: North American Die Casting Association, Wheeling, Illinois.

CASE STUDY 11.4 Die Casting of a Headlight Mount

Figure 11.23 shows a die-cast aluminum component of a daytime running lamp and turn signal for an automobile. Aluminum was preferable to plastic, because of its higher heat sink characteristics and rigidity, and also because tight tolerances were required for mounting and providing wiring access to LED bulbs. The fin size, thickness, and spacing were determined from a heat transfer analysis. Given this constraint, the fins were tapered to allow for easy removal from a die, and the corner radii were designed to prevent distortion during ejection. The part was then oriented so that mounting holes and pockets were coplanar to the die parting line to simplify die fabrication.

Heating channels were incorporated into the die near the thin sections to slow cooling, while cooling channels were incorporated near the thick sections. The resulting thermal balance led to lower distortion in the final product. The final product was cast from 380 aluminum, and measures 100 mm × 75 mm × 100 mm for the turn signal and 250 mm × 100 mm × 50 mm for the daytime running light sub-assembly.

FIGURE 11.23 Die-cast running light and turn signal mounts produced from die-cast aluminum. *Source:* Courtesy of American Foundry Society.

11.4.6 Centrifugal Casting

As its name implies, the *centrifugal-casting* process utilizes *inertia* (caused by rotation) to force the molten metal into the mold cavities, a method that was first suggested in the early 1800s. The capabilities of centrifugal casting are given in Table 11.2. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

True Centrifugal Casting. In *true centrifugal casting*, hollow cylindrical parts (such as pipes, gun barrels, bushings, engine-cylinder liners, bearing rings with or without flanges, and street lampposts) are produced by the technique shown in Fig. 11.24. In this process, molten metal is poured into a rotating mold; the axis of rotation

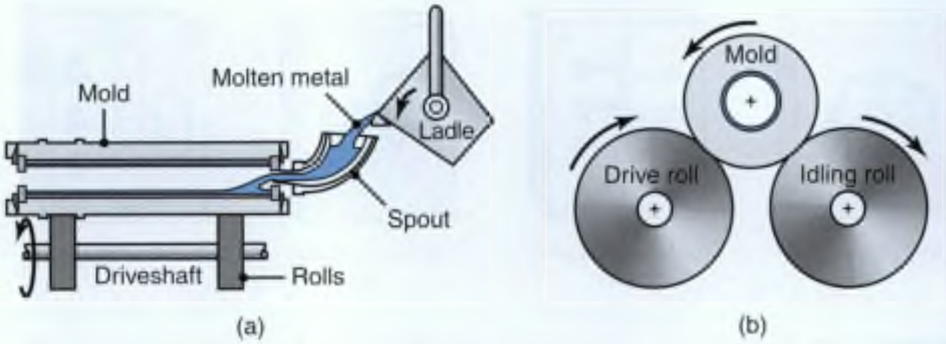


FIGURE 11.24 (a) Schematic illustration of the centrifugal-casting process; pipes, cylinder liners, and similarly shaped parts can be cast with this process. (b) Side view of the machine.

is usually horizontal, but can be vertical for short workpieces. Molds are made of steel, iron, or graphite, and may be coated with a refractory lining to increase mold life. The mold surfaces can be shaped so that pipes with various external designs can be cast. The inner surface of the casting remains cylindrical, because the molten metal is distributed uniformly by the centrifugal forces. However, because of density differences, lighter elements (such as dross, impurities, and pieces of the refractory lining in the mold) tend to collect on the inner surface of the casting; consequently, the properties of the casting can vary throughout its thickness.

Cylindrical parts ranging from 13 mm to 3 m in diameter and 16 m long can be cast centrifugally, with wall thicknesses ranging from 6 to 125 mm. The pressure generated by the centrifugal force is high; such high pressure is necessary for casting thick-walled parts. Castings with good quality, dimensional accuracy, and external surface detail are produced by this process.

Video Solution 11.2 Force and Energy in Centrifugal Casting

Semicentrifugal Casting. An example of semicentrifugal casting is shown in Fig. 11.25(a). This method is used to cast parts with rotational symmetry, such as a wheel with spokes.

Centrifuging. In *centrifuging*, also called *centrifuge casting*, mold cavities are placed at a certain distance from the axis of rotation. The molten metal is poured from the center, and is forced into the mold by centrifugal forces (Fig. 11.25b). The properties of the castings can vary by distance from the axis of rotation, as in true centrifugal casting.

11.4.7 Squeeze Casting and Semisolid-metal Forming

Two casting processes that incorporate the features of both casting and forging (Chapter 14) are squeeze casting and semisolid-metal forming.

Squeeze Casting. The *squeeze-casting* or *liquid-metal forging* process was invented in the 1930s, but developed for industrial applications in the 1960s, and involves the solidification of molten metal under high pressure (Fig. 11.26). Typical products made are automotive components and mortar bodies (a short-barreled cannon). The machinery includes a die, punch, and ejector pin. The pressure applied by the punch keeps the entrapped gases in solution, and the contact under high pressure at the

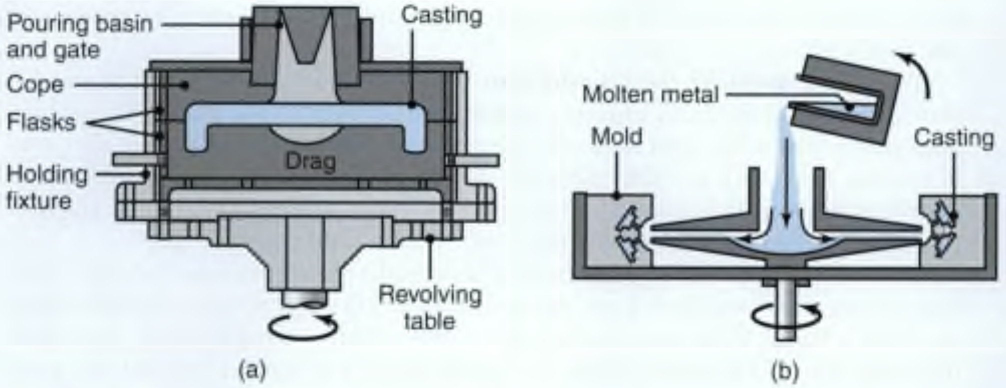


FIGURE 11.25 (a) Schematic illustration of the semicentrifugal casting process; wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging; the molds are placed at the periphery of the machine and the molten metal is forced into the molds by centrifugal force.

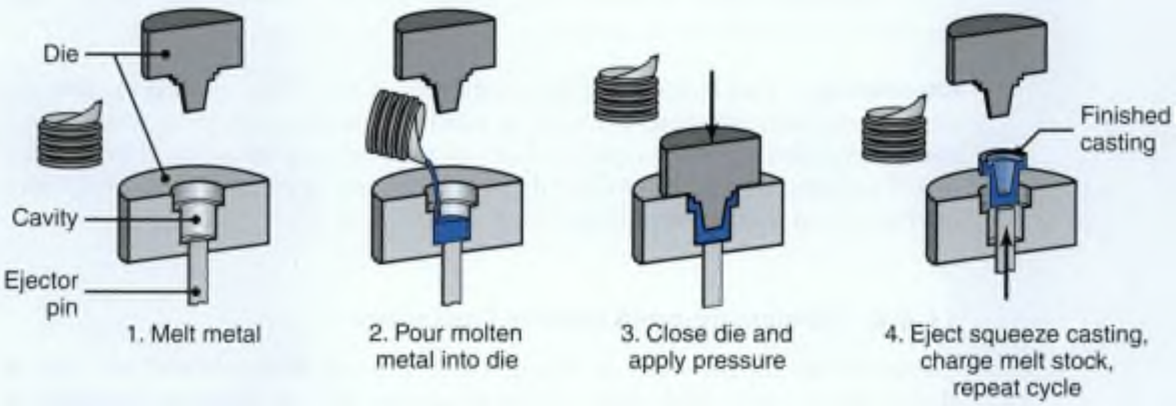


FIGURE 11.26 Sequence of operations in the squeeze-casting process; this process combines the advantages of casting and forging.

die–metal interface promotes rapid heat transfer, thus resulting in a casting with a fine microstructure and good mechanical properties.

The application of pressure also overcomes feeding difficulties that may arise when casting metals with a long freezing range (Section 10.2.2). Complex parts can be made to near-net shape, with fine surface detail using both nonferrous and ferrous alloys.

Semisolid-metal Forming. *Semisolid-metal forming* (also called *mushy-state processing*; see Fig. 10.4) was developed in the 1970s. When it enters the die, the metal (consisting of liquid and solid components) is stirred so that all of the dendrites are crushed into fine solids; when cooled in the die, it develops into a fine-grained structure. The alloy exhibits thixotropic behavior, described in Section 10.2.3; hence the process is also called **thixoforming** or **thixomolding**, meaning its viscosity decreases when agitated. Thus, at rest and above its solidus temperature, the molten alloy has the consistency of butter, but when agitated vigorously, its consistency becomes more like motor oil.

Processing metals in their mushy state also has led to developments in *mushy-state extrusion*, similar to injection molding (described in Section 19.3), *forging*, and *rolling* (hence the term *semisolid metalworking*). These processes are also used in making parts with specially designed casting alloys, wrought alloys, and metal-matrix composites (Section 9.5). They also have the capability for blending granules of different alloys, called *thixoblending*, for specific applications.

Thixotropic behavior also has been utilized in developing technologies that combine casting and forging of parts, using cast billets that are forged when the metal is 30–40% liquid. Parts made include automotive control arms, brackets, and steering components. Processing steels by thixoforming has not yet reached the same stage as with aluminum and magnesium, largely because of the high temperatures involved which adversely affect die life and the difficulty in making complex shapes.

The advantages of semisolid metal forming over die casting are: (a) the structures developed are homogeneous, with uniform properties, lower porosity, and high strength; (b) both thin and thick parts can be made; (c) casting alloys as well as wrought alloys can be used; (d) parts can subsequently be heat treated; and (e) the lower superheat results in shorter cycle times. However, material and overall costs are higher than those for die casting.

Rheocasting. This technique, first investigated in the 1960s, is used for forming metals in the semisolid state. The metal is heated to just above its solidus temperature, and poured into a vessel to cool it down to the semisolid state; the slurry is then mixed and delivered to the mold or die. This process is being used successfully with aluminum and magnesium alloys.

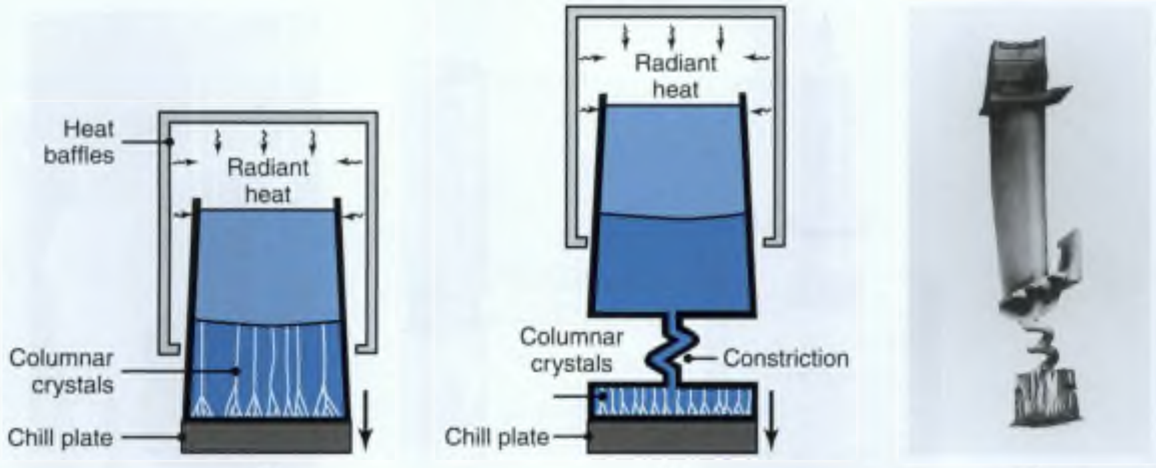
11.4.8 Composite-mold Casting Operations

Composite molds are made of two or more different materials and are used in shell molding and various other casting processes; they are generally employed in casting complex shapes, such as impellers for turbines. Composite molds increase the strength of the mold, improve the dimensional accuracy and surface finish of the castings, and can help reduce overall costs and processing time. Molding materials commonly used are shells (made as described in Section 11.2.2), plaster, sand with binder, metal, and graphite. These molds also may include cores and chills to control the rate of solidification in critical areas of castings.

11.5 Casting Techniques for Single-crystal Components

This section describes the techniques used to cast single-crystal components, such as gas turbine blades which generally are made of nickel-based superalloys, and used in the hot stages of the engine.

Conventional Casting of Turbine Blades. In the *conventional-casting process*, the molten metal is poured into a ceramic mold, and begins to solidify at the mold walls. The grain structure developed is polycrystalline, similar to that shown in



(a) (b) (c)

FIGURE 11.27 Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with the constriction portion still attached. (See also Fig. 1.1) *Source:* (a) and (b) After B.H. Kear, (c) Courtesy of ASM International.

Fig. 10.2c. However, the presence of grain boundaries makes this structure susceptible to creep and cracking along the boundaries, under the centrifugal forces and elevated temperatures commonly encountered in an operating gas turbine.

Directionally Solidified Blades. The *directional-solidification process* (Fig. 11.27a) was first developed in 1960. The ceramic mold, supported by a water-cooled chill plate, is preheated by radiant heating; after the metal is poured into the mold, the chill-plate assembly is lowered slowly. Crystals begin to grow at the chill-plate surface and on upward, like the *columnar grains* shown in Fig. 10.3. The blade is solidified directionally, with longitudinal but no transverse grain boundaries. The blade is thus stronger in the direction of centrifugal forces developed in the gas turbine.

Single-crystal Blades. In *crystal growing*, developed in 1967, the mold has a constriction in the shape of a corkscrew or helix (Figs. 11.27b and c), with a cross-section so small that it allows only one crystal to fit through. The mechanism of crystal growth is such that only the most favorably oriented crystals are able to grow through the helix (a situation similar to that shown in Fig. 10.3), because all others are intercepted by the walls of the helical passage.

As the assembly is slowly lowered, a single crystal grows upward through the constriction and begins to grow in the mold; strict control of the rate of movement is essential. Although single-crystal blades are more expensive than other types, the absence of grain boundaries makes them resistant to creep and thermal shock, hence they have a longer and more reliable service life.

Single-crystal Growing. Single-crystal growing is a major activity in the semiconductor industry, in the manufacture of the silicon wafers for microelectronic devices (Chapter 28). There are two basic methods of crystal growing:

- In the **crystal-pulling method**, also known as the **Czochralski** (CZ) **process** (Fig. 11.28), a seed crystal is dipped into the molten metal, and then pulled

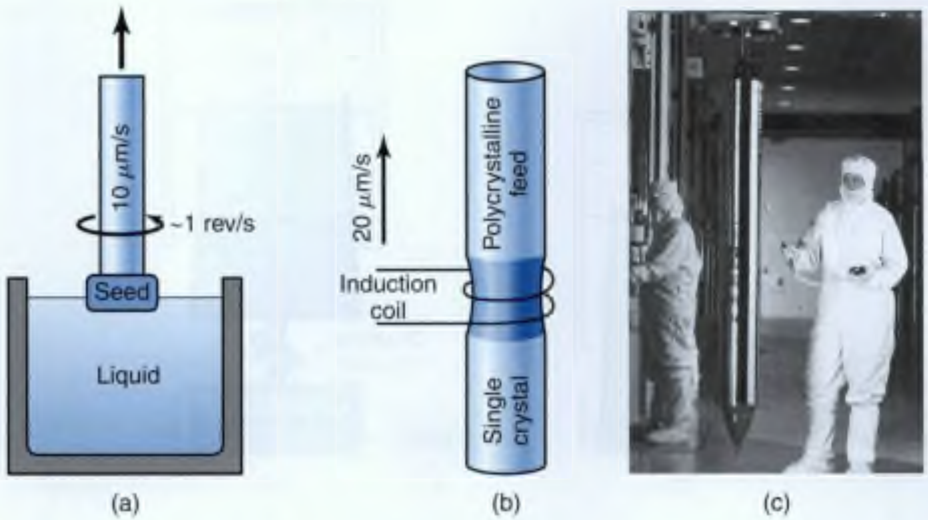


FIGURE 11.28 Two methods of crystal growing: (a) crystal pulling (Czochralski process) and (b) the floating-zone method. Crystal growing is especially important in the semiconductor industry (Chapter 28). (c) A single-crystal ingot produced by the Czochralski process. *Source:* Courtesy of Intel Corporation.

up slowly (at a rate of about 10 μm/s) while being rotated. The liquid metal begins to solidify on the seed, and the crystal structure of the seed continues throughout. *Dopants* (alloying elements, Section 28.3) may be added to the liquid metal to impart specific electrical properties. Single crystals of silicon, germanium, and various other elements are grown using this process. Singlecrystal ingots up to 400 mm in diameter and over 2 m in length have been produced by this technique, although 300 mm ingots are more common in the production of silicon wafers for integrated circuit manufacture (Part V).

- The **floating-zone method** (Fig. 11.28b) starts with a rod of polycrystalline silicon resting on a single crystal; an induction coil then heats these two pieces while the coil moves slowly upward. The single crystal grows upward, while maintaining its orientation. Thin wafers are then cut from the rod, cleaned, and polished for use in microelectronic device fabrication. This process is suitable for producing diameters under 150 mm with very low levels of impurities.

11.6 Rapid Solidification

The properties of *amorphous alloys*, also known as *metallic glasses*, were described in Section 6.14. The technique for making these alloys (called *rapid solidification*) involves cooling the molten metal, at rates as high as 10^6 K/s, so that it does not have sufficient time to crystallize (see also Fig. 1.11). Rapid solidification results in a significant extension of solid solubility (Section 4.2), grain refinement, and reduced microsegregation (see Section 10.2.3), among other effects.

In a common method, called **melt spinning** (Fig. 11.29), the alloy is melted by induction in a ceramic crucible. It is then propelled, under high gas pressure, against a rotating copper disk (chill block), which chills the alloy rapidly (**splat cooling**).

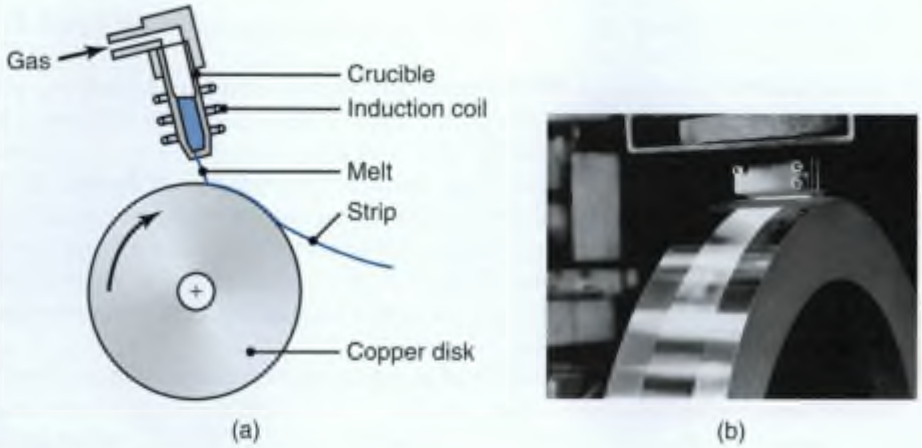


FIGURE 11.29 (a) Schematic illustration of melt spinning to produce thin strips of amorphous metal. (b) Photograph of nickel-alloy production through melt spinning. *Source:* Courtesy of Siemens AG.

11.7 Inspection of Castings

Several methods can be used to inspect castings to determine their quality and the presence and types of any defects. Castings can be inspected *visually*, or *optically*, for surface defects. Subsurface and internal defects are investigated using various nondestructive techniques, described in Section 36.10. In *destructive testing* (Section 36.11), specimens are removed from various sections of a casting, and tested for strength, ductility, and other mechanical properties, and to determine the presence, location, and distribution of porosity and any other defects.

Pressure tightness of cast components (such as valves, pumps, and pipes) is usually determined by sealing the openings in the casting, then pressurizing it with water, oil, or air. For leak tightness requirements in critical applications, pressurized helium or specially scented gases, with detectors (*sniffers*), are used. The casting is then inspected for leaks while the pressure is maintained; unacceptable or defective castings are remelted for reprocessing.

11.8 Melting Practice and Furnaces

Melting practice is an important aspect of casting operations, because it has a direct bearing on the quality of castings. Furnaces are charged with *melting stock*, consisting of metal, alloying elements, and various other materials such as **flux** and slag-forming constituents. Fluxes are inorganic compounds that refine the molten metal by removing dissolved gases and various impurities; they may be added manually or can be injected automatically into the molten metal.

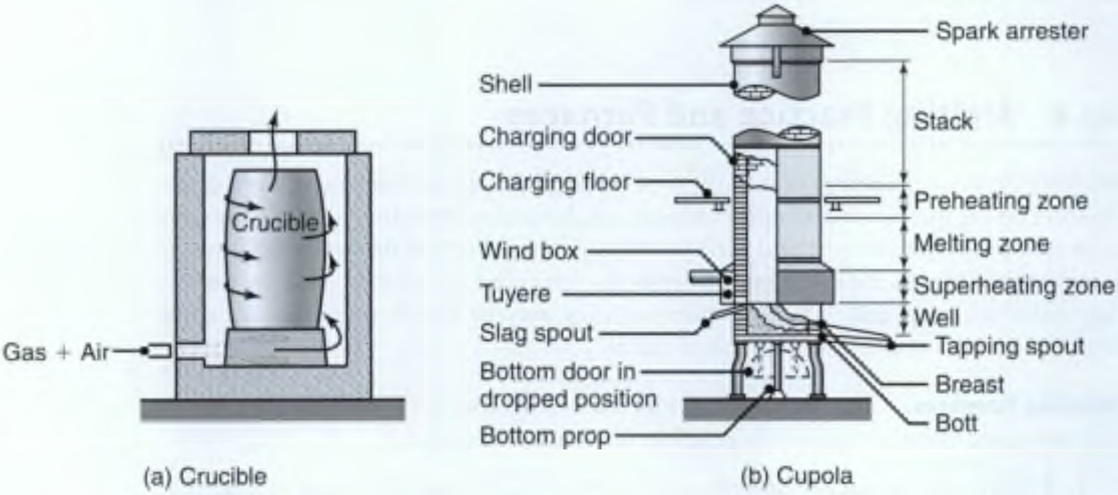
Melting Furnaces. The melting furnaces commonly used in foundries are electric-arc furnaces, induction furnaces, crucible furnaces, and cupolas.

1. **Electric arc** furnaces, described in Section 5.2.3 and illustrated in Fig. 5.2, are used extensively in foundries, because of their high rate of melting (thus high-production rate), much less pollution than other types, and their ability to

hold the molten metal (*i.e.*, keeping it at a constant temperature for a period of time) for alloying purposes.

2. **Induction** furnaces (Fig. 5.2c) are especially useful in smaller foundries, and produce smaller composition-controlled melts. There are two basic types. The *coreless induction furnace* consists of a crucible, surrounded with a water-cooled copper coil through which high-frequency current passes. Because there is a strong electromagnetic stirring action during induction heating, this type of furnace has excellent mixing characteristics for alloying and adding a new charge of metal into the furnace. The other type, called a *core* or *channel furnace*, uses low-frequency current (as low as 60 Hz), and has a coil that surrounds only a small portion of the unit.

   These furnaces are commonly used in nonferrous foundries, and are particularly suitable for (a) superheating (heating above normal casting temperature to improve fluidity), (b) holding, which makes it suitable for die-casting applications, and (c) duplexing (using two furnaces—for instance, melting the metal in one furnace and transferring it to another).
3. **Crucible** furnaces (Fig. 11.30a), which have been used extensively throughout history, are heated with various fuels, such as commercial gases, fuel oil, and fossil fuel, and with electricity. Crucible furnaces may be stationary, tilting, or movable.
4. **Cupolas** are basically vertical, refractory-lined steel vessels, charged with alternating layers of metal, coke, and flux (Fig. 11.30b). Although they require major investments and are increasingly replaced by induction furnaces, cupolas operate continuously, have high melting rates, and produce large amounts of molten metal.
5. **Levitation melting** involves *magnetic suspension* of the molten metal. An induction coil simultaneously heats a solid billet and stirs and confines the melt, thus eliminating the need for a crucible (which could contaminate the molten metal with oxide inclusions). The molten metal flows downward into an investment-casting mold, placed directly below the coil. Investment castings made by this method are free of refractory inclusions and of gas porosity, and have a uniform fine-grained structure.



(a) Crucible (b) Cupola

FIGURE 11.30 Two types of melting furnaces used in foundries.

11.9 Foundries and Foundry Automation

Casting operations are usually carried out in **foundries** (from the Latin *fundere*, meaning "melting and pouring"). Although these operations traditionally have involved much manual labor, modern foundries have incorporated automation and computer integration of all aspects of their operations.

As outlined in Fig. 11.2, foundry operations initially involve two separate groups of activities. The first group is pattern and moldmaking. Computer-aided design and manufacturing (Chapter 38) and rapid-prototyping techniques (Chapter 20) are now widely used to minimize trial and error, and thus improve efficiency. A variety of automated machinery is used to minimize labor costs, which can be significant in the production of castings.

The second group of activities involves melting the metals, and controlling their composition and impurities. Operations such as pouring into molds (some carried along conveyors), shakeout, cleaning, heat treatment, and inspection, also are automated. Automation minimizes labor, reduces the possibility of human error, increases the production rate, and attains higher quality levels. Industrial robots (Section 37.6) are now used extensively in foundry operations, such as for cleaning, riser cutting, mold venting, mold spraying, pouring, sorting, and inspection. Other operations involve automatic storage and retrieval systems for cores and patterns, using automated guided vehicles (Section 37.5).

SUMMARY

- Expendable-mold, permanent-pattern processes include sand, shell-mold, plaster-mold, and ceramic-mold casting. These processes require the destruction of the mold for each casting produced, but mold production is facilitated by reusable patterns.
- Expendable-mold, expendable-pattern processes include lost-foam and investment casting. In these processes, a pattern is consumed for each mold produced, and the mold is destroyed after each casting.
- Permanent-mold processes have molds or dies that can be used to produce castings at high production rates. Common permanent-mold processes include slush casting, pressure casting, die casting, and centrifugal casting.
- The molds used in permanent-mold casting are made of metal or graphite, and are used repeatedly to produce a large number of parts. Because metals are good heat conductors but do not allow gases to escape, permanent molds have fundamentally different effects on castings than sand or other aggregate mold materials.
- In permanent-mold casting, die and equipment costs are relatively high, but the processes are economical for large production runs. Scrap loss is low, dimensional accuracy is relatively high, and good surface detail can be achieved.
- Other casting processes include squeeze casting (a combination of casting and forging), semisolid-metal forming, rapid solidification (for the production of amorphous alloys), and casting of single-crystal components (such as turbine blades and silicon ingots for making wafers in integrated-circuit manufacture).
- Melting processes and their control also are important factors in casting operations. They include proper melting of the metals, preparation for alloying and removal of slag and dross, and pouring the molten metal into the molds. Inspection of castings for possible internal or external defects also is essential.

- Castings are generally subjected to subsequent processing, such as heat treatment and machining operations, to produce the final desired shapes, surface characteristics, and the required surface finish and dimensional accuracy.

KEY TERMS

Binders
Centrifugal casting
Ceramic-mold casting
Chaplets
Composite mold
Core print
Cores
Crystal growing
Die casting
Evaporative-pattern casting
Expendable mold
Expendable-pattern casting
Fluxes
Foundry
Green molding sand
Insert molding
Investment casting
Levitation melting
Lost-foam process
Lost-wax process
Parting agent
Patterns
Permanent mold
Permanent-mold casting
Plaster-mold casting
Precision casting
Pressure casting
Rammed-graphite molding
Rapid prototyping
Rapid solidification
Rheocasting
Sand casting
Semisolid-metal forming
Shell-mold casting
Slush casting
Squeeze casting
Thixotropy
Vacuum casting

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REVIEW QUESTIONS

11.1 Describe the differences between expendable and permanent molds.

11.2 Name the important factors in selecting sand for molds.

11.3 What are the major types of sand molds? What are their characteristics?

11.4 List important considerations when selecting pattern materials.

11.5 What is the function of a core?

11.6 What is the difference between sand-mold and shell-mold casting?

11.7 What are composite molds? Why are they used?

11.8 Describe the features of plaster-mold casting.

11.9 Name the type of materials typically used for permanent-mold casting processes.

11.10 What are the advantages of pressure casting over other processes?

11.11 List the advantages and limitations of die casting.

11.12 What is the purpose of a riser? What is a blind riser?

11.13 Explain the purpose of a vent and a runner in a casting mold.

11.14 How are shell molds produced?

11.15 What keeps the mold together in vacuum casting?

11.16 What is squeeze casting? What are its advantages?

11.17 What are the advantages of the lost-foam casting process?

11.18 How are single-crystal turbine blades produced?

QUALITATIVE PROBLEMS

11.19 What are the reasons for the large variety of casting processes that have been developed over the years? Explain with specific examples.

11.20 Why are risers not as useful in die casting as they are in sand casting?

11.21 Describe the drawbacks to having a riser that is (a) too large and (b) too small.

11.22 Why can blind risers be smaller than open-top risers?

11.23 Why does die casting produce the smallest cast parts?

11.24 Why is the investment-casting process capable of producing fine surface detail on castings?

11.25 What differences, if any, would you expect in the properties of castings made by permanent-mold versus sand-casting processes?

11.26 Recently, cores for sand casting have been produced from salt. What advantages and disadvantages would you expect from using salt cores?

11.27 Would you recommend preheating the molds used in permanent-mold casting? Would you remove the casting soon after it has solidified? Explain your reasons.

11.28 Give reasons for, and examples of, using die inserts.

11.29 Referring to Fig. 11.3, do you think it is necessary to weigh down or clamp the two halves of the mold? Explain your reasons. Do you think that the kind of metal cast, such as gray cast iron versus aluminum, should make a difference in the clamping force? Explain.

11.30 Explain why squeeze casting produces parts with better mechanical properties, dimensional accuracy, and surface finish than do expendable-mold processes.

11.31 How are the individual wax patterns attached on a "tree" in investment casting?

11.32 Describe the measures that you would take to reduce core shifting in sand casting.

11.33 You have seen that, even though die casting produces thin parts, there is a limit to how thin they can be. Why can't even thinner parts be made by this process?

11.34 How are hollow parts with various cavities made by die casting? Are cores used? If so, how? Explain.

11.35 It was stated that the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. Explain why.

11.36 How are risers and sprues placed in sand molds? Explain, with appropriate sketches.

11.37 In shell-mold casting, the curing process is critical to the quality of the finished mold. In this stage of the process, the shell-mold assembly and cores are placed in an oven for a short period of time to complete the curing of the resin binder. List probable causes of unevenly cured cores or of uneven core thicknesses.

11.38 Why does the die-casting machine shown in Fig. 11.21 have such a large mechanism to close the dies? Explain.

11.39 Chocolate forms are available in hollow shapes. What process should be used to make these chocolates?

11.40 What are the benefits to heating the mold in investment casting before pouring in the molten metal? Are there any drawbacks? Explain.

11.41 The "slushy" state of alloys refers to that state between the solidus and liquidus temperatures, as described in Section 10.2.2. Pure metals do not have such a slushy state. Does this mean that pure metals cannot be slush cast? Explain.

11.42 Can a chaplet also act as a chill? Explain.

11.43 Rank the casting processes described in this chapter in terms of their solidification rate. That is, which processes extract heat the fastest from a given volume of metal?

QUANTITATIVE PROBLEMS

11.44 Estimate the clamping force for a die-casting machine in which the casting is rectangular with projected dimensions of 100 mm × 150 mm. Would your answer depend on whether it is a hot-chamber or cold-chamber process? Explain.

11.45 The blank for the spool shown in Fig. P11.45 is to be sand cast out of A-319, an aluminum casting alloy. Make a sketch ofthe wooden pattern for this part, and include all necessaryallowances for shrinkage and machining.

11.46 Repeat Problem 11.45, but assume that the aluminum spool is to be cast by expendable-pattern casting. Explain the important differences between the two patterns.

11.47 In sand casting, it is important that the cope-mold half be weighted down with sufficient force to keep it from floating when the molten metal is poured in. For the casting shown in Fig. P11.47, calculate the minimum amount of weight necessary to keep the cope from floating up as the molten metal is poured in. (*Hint:* The buoyancy force exerted by the molten metal on the cope is dependent on the effective height of the metal head above the cope.)

11.48 If an acceleration of 100 g is necessary to produce a part in true centrifugal casting and the part has an inner diameter of 200 mm., a mean outer diameter of 350 mm., and a length of 6 mm, what rotational speed is needed?

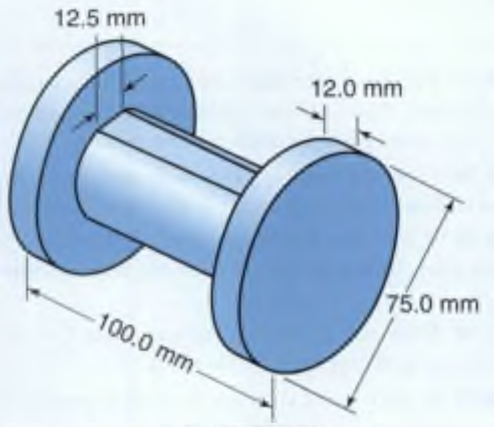
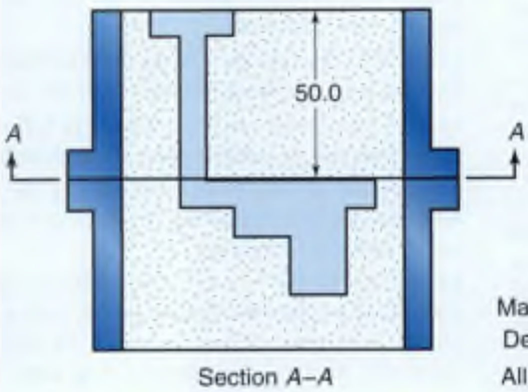


FIGURE P11.45



11.49 A jeweler wishes to produce 24 gold rings in one investment-casting operation, as illustrated in Fig. II.1b. The wax parts are attached to a wax central sprue15 mm in diameter. The rings are located in four rows, each 12.5 mm from the other on the sprue. The rings require a 3mm diameter, 12.5-mm-long runner to the sprue. Estimate the weight of gold needed to completely fill the rings, runners, and sprues. The specific gravity of gold is 19.3.

11.50 Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects of casting processes to test the understanding of the students. Prepare two quantitative problems and supply the answers.

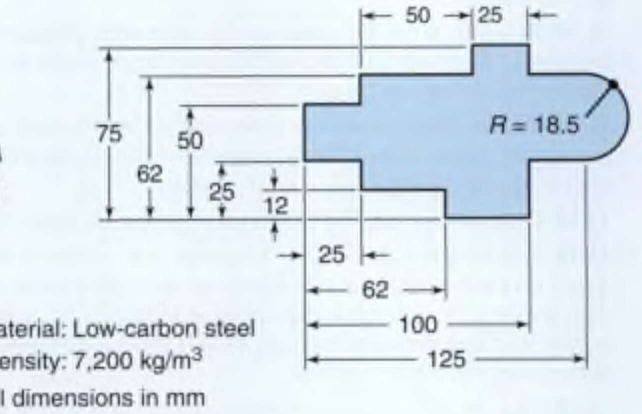


FIGURE P11.47

SYNTHESIS, DESIGN, AND PROJECTS

11.51 Describe the procedures that would be involved in making a large outdoor bronze statue. Which casting process(es) would be suitable? Why?

11.52 The optimum shape of a riser is spherical to ensure that it cools more slowly than the casting it feeds; however, spherically shaped risers are difficult to cast. (a) Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface-area-to-volume ratio. (b) Compare the solidification time of the riser in part (a) with that of a riser shaped like a right circular cylinder. Assume that the volume of each riser is the same and the height of each is equal to the diameter. (See Example 10.1.)

11.53 Sketch and describe a casting line consisting of machinery, conveyors, robots, sensors, etc., that automatically could perform the expendable-pattern casting process.

11.54 Outline the casting processes that would be most suitable for making small toys. Explain your choices.

11.55 Make a list of the mold and die materials used in the casting processes described in this chapter. Under each type of material, list the casting processes that are employed, and explain why these processes are suitable for that particular mold or die material.

11.56 Write a brief paper on the permeability of molds and the techniques that are used to determine permeability.

11.57 Light metals commonly are cast in vulcanized rubber molds. Conduct a literature search and describe the mechanics of this process.

11.58 It sometimes is desirable to cool metals more slowly than they would be if the molds were maintained at room temperature. List and explain the methods you would use to slow down the cooling process.

11.59 The part shown in Fig. P11.59 is a hemispherical shell used as an acetabular (mushroom-shaped) cup in a total hip replacement. Select a casting process for making this part, and provide a sketch of all the patterns or tooling needed if it is to be produced from a cobalt–chrome alloy.

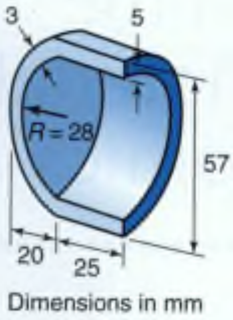


FIGURE P11.59

11.60 Porosity that has developed in the boss of a casting is illustrated in Fig. P11.60. Show that the porosity can be eliminated simply by repositioning the parting line of this casting.

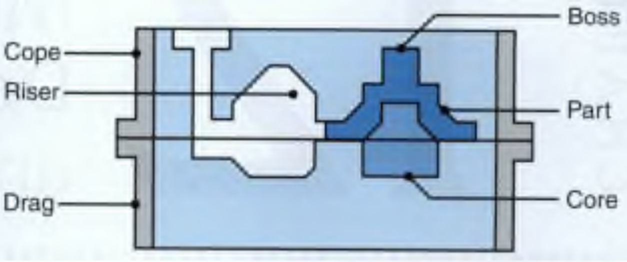


FIGURE P11.60

11.61 In Fig. II.1b the gemstones have been cast in place. Design a ring with a means of securing a gemstone in the wax pattern, such that it will remain in the mold as the wax is being melted. Could such an approach be used in lost-foam casting?

CHAPTER

12 Metal Casting: Design, Materials, and Economics

- This final chapter on metal casting serves as a general guide to the interrelationships among product design, material, process selection, and economical considerations in casting.
- The chapter describes in detail the design considerations for casting operations, and discusses the general guidelines for successful casting.
- The characteristics and applications of the most common ferrous and nonferrous alloys are then described.
- The chapter ends with a discussion of casting economics.

12.1 Introduction

In the preceding two chapters, it was noted that successful casting practice requires the proper control of a large number of variables. These variables pertain to the particular characteristics of the metals and alloys cast, method of casting, mold and die materials, mold design, and processing parameters. Factors such as the flow of the molten metal in the mold cavities, the gating systems, the rate of cooling, and the gases evolved all influence the quality of a casting.

This chapter describes general design considerations for metal casting and presents guidelines for avoiding defects. It then describes the characteristics of the metals and alloys that are commonly cast, together with their typical applications. Because the economics of casting operations are just as important as their technical aspects, this chapter also briefly outlines the basic economic factors that are relevant to casting operations.

12.2 Design Considerations in Casting

As in all manufacturing operations, certain *design principles* pertaining also to casting have been developed over many years. Although these principles have been established primarily through experience, analytical methods, process simulation and modeling, and computer-aided design and manufacturing techniques all have come into wide use as well, improving the quality of castings and productivity, and resulting in significant cost savings.

All casting processes share some basic characteristics. Consequently, a number of design considerations apply equally to, for example, sand casting and die casting; however, each process will have its own particular design considerations. Sand casting will require consideration of mold erosion and associated sand inclusions in the casting, whereas die casting will not have this concern, although it has others, such as heat checking of dies, which reduces die life.

Troubleshooting the causes of defects in cast products is often complicated, and the considerations presented in this chapter are to serve only as guidelines. Furthermore, defects frequently are random and can be difficult to reproduce, thus complicating the implementation of corrective measures. In most cases, a given mold design will produce mostly good parts, as well as some defective parts. For these reasons, strict quality control procedures are implemented, especially for critical applications. (See Chapter 36.)

12.2.1 General Design Considerations for Castings

There are two types of design issues in casting: (a) geometric features, tolerances, etc. that should be incorporated into the part and (b) mold features that are needed to produce the desired casting. Robust design of castings usually involves the following steps:

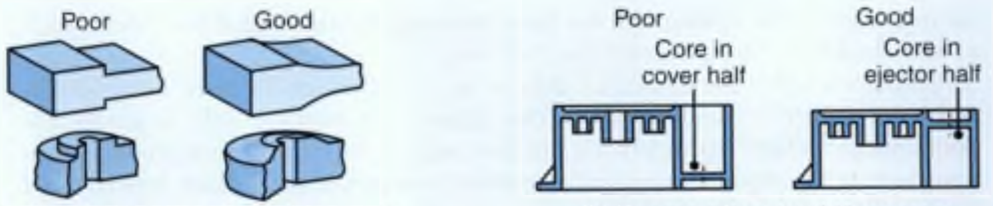
1. Design the part so that the shape is cast as easily as possible. Several design considerations are given in this chapter to assist in such efforts.
2. Select a casting process and a material suitable for the part, size, required production quantity, mechanical properties, and so on. Often, steps 1 and 2 in this list have to be specified simultaneously, which can be a demanding design challenge.
3. Locate the parting line of the mold in the part.
4. Design and locate the gates to allow uniform feeding of the mold cavity with molten metal.
5. Select an appropriate runner geometry for the system.
6. Locate mold features, such as sprue, screens, and risers, as appropriate.
7. Make sure proper controls and good practices are in place.

Design of Parts to be Cast. The following considerations are important in designing castings, as outlined in Fig. 12.1:

1. **Corners, angles, and section thickness.** Sharp corners, angles, and fillets should be avoided as much as possible, because they act as stress raisers and may cause cracking and tearing of the metal (as well as of the dies) during solidification. Fillet radii should be selected to minimize stress concentrations and to ensure proper molten-metal flow during pouring. Fillet radii usually range from 3 to 25 mm, although smaller radii may be permissible in small castings and for specific applications. On the other hand, if the fillet radii are too large, the volume of the material in those regions also is large, and consequently the cooling rate is lower.

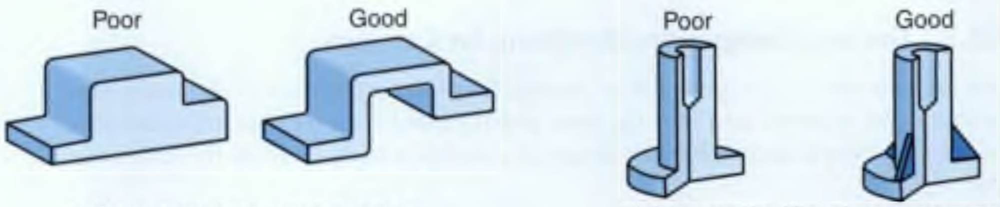
   Section changes in castings should be blended smoothly into each other. The location of the largest circle that can be inscribed in a particular region (Figs. 12.2a and b) is critical so far as shrinkage cavities are concerned. Because the cooling rate in regions with larger circles is lower, these regions are called **hot spots**, and can cause **shrinkage cavities** and **porosity** (Figs. 12.2c and d).

   Cavities at hot spots can be eliminated by using small cores, and although they produce cored holes in the casting (Fig. 12.2e), these holes do not affect strength significantly. It is also important to try to maintain uniform cross-sections and wall thicknesses throughout the casting, in order to avoid or minimize shrinkage cavities. Although they increase the production cost, *metal paddings* or *chills* in the mold can eliminate or minimize hot spots (see Fig. 10.14).



(a) Use radii or fillets to avoid corners and provide uniform cross-section.

(b) Deep cavities should be on one side of the casting where possible.



(c) Wall sections should be uniform.

(d) Ribs and/or fillets improve bosses.

(e) Sloping bosses can be designed for straight die parting to simplify die design.

(f) Side cores can be eliminated with this hole design.

FIGURE 12.1 Suggested design modifications to avoid defects in castings. *Source:* Images provided by: North American Die Casting Association, Wheeling, Illinois.

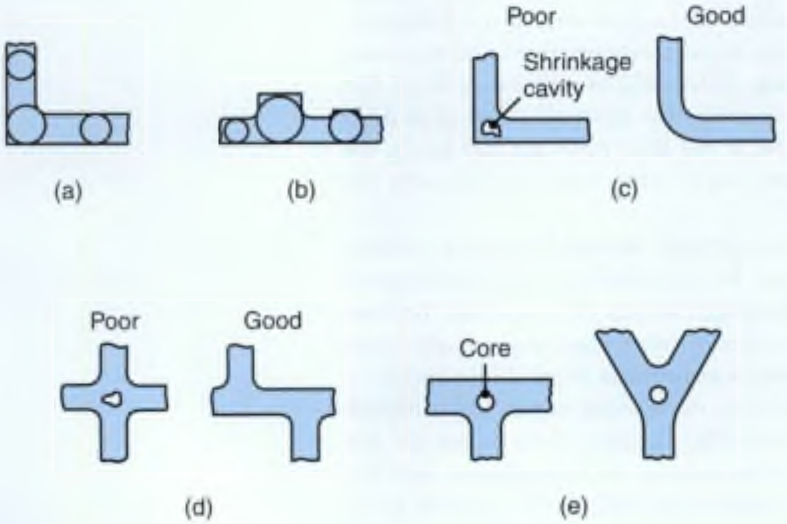


FIGURE 12.2 Examples of designs showing the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities.

2. **Flat areas.** Large flat areas (plane surfaces) should be avoided, since (a) they may warp during cooling because of temperature gradients or (b) cause poor surface finish because of uneven flow of the metal during pouring. One of the common techniques for avoiding these problems is to break up flat surfaces with staggered ribs and serrations, as described below.
3. **Ribs.** One method of producing uniform thickness parts is to eliminate large, bulky volumes in the casting, as shown in Fig. 12.1. However, this can result in a loss in stiffness and, especially with flat regions, can lead to warping. One solution to these problems is to use ribs or support structure on the casting, as shown in Fig. 12.3. These are usually placed on the surface

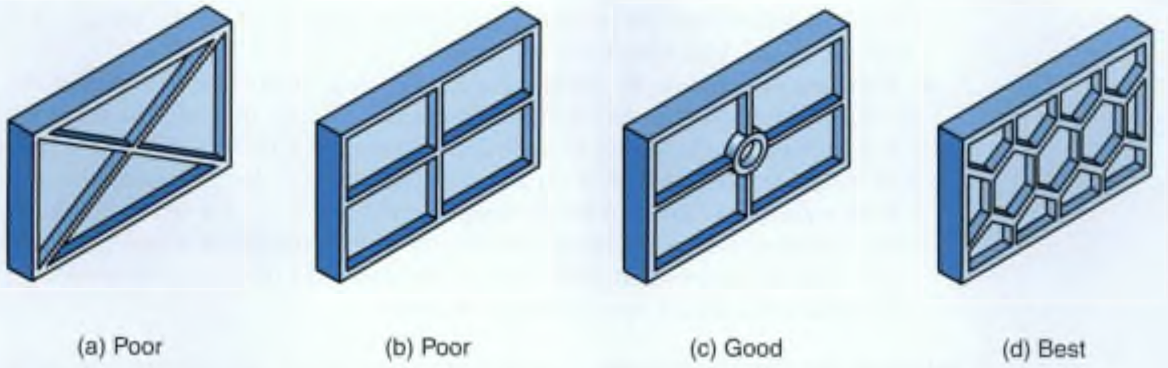

(a) Poor (b) Poor (c) Good (d) Best

FIGURE 12.3 Rib designs for use on thin sections or flat surfaces to reduce or eliminate warping.

that is less visible. Ribs should, in general, have a thickness around 80% of the adjoining member thickness, and should be deeper than their strut thickness. It usually is beneficial to have the ribs solidify before the members they adjoin. Ribbing should not be used on both sides of a casting, and ribs should not meet at acute angles, because of complications to molding.

4. **Shrinkage.** To avoid cracking of the casting during cooling, there should be allowances for shrinkage during solidification and/or cooling to room temperature. In castings with intersecting ribs, the tensile stresses developed can be reduced by staggering the ribs or by changing the intersection geometry. Pattern dimensions also should allow for shrinkage of the metal during solidification and cooling. Allowances for shrinkage, known as **patternmaker's shrinkage allowances,** usually range from about 10 to 20 mm/m. Table 12.1 gives the normal shrinkage allowance for metals commonly sand cast.
5. **Draft.** A small draft (taper) is typically provided in sand-mold patterns to enable removal of the pattern without damaging the mold (see Fig. 11.5). Drafts generally range from 5 to 15 mm/m. Depending on the quality of the pattern, draft angles usually range from 0.5° to 2°. The angles on inside surfaces typically are twice this range; they have to be higher than those for outer surfaces because the casting shrinks inward toward the core as it cools.
6. **Dimensional tolerances.** Dimensional tolerances depend on the particular casting process employed, size of the casting, and type of pattern used. Tolerances should be as wide as possible, within the limits of good part performance, as otherwise the cost of the casting increases. In commercial practice, tolerances are typically in the range of ±0.8 mm for small castings, and increase with the size of the castings. Tolerances for large castings, for instance, may be as much as ±6 mm.
7. **Lettering and markings.** It is common practice to include some form of part identification, such as lettering, numbers, or corporate logos, in castings. These features can be sunk into the casting or can protrude from the surface; which one is more desirable depends on the method of producing the molds. For example, in sand casting, a pattern plate is produced by machining on a computer numerically controlled milling machine (Section 24.2), because it is simpler to

TABLE 12.1

Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

Metal	Shrinkage allowance (%)
Cast irons	
Gray cast iron	0.83–1.3
White cast iron	2.1
Malleable cast iron	0.78–1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Copper alloys	
Yellow brass	1.3–1.6
Phosphor bronze	1.0–1.6
Aluminum bronze	2.1
High-manganese steel	2.6

machine letters into the pattern plate. On the other hand, in die casting, it is simpler to machine letters into the mold.

8. **Finishing operations.** In designing a casting, it is important to consider the subsequent machining and finishing operations, if any, that may be required. For example, if a hole is to be drilled in a casting, it is better to locate the hole on a flat surface rather than on a curved surface, in order to prevent the drill from wandering. An even better design would incorporate a small dimple on the curved surface as a starting point for the drilling operation. Castings should also include features that allow them to be clamped easily in machine tools, if secondary machining operations are necessary.

Selecting the Casting Process. Casting processes cannot be selected separately from economic considerations, as described in Section 12.4. Table 11.1 lists some of the advantages and limitations of casting processes that have an impact on casting design.

Locating the Parting Line. A part should be oriented in a mold so that the large portion of the casting is relatively low and the height of the casting is minimized. Part orientation also determines the distribution of porosity. For example, in casting aluminum, hydrogen is soluble in liquid metal but is not soluble as the aluminum solidifies (see Fig. 10.15). Thus, hydrogen bubbles can form during the casting of aluminum, which float upward due to buoyancy and cause a higher porosity in the top regions of castings; critical surfaces should be oriented so that they face downward.

A properly oriented casting then can have the parting line specified; the parting line is the line or plane separating the upper (cope) and lower (drag) halves of molds (see Fig. 11.4). In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the parting line should be at the corners or edges of castings, rather than on flat surfaces in the middle of the casting, so that the **flash** at the **parting line** (material squeezing out between the two halves of the mold) will not be as visible. The location of the parting line is important because it influences mold design, ease of molding, number and shape of cores required, method of support, and the gating system.

The parting line should be placed as low as possible (relative to the casting) for less dense metals (such as aluminum alloys) and located at around midheight for denser metals (such as steels). However, the molten metal should not be allowed to flow vertically, especially when unconstrained by a sprue. The placement of the parting line has a large effect on the remainder of the mold design; for example, in sand casting, it is typical that the runners, gates, and sprue well are all placed in the drag on the parting line. Also, the placement of the parting line and orientation of the part determine the number of cores needed, especially when it is preferable to avoid the use of cores, whenever practical.

Locating and Designing Gates. Gates are the connections between the runners and the part to be cast. Some considerations in designing gating systems are:

- Multiple gates often are preferable, and are necessary for large parts. Multiple gates have the benefits of allowing lower pouring temperature and reducing the temperature gradients in the casting.
- Gates should feed into thick sections of castings.

- A fillet should be used where a gate meets a casting; this feature produces less turbulence than abrupt junctions.
- The gate closest to the sprue should be placed sufficiently away from the sprue, so that the gate can be easily removed. This distance may be as small as a few mm for small castings and up to 500 mm for large ones.
- The minimum gate length should be three to five times the gate diameter, depending on the metal being cast. The gate cross-section should be large enough to allow the filling of the mold cavity, and should be smaller than the runner cross-section.
- Curved gates should be avoided; when necessary, a straight section in the gate should be located immediately adjacent to the casting.

Runner Design. The runner is a horizontal distribution channel that receives molten metal from the sprue and delivers it to the gates. Runners are used to trap dross (a mixture of oxide and metal that forms on the surface of metals) and keep it from entering the gates and mold cavity. Commonly, dross traps are placed at the ends of runners, and the runner projects above the gates to ensure that the metal in the gates is tapped from below the surface. A single runner is used for simple parts, but two-runner systems may be necessary for more complicated castings.

Designing Various Mold Features. The main goal in designing a *sprue* (described in Section 10.3) is to achieve the required molten-metal flow rates, while preventing aspiration (entrainment of air) or excessive dross formation. Flow rates are determined such that turbulence is avoided, but so that the mold is filled quickly as compared to the solidification time required. A *pouring basin* can be used to ensure that the metal flow into the sprue is uninterrupted; also, if molten metal is maintained in the pouring basin during pouring, the dross will float and will not enter the mold cavity. *Filters* are used to trap large contaminants; they also serve to reduce the metal velocity and make the flow more laminar. *Chills* can be used to speed solidification of the metal in a particular region of a casting.

Establishing Good Practices. It has been widely observed that a given mold design can produce acceptable parts as well as defective ones, and rarely will produce only good or only defective castings. To check for defective ones, quality control procedures are necessary. Some common concerns are:

- Starting with a high-quality molten metal is essential for producing superior castings. Pouring temperature, metal chemistry, gas entrainment, and handling procedures all can affect the quality of metal being poured into a mold.
- The pouring of metal should not be interrupted, because it can lead to dross entrainment and turbulence. The meniscus of the molten metal in the mold cavity should experience a continuous, uninterrupted, and upward advance.
- The different cooling rates within the body of a casting cause residual stresses; thus, stress relieving (Section 4.11) may be necessary to avoid distortions of castings in critical applications.

12.2.2 Design for Expendable-mold Casting

Expendable-mold processes have certain specific design requirements, involving mainly the mold material, size of parts, and the manufacturing method. Note that a casting in an expendable-mold process (such an investment casting) will cool much more slowly than it would in, say, die casting. This has important implications in the layout of molds. Important design considerations for expendable-mold casting are:

Mold Layout. The features in the mold must be placed logically and compactly, using gates as necessary. One of the most important goals in mold layout is to have solidification initiate at one end of the mold and progress in a uniform front across the casting, with the risers solidifying last. Traditionally, mold layout has been based on experience and on considerations of fluid flow and heat transfer. Commercial computer programs have now become widely available, that assist in the analysis of fluid flow and heat transfer in casting. These programs simulate mold filling and allow the rapid evaluation and design of mold layouts.

Riser Design. A major concern in the design of castings is the size of risers and their placement. Risers are very useful in affecting the solidification-front progression across a casting, and are an essential feature in the mold layout, described previously. Blind risers are good design features and maintain heat longer than open risers do.

Risers are designed according to the following basic rules:

1. The riser must not solidify before the casting does. This rule usually is satisfied by avoiding the use of small risers and by using cylindrical risers with small aspect ratios (i.e., small ratios of height to cross-section). Spherical risers are the most efficient shape, but are difficult to work with.
2. The riser volume must be large enough to provide a sufficient amount of molten metal to compensate for shrinkage in the casting.
3. Junctions between the casting and the riser should not develop hot spots, where shrinkage porosity can occur.
4. Risers must be placed such that the molten metal can be delivered to locations where it is most needed.
5. There must be sufficient pressure to drive the molten metal into locations in the mold where it is needed. Thus, risers are not as useful for metals with low density (such as aluminum alloys) as they are for those with higher density (such as steel and cast irons).
6. The pressure head from the riser should suppress cavity formation and encourage complete filling of the mold cavity.

Machining Allowance. Most expendable-mold castings require some additional finishing operations, such as machining and grinding; thus, allowances have to be made in casting design for these operations. Machining allowances, which are included in pattern dimensions, depend on the type of casting operation, and they increase with the size and section thickness of the casting. Allowances usually range from about 2 to 5 mm for small castings to more than 25 mm for large castings.

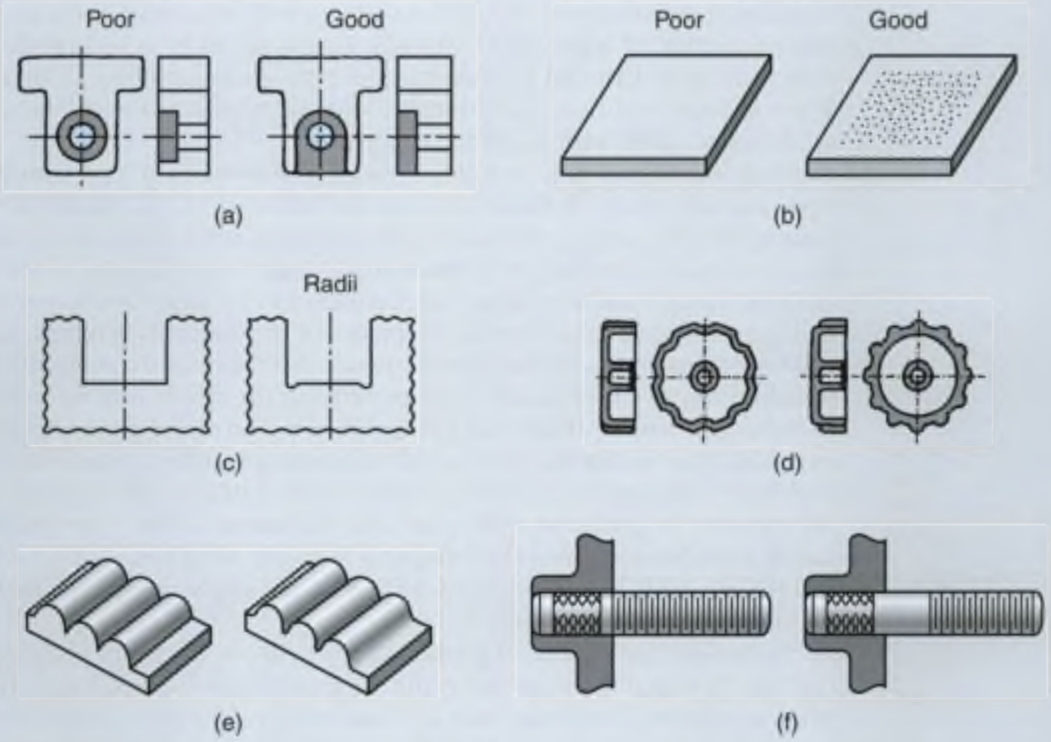
12.2.3 Design for Permanent-mold Casting

Typical design guidelines for permanent-mold casting are discussed in Example 12.1. Special considerations are generally included in designing tooling for die casting. Although designs may be modified to eliminate the draft for better dimensional accuracy, a draft angle of 0.5° or even 0.25° is usually required; otherwise, galling (localized seizure or sticking of two surfaces, Section 33.5) may take place between the part and the dies, and cause distortion of the casting. Die-cast parts are nearly net shaped, typically requiring only the removal of gates and minor trimming to remove flashing and other minor defects. The surface finish and dimensional accuracy of die-cast parts are very good (see Table 11.2), and in general, they do not require a machining allowance.

CASE STUDY 12.1 Illustrations of Poor and Good Casting Designs

Several examples of poor and good designs in permanent-mold and die casting are illustrated in Fig. 12.4. The significant differences in design are outlined here for each example:

- **(a)** The lower portion of the design on the left has a thin wall, with no apparent function. This location of the part may fracture if subjected to high forces or impact. The good design eliminates this problem, and also may simplify die and mold manufacturing.
- **(b)** Large flat surfaces always present difficulties in casting metals (as well as nonmetallic materials, described in Part III), as they tend to warp and develop uneven surfaces. A common practice to avoid this situation is to break up the surface with ribs (see Fig. 12.3) and serrations on the reverse side of the casting. This approach greatly reduces distortion, while not adversely affecting the appearance and function of the flat surface. In addition to ribs, it is beneficial to use a textured surface, as shown in Fig. 12.4b, since very smooth surfaces are difficult to cast without objectionable aesthetic features.
- **(c)** This example of poor and good design is relevant not only to castings, but also to parts that



(a) (b) (c) (d) (e) (f)

FIGURE 12.4 Examples of undesirable (poor) and desirable (good) casting designs. *Source:* Images provided by: North American Die Casting Association, Wheeling, Illinois.

(*continued*)

are machined or ground. It is difficult to produce sharp internal radii or corners that may be required for functional purposes, such as inserts designed to reach the bottom of the part cavity. Also, in the case of lubricated cavities, the lubricant can accumulate at the bottom and, because it is incompressible, prevent full insertion of an insert. The placement of a small radius at the corners or periphery at the bottom of the part eliminates this problem.

(d) A part could function, for instance, as a knob to be gripped and rotated, hence the outer features along its periphery. Note in the design on the left that the inner periphery of the knob also has features which are not functional but help save material. The die for the good design is easier to manufacture.

(e) Note that the poor design has sharp fillets at the base of the longitudinal grooves, meaning that the die has sharp (knife-edge) protrusions. It is thus possible that, with overextended use of the die, these edges may chip off.

(f) The poor design on the left has threads reaching the right face of the casting. It then is possible that, during casting, some molten metal will penetrate this region, forming a flash and interfering with the function of the threaded insert, such as when a nut is used. The good design incorporates an offset on the threaded rod, eliminating this problem. This design consideration is also applicable for injection molding of plastics, an example of which is shown in Fig. 19.9.

12.2.4 Computer Modeling of Casting Processes

Because casting involves complex interactions among several material and process variables, a quantitative study of these interactions is essential to the proper design and production of high-quality castings. Rapid advances in computers and modeling techniques have led to important innovations in modeling casting processes. These include fluid flow, heat transfer, and the microstructures developed during solidification under various casting conditions.

Modeling of *fluid flow* in molds is based on Bernoulli's and the continuity equations (Section 10.3). A model predicts the behavior of the molten metal during pouring into the gating system and its travel into the mold cavity, as well as the velocity and pressure distributions in the molds. Modern software can couple fluid flow and *heat transfer* and the effects of such parameters as surface conditions (roughness, mold permeability, etc.), thermal properties of the materials involved, and natural and forced convection on cooling rate. Recall that the surface conditions vary during solidification, as a layer of air develops between the casting and the mold wall due to shrinkage. Similar studies are being conducted on modeling the development of *microstructures* in casting. These studies encompass heat flow, temperature gradients, nucleation and growth of crystals, formation of dendritic and equiaxed structures, impingement of grains on each other, and movement of the liquid–solid interface during solidification. Several commercial software programs, such as Magmasoft, SOLIDCast, CAP, NovaFlow, Flow 3-D, WinCast, and Star-Cast, are now available for modeling casting processes.

The models are capable of predicting, for example, the width of the mushy zone (see Fig. 10.4) during solidification and the grain size in castings. Similarly, the capability to calculate isotherms (lines of equal temperature) gives insight into possible hot spots and the subsequent development of shrinkage cavities. With the availability of user-friendly software and advances in computer-aided design and manufacturing (Chapter 38), modeling techniques are becoming easier to implement. The benefits of this approach are improved quality, easier planning and cost estimating, increased productivity, and faster response to design modifications.

12.3 Casting Alloys

The general properties and applications of ferrous and nonferrous metals and alloys were presented in Chapters 5 and 6, respectively. This section describes the properties and applications of cast metals and alloys; their properties and casting and manufacturing characteristics are summarized in Fig. 12.5 and Tables 12.2–12.5. In addition to their casting characteristics, other important considerations in casting alloys include their machinability and weldability, as alloys typically are assembled with other components to produce the entire part.

The most commonly used casting alloy (in tonnage) is gray iron, followed by ductile iron, aluminum, zinc, lead, copper, malleable iron, and magnesium. Shipments of castings, in the United States alone, are around 14 million metric tons per year.

12.3.1 Nonferrous Casting Alloys

Aluminum-based Alloys. Aluminum alloys have a wide range of mechanical properties, mainly because of various hardening mechanisms and heat treatments that can be used (Section 4.9). Parts made of aluminum and magnesium alloys are known as **light-metal** castings. These alloys have high electrical conductivity and generally good atmospheric corrosion resistance; however, their resistance to some acids and all alkalis is poor, and care must be taken to prevent galvanic corrosion. Aluminum alloys are lightweight, nontoxic, and have good machinability. Except for alloys containing silicon, they generally have low resistance to wear and abrasion. Aluminum-based alloys have numerous applications, including architectural and decorative uses. An increasing trend is their use in automobiles, for components such as engine blocks, cylinder heads, intake manifolds, transmission cases, suspension components, wheels, and brakes.

Magnesium-based Alloys. The lowest density of all commercial casting alloys are those in the magnesium-based group; they have good corrosion resistance and moderate strength, depending on the particular heat treatment used. Typical applications include automotive wheels, housings, and air-cooled engine blocks. Because of their light weight, magnesium castings are being increasingly used in automobiles to increase fuel economy.

Copper-based Alloys. Copper-based alloys have the advantages of good electrical and thermal conductivity, corrosion resistance, and nontoxicity, as well as wear properties thus making them suitable as bearing materials. A wide variety of copper-based alloys is available, including brasses, aluminum bronzes, phosphor bronzes, and tin bronzes.

Zinc-based Alloys. A low-melting-point alloy group, zinc-based alloys have good corrosion resistance, good fluidity, and sufficient strength for structural applications. These alloys are commonly used in die casting, particularly for parts with intricate shapes and thin walls.

Tin-based Alloys. Although low in strength, these alloys have good corrosion resistance and are typically used for linings or bearing surfaces.

Lead-based Alloys. These alloys have applications similar to tin-based alloys, but the toxicity of lead is a major drawback to their wider application.

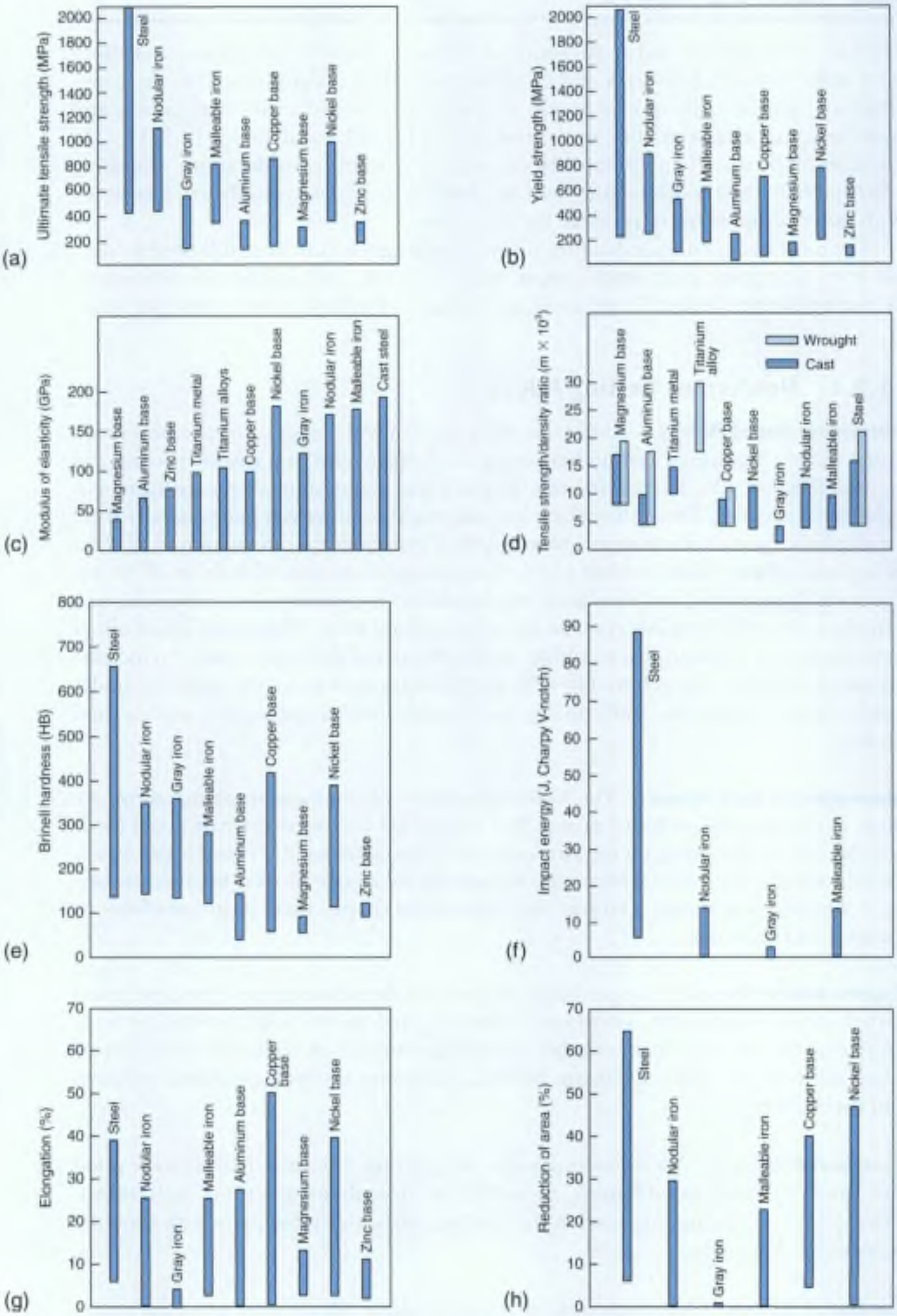


FIGURE 12.5 Mechanical properties for various groups of cast alloys; note that even within the same group, the properties vary over a wide range, particularly for cast steels. *Source:* Courtesy of Steel Founders' Society of America.

TABLE 12.2

Typical Applications for Castings and Casting Characteristics

Type of alloy	Castability*	Weldability*	Machinability*	Typical applications
Aluminum	E	F	G–E	Pistons, clutch housings, intake manifolds
Copper	F–G	F	F–G	Pumps, valves, gear blanks, marine propellers
Iron				
Ductile	G	D	G	Crankshafts, heavy-duty gears
Gray	E	D	G	Engine blocks, gears, brake disks and drums, machine bases
Malleable iron	G	D	G	Farm and construction machinery, heavy-duty bearings, railroad rolling stock
White iron	G	VP	VP	Mill liners, shot-blasting nozzles, railroad brake shoes, crushers, and pulverizers
Magnesium	G–E	G	E	Crankcase, transmission housings
Nickel	F	F	F	Gas turbine blades, pump and valve components for chemical plants
Steel				
Carbon and low alloy	F	E	F	Die blocks, heavy-duty gear blanks, aircraft undercarriage members, railroad wheels
High alloy	F	E	F	Gas-turbine housings, pump and valve components, rock-crusher jaws
Zinc	E	D	E	Door handles, radiator grills

*E = Excellent; G = Good; F = Fair; VP = Very poor; D = Difficult.

TABLE 12.3

Properties and Typical Applications of Cast Irons

Cast iron	Type	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Gray	Ferritic	170	140	0.4	Pipe, sanitary ware
	Pearlitic	275	240	0.4	Engine blocks, machine tools
	Martensitic	550	550	0	Wear surfaces
Ductile (Nodular)	Ferritic	415	275	18	Pipe, general service
	Pearlitic	550	380	6	Crankshafts, highly stressed parts
	Tempered martensite	825	620	2	High-strength machine parts, wear-resistant parts
Malleable	Ferritic	365	240	18	Hardware, pipe fittings, general engineering service
	Pearlitic	450	310	10	Railroad equipment, couplings
	Tempered martensite	700	550	2	Railroad equipment, gears, connecting rods
White	Pearlitic	275	275	0	Wear-resistant parts, mill rolls

High-temperature Alloys. High-temperature alloys have a wide range of properties, and typically require temperatures of up to 1650°C for casting titanium and superalloys, and even higher for refractory alloys (Mo, Nb, W, and Ta). Special techniques are used to cast these alloys for nozzles and various jet- and rocketengine components. Some high-temperature alloys are more suitable and economical

TABLE 12.4

Mechanical Properties of Gray Cast Irons

ASTM class	Ultimate tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Hardness (HB)
20	152	572	66–97	156
25	179	669	79–102	174
30	214	752	90–113	210
35	252	855	100–119	212
40	293	965	110–138	235
50	362	1130	130–157	262
60	431	1293	141–162	302

TABLE 12.5

Properties and Typical Applications of Nonferrous Cast Alloys

Alloys (UNS)	Condition	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Typical applications
Aluminum alloys					
195 (AO1950)	Heat treated	220–280	110–220	8.5–2	Sand castings
319 (AO3190)	Heat treated	185–250	125–180	2–1.5	Sand castings
356 (AO3560)	Heat treated	260	185	5	Permanent mold castings
Copper alloys					
Red brass (C83600)	Annealed	235	115	25	Pipe fittings, gears
Yellow brass (C86400)	Annealed	275	95	25	Hardware, ornamental
Manganese bronze (C86100)	Annealed	480	195	30	Propeller hubs, blades
Leaded tin bronze (C92500)	Annealed	260	105	35	Gears, bearings, valves
Gun metal (C90500)	Annealed	275	105	30	Pump parts, fittings
Nickel silver (C97600)	Annealed	275	175	15	Marine parts, valves
Magnesium alloys					
AZ91A	F	230	150	3	Die castings
AZ63A	T4	275	95	12	Sand and permanent mold castings
AZ91C	T6	275	130	5	High-strength parts
EZ33A	T5	160	110	3	Elevated-temperature parts
HK31A	T6	210	105	8	Elevated-temperature parts
QE22A	T6	275	205	4	Highest-strength parts

for casting than for shaping by other manufacturing methods, such as forging and powder metallurgy techniques.

12.3.2 Ferrous Casting Alloys

Cast Irons. Cast irons represent the largest quantity of all metals cast; they can be cast easily into intricate shapes, and generally possess several desirable properties, such as wear resistance, high hardness, and good machinability. The term *cast iron* refers to a family of alloys, and as described in Section 4.6, they are classified as gray cast iron (gray iron), ductile (nodular or spheroidal) iron, white cast iron, malleable iron, and compacted-graphite iron. Their general properties and typical applications are given in Tables 12.3 and 12.4.

1. **Gray cast iron.** Gray iron castings have relatively few shrinkage cavities and low porosity. Various forms of gray cast iron are *ferritic, pearlitic,* and *martensitic*, and because of differences in their structures, each type has different properties (Table 12.4). Gray cast irons are specified by a two-digit ASTM designation; thus, for example, class 20 specifies that the material must have a minimum tensile strength of 140 MPa. Typical uses of gray cast iron are in engine blocks, electric-motor housings, pipes, and wear surfaces for machines; also, because of its high damping capacity, gray iron is used widely for machine-tool bases (Section 25.3).
2. **Ductile (nodular) iron.** Typically used for machine parts, housings, gears, pipe, rolls for rolling mills, and automotive crankshafts, ductile irons are specified by a set of two-digit numbers. For example, class or grade 80-55-06 indicates that the material has a minimum tensile strength of 550 MPa, a minimum yield strength of 380 MPa, and 6% elongation in 50 mm.
3. **White cast iron.** Because of its very high hardness and wear resistance, white cast iron is used typically for rolls for rolling mills, railroad-car brake shoes, and liners in machinery for processing abrasive materials.
4. **Malleable iron.** The principal use of malleable iron is for railroad equipment and various types of hardware, fittings, and components for electrical applications. Malleable irons are specified by a five-digit designation; for example, 35018 indicates that the yield strength of the material is 240 MPa and its elongation is 18% in 50 mm.
5. **Compacted-graphite iron.** First produced commercially in 1976, compacted-graphite iron (CGI) has properties that are between those of gray irons and ductile irons. Gray iron has good damping and thermal conductivity, but low ductility, whereas ductile iron has poor damping and thermal conductivity, but high tensile strength and fatigue resistance. CGI has damping and thermal properties similar to gray iron, and strength and stiffness comparable to those of ductile iron. Because of its strength, castings made of CGI can be smaller and thus lighter; it is easy to cast and has consistent properties throughout the casting. Also, its machinability is better than that of ductile iron, an important consideration since CGI is used for automotive engine blocks and cylinder heads, which require extensive machining on their surfaces.

Cast Steels. Because of the high temperatures required to melt steels (up to about 1650°C), casting them requires special considerations. The high temperatures involved present difficulties in the selection of mold materials, particularly in view of the high reactivity of steels with oxygen during the melting and pouring of the metal. Steel castings possess properties that are more uniform (isotropic) than those made by mechanical working processes (Part III). Although cast steels can be welded, welding alters the cast microstructure in the heat-affected zone (see Fig. 30.20), thus influencing the strength, ductility, and toughness of the base metal. Subsequent heat treatment would be required to restore the mechanical properties of the casting. Cast weldments have gained importance for assembling large machines and structures. Cast steels have important applications in mining, chemical plants, oil fields, heavy construction, and equipment for railroads.

Cast Stainless Steels. Casting of stainless steels involves considerations similar to those for steels. Stainless steels generally have long freezing ranges and high melting temperatures. They can develop several structures, depending on their composition and processing parameters. Cast stainless steels are available in several compositions, and they can be heat treated and welded; the parts have high heat and corrosion resistance, especially in the chemical and food industries. Nickel-based casting alloys are used for very corrosive environments and for very high temperature service.

12.4 Economics of Casting

As is the case with all manufacturing processes, the cost of each cast part (**unit cost**) depends on several factors, including materials, equipment, and labor. Of the various casting processes described in Chapter 11, some require more labor than others, some require expensive dies and machinery, and some require long production times to produce the castings (Table 12.6). Each of these individual factors thus affects the overall cost of a casting operation and to varying degrees. As can be seen in Table 12.6, relatively little cost is involved in making molds for sand casting, whereas molds for various casting processes and dies for die casting require expensive materials and manufacturing operations. There are also major costs involved in making patterns for casting, although (as stated in Section 11.2.1) much progress is being made in utilizing rapid-prototyping techniques (Chapter 20) to reduce costs and time.

Costs are also incurred in melting and pouring the molten metal into molds, and in heat treating, cleaning, and inspecting the castings. Heat treating is an important part of the production of many alloy groups (especially ferrous castings), and may be necessary for improved mechanical properties. However, heat treating may also introduce another set of production problems (such as scale formation on casting surfaces and warpage of the part) that can be a significant aspect of production costs.

The labor and skills required for these operations can vary considerably, depending on the particular casting operation and level of automation in the foundry. Investment casting, for example, requires much labor because of the several steps involved in the operation. Some automation is possible, such as using robots (Fig. 11.13a), whereas operations such as a highly automated die-casting process can maintain high production rates with little labor required.

TABLE 12.6

General Cost Characteristics of Casting Processes

	Cost*			
Casting process	Die	Equipment	Labor	Production rate (pieces/h)
Sand	L	L	L–M	< 20
Shell mold	L–M	M–H	L–M	< 10
Plaster	L–M	M	M–H	< 10
Investment	M–H	L–M	H	< 1000
Permanent mold	M	M	L–M	< 60
Die	H	H	L–M	< 200
Centrifugal	M	H	L–M	< 50

*L = Low; M = Medium; H = High.

Note that the equipment cost per casting will decrease as the number of parts cast increases; sustained high production rates can justify the high cost of dies and machinery. However, if demand is relatively small, the cost per casting increases rapidly, and it then becomes more economical to manufacture the parts by other casting processes described in this chapter, or by other manufacturing processes described in detail in Parts III and IV.

SUMMARY

- General guidelines have been established to aid in the production of castings that are free from defects, and meet dimensional tolerances, surface finish, service requirements, and various specifications and standards. The guidelines concern the shape of the casting and various techniques to minimize hot spots that could lead to shrinkage cavities. Because of the large number of variables involved, close control of all parameters is essential, particularly those related to the nature of liquid-metal flow into the molds and dies, and the rate of cooling in different regions of the mold.
- Numerous nonferrous and ferrous casting alloys are available, with a wide range of properties, casting characteristics, and applications. Because many castings are designed and produced to be assembled with other mechanical components and structures (subassemblies), several other considerations, such as weldability, machinability, and surface characteristics, also are important.
- Within the limits of good performance, the economics of casting is just as important as the technical considerations. Factors affecting the overall cost are the cost of materials, molds, dies, equipment, and labor, each of which varies with the particular casting operation.

KEY TERMS

Cast iron
Compacted-graphite iron
Design principles
Draft
Flash
Hot spots
Machining allowance
Parting line
Patternmaker's shrinkage allowance
Porosity
Shrinkage cavities
Unit cost

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REVIEW QUESTIONS

12.1 Why are steels more difficult to cast than cast irons?

12.2 What is the significance of hot spots in metal casting?

12.3 What is shrinkage allowance? Machining allowance?

12.4 Explain the reason for drafts in molds.

12.5 Why are ribs useful for flat surfaces?

12.6 What are light castings and where are they used most commonly?

12.7 Name the types of cast irons generally available, and list their major characteristics and applications.

12.8 Comment on your observations regarding Fig. 12.5.

12.9 Describe the difference between a runner and a gate.

12.10 What is the difference between machining allowance and dimensional tolerance?

12.11 What is dross? Can it be eliminated?

QUALITATIVE PROBLEMS

12.12 Describe your observation concerning the design modifications shown in Fig. 12.1.

12.13 If you need only a few castings of the same design, which three processes would be the most expensive per piece cast?

12.14 Do you generally agree with the cost ratings in Table 12.6? If so, why?

12.15 Describe the nature of the design differences shown in Fig. 12.4. What general principles do you observe in this figure?

12.16 Note in Fig. 12.5 that the ductility of some cast alloys is very low. Do you think this should be a significant concern in engineering applications of castings? Explain.

12.17 Do you think that there will be fewer defects in a casting made by gravity pouring versus one made by pouring under pressure? Explain.

12.18 Explain the difference in the importance of drafts in green-sand casting versus permanent-mold casting.

12.19 What type of cast iron would be suitable for heavy-machine bases, such as presses and machine tools? Why?

12.20 Explain the advantages and limitations of sharp and rounded fillets, respectively, in casting design.

12.21 Explain why the elastic modulus, E, of gray cast iron varies so widely, as shown in Table 12.4.

12.22 If you were to incorporate lettering or numbers on a sand-cast part, would you make them protrude from the surface or recess them into the surface? What if the part were to be made by investment casting? Explain.

12.23 The general design recommendations for a well in sand casting (see Fig. 11.3) are that (a) its diameter should be at least twice the exit diameter of the sprue and (b) its depth should be approximately twice the depth of the runner. Explain the consequences of deviating from these guidelines.

12.24 The heavy regions of parts typically are placed in the drag in sand casting and not in the cope. Explain why.

12.25 What are the benefits and drawbacks to having a pouring temperature that is much higher than the metal's melting temperature? What are the advantages and disadvantages in having the pouring temperature remain close to the melting temperature?

QUANTITATIVE PROBLEMS

12.26 When designing patterns for casting, patternmakers use special rulers that automatically incorporate solid shrinkage allowances into their designs. For example, a 300-mm patternmaker's ruler is longer than 300 mm. How long should a patternmaker's ruler be for making patterns for (a) aluminum castings and (b) high-manganese steel?

12.27 Using the information given in Table 12.2, develop approximate plots of (a) castability versus weldability and (b) castability versus machinability, for at least five of the materials listed in the table.

12.28 The part in Figure P12.28 is to be cast of 10% Sn bronze, at the rate of 100 parts per month. To find an appropriate casting process, consider all casting processes, then reject those that are (a) technically inadmissible, (b) technically feasible but too expensive for the purpose, and (c) identify the most economical one. Write a rationale using common-sense assumptions about cost.

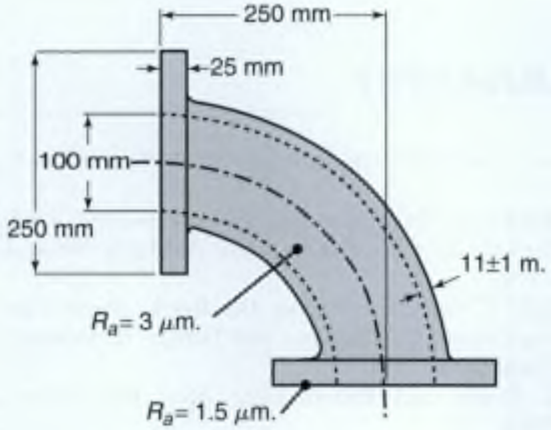


FIGURE P12.28

SYNTHESIS, DESIGN, AND PROJECTS

12.29 Describe the general design considerations pertaining to metal casting.

12.30 Add more examples of applications to those shown in Fig. 12.2.

12.31 Explain how ribs and serrations are helpful in casting flat surfaces that otherwise may warp. Give a specific illustration.

12.32 List casting processes that are suitable for making hollow parts with (a) complex external features, (b) complex internal features, and (c) both complex external and complex internal features. Explain your choices.

12.33 Small amounts of slag and dross often persist after skimming, and are introduced into the molten metal flow in casting. Recognizing that slag and dross are less dense than the molten metal, design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

12.34 If you need only a few units of a particular casting, which process(es) would you use? Why?

12.35 For the cast metal wheel illustrated in Fig. P12.35, show how (a) riser placement, (b) core placement, (c) padding, and (d) chills may be used to help feed molten metal and eliminate porosity in the isolated hub boss.

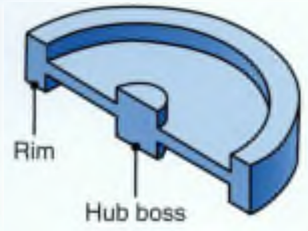
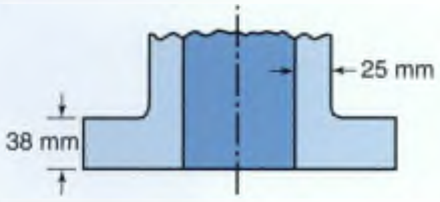


FIGURE P12.35

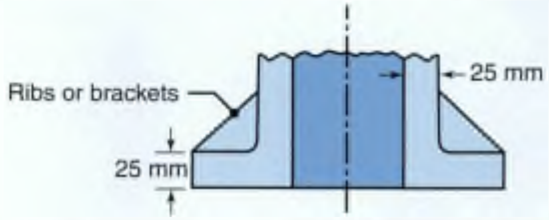
12.36 Assume that the introduction to this chapter is missing. Write a brief introduction to highlight the importance of the topics covered in it.

12.37 In Fig. P12.37, the original casting design shown in (a) was resized and modified to incorporate ribs in the design shown in (b). The casting is round and has a vertical axis of symmetry. What advantages do you think the new design has as a functional part over the old one?



(a)

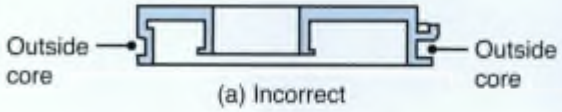
FIGURE P12.37



(b)

FIGURE P12.37 *(continued)*

12.38 An incorrect and a correct design for casting are shown in Fig. P12.38. Review the changes made and comment on their advantages.



(a) Incorrect

(b) Correct

FIGURE P12.38

12.39 Using the method of inscribed circles, shown in Fig. 12.2, justify the trend shown in Fig. 12.3.

12.40 A growing trend is the production of patterns and molds through rapid-prototyping approaches, described in Chapter 20. Consider the case of an injection molding operation, where the patterns are produced by rapid prototyping, and then hand assembled onto trees and processed in traditional fashion. What design rules discussed in this chapter would still be valid, and which would not be as important in this case?

12.41 Repeat Problem 12.40 for the case where (a) a pattern for sand casting is produced by rapid prototyping and (b) a sand mold for sand casting is produced.

PART III

Forming and Shaping Processes and Equipment

When inspecting the numerous products all around us, we soon realize that a wide variety of materials and processes have been used in making them, as can be seen from the example of an automobile shown in Fig. III.1. It will also be noted that some products consist of a few parts, such as eyeglasses, pencils, and light fixtures, while others consist of hundreds or thousands of parts, such as clocks, automobiles, and computers, or even millions of parts, as in airplanes and ships.

Some products have simple shapes, with smooth curvatures, yet others have complex configurations and detailed surface features. Some are used in critical applications, such as elevator cables and turbine blades, whereas others are used for routine applications, such as paper clips, forks, and door keys. Some are very thin, such as aluminum foil and plastic film, whereas others are very thick, as in ship hulls, boiler plates, and large machine bases.

Note that the words **forming** and **shaping** are both used in the title of this part of the book. Although there are not always clear distinctions between the two terms, *forming* generally indicates changing the shape of an existing solid body. Thus, in **forming processes**, the starting material (usually called the workpiece, stock, or blank) may be in the shape of a plate, sheet, bar, rod, wire, or tubing. For example, an ordinary wire coat hanger is made by forming a straight piece of wire, by bending

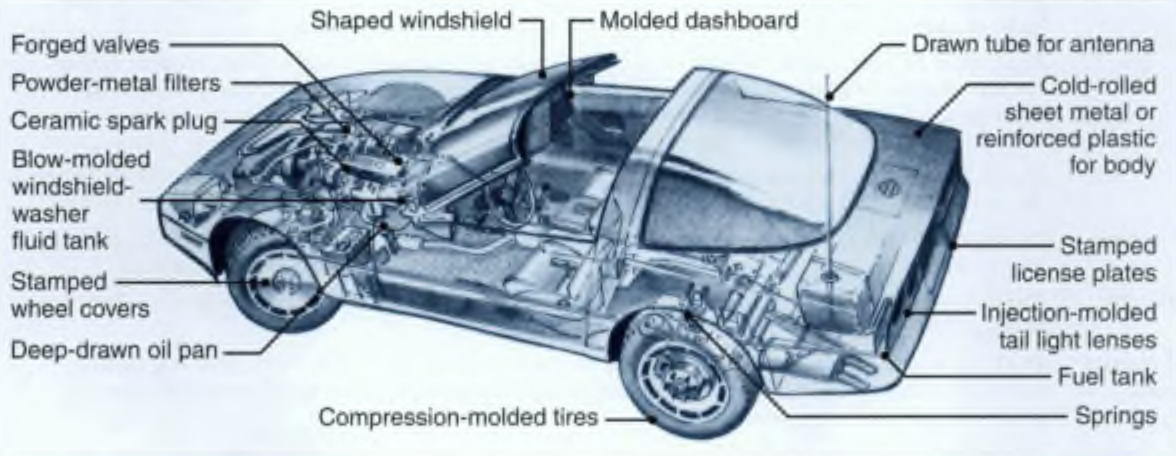


FIGURE III.1 Formed and shaped parts in a typical automobile.

and twisting it into the shape of a hanger. Likewise, the sheet metal body for an automobile is generally made of flat, cold-rolled steel sheet, which is then formed into various shapes, such as hood, roof, trunk, and door panels, using a pair of large dies.

Shaping processes typically involve molding and casting, producing a part that generally is at or near the final desired shape. A plastic coat hanger, for example, is made by forcing molten plastic into a two-piece mold, with a cavity in the shape of the hanger. Telephone and computer housings, refrigerator-door liners, some auto-body parts, and countless other plastic products are likewise shaped by forcing molten polymer into a mold, and removing it after it solidifies.

Some forming and shaping operations produce long *continuous* products, such as plates, sheets, tubing, wire, and rod and bars with various cross-sections, which then are shaped into specific products. Rolling, extrusion, and drawing processes (Chapters 13 and 15) are capable of making such long products, which then are cut into desired lengths. On the other hand, processes such as forging (Chapter 14), sheet metal forming and stamping (Chapter 16), powder metallurgy (Chapter 17), ceramic casting and glass pressing (Chapter 18), and processes involving plastics and reinforced plastics (Chapter 19), typically produce *discrete* products.

The initial raw material used in forming and shaping metals is usually molten metal, which is *cast* into individual *ingots* or *continuously cast* into slabs, rods, or pipes. Cast structures are converted to *wrought structures* by plastic-deformation processes. The raw material used also may consist of *metal powders*, which then are pressed and sintered (heated without melting) into individual parts. For plastics, the

TABLE III.1

General Characteristics of Forming and Shaping Processes

Process	Characteristics
Rolling	
Flat	Production of flat plate, sheet, and foil at high speeds; good surface finish, especially in cold rolling; very high capital investment; low-to-moderate labor cost
Shape	Production of various structural shapes (such as I-beams and rails) at high speeds; includes thread rolling; requires shaped rolls and expensive equipment; low-to-moderate labor cost; requires moderate operator skill
Forging	Production of discrete parts with a set of dies; some finishing operations usually required; usually performed at elevated temperatures, but also cold for smaller parts; die and equipment costs are high; moderate-to-high labor cost; requires moderate-to-high operator skill
Extrusion	Production of long lengths of solid or hollow shapes with constant cross-section; product is then cut into desired lengths; usually performed at elevated temperatures; cold extrusion has similarities to forging and is used to make discrete products; moderate-to-high die and equipment cost; low-to-moderate labor cost; requires low-to-moderate operator skill
Drawing	Production of long rod and wire with various cross-sections; good surface finish; low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill
Sheet-metal forming	Production of a wide variety of shapes with thin walls and simple or complex geometries; generally low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill
Powder metallurgy	Production of simple or complex shapes by compacting and sintering metal powders; moderate die and equipment cost; low labor cost and skill
Processing of plastics and composite materials	Production of a wide variety of continuous or discrete products by extrusion, molding, casting, and fabricating processes; moderate die and equipment costs; requires high operator skill in processing of composite materials
Forming and shaping of ceramics	Production of discrete products by various shaping, drying, and firing processes; low-to-moderate die and equipment cost; requires moderate-to-high operator skill

starting material is usually pellets, flakes, or powder; for ceramics, it is clays and oxides, obtained from ores or produced synthetically.

In this part of the text, the important factors involved in each forming and shaping process are described, along with how material properties and processes affect the quality and integrity of the product made (Table III.1). Detailed mathematical models of processes are available, as can be found in the Bibliographies at the end of the chapters; this book will provide only simple models for the various forming and shaping processes considered.

We also explain why some materials can be processed only by certain specific manufacturing methods, and why parts with particular shapes can only be processed by certain techniques and not by others. Also included are the characteristics of the machinery and equipment used, which can significantly influence product quality, production rate, and the economics of a particular manufacturing operation.

CHAPTER

13

Metal-rolling Processes and Equipment

EXAMPLE:

- This chapter describes the rolling of metals, which is the most important metal-forming operation based on volume of metals rolled.
- The chapter begins with a description of the flat-rolling process and analyzes the force, torque, and power required, in terms of relevant material and process parameters; it also includes a review of defects and their causes in rolled products.
- Shape-rolling processes are then described, where workpieces pass through a series of shaped rolls.
- Special rolling processes, such as cross rolling, ring rolling, thread rolling, tube rolling, and tube piercing, are also described.
- The chapter ends with a description of the characteristics of rolling mills and roll arrangements for making specific products.

Typical products made by various rolling processes: Plates for ships, bridges, structures, machines; sheet metal for car bodies, aircraft fuselages, appliances, containers; foil for packaging; I-beams, railroad rails, architectural shapes, large rings, seamless pipe and tubing; bolts, screws, and threaded components.

Alternative processes: Continuous casting, extrusion, drawing, machining of threaded components.

13.1 Introduction

Rolling is the process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of **rolls** (Fig. 13.1), a process that is similar to rolling dough with a rolling pin. Rolling, which accounts for about 90% of all metals produced by metalworking processes, was first developed in the late 1500s. Modern steelmaking practices and the production of various ferrous and nonferrous metals and alloys now generally integrate *continuous casting* with rolling processes; this method greatly improves productivity and lowers production costs, as described in Section 5.4. Nonmetallic materials also are rolled to reduce their thickness and enhance their properties.

Rolling is first carried out at elevated temperatures (*hot rolling*). During this phase, the coarse-grained, brittle, and porous structure of the ingot or the continuously cast metal is broken down into a *wrought structure*, having a finer grain size and enhanced properties, such as increased strength and hardness. Subsequently,

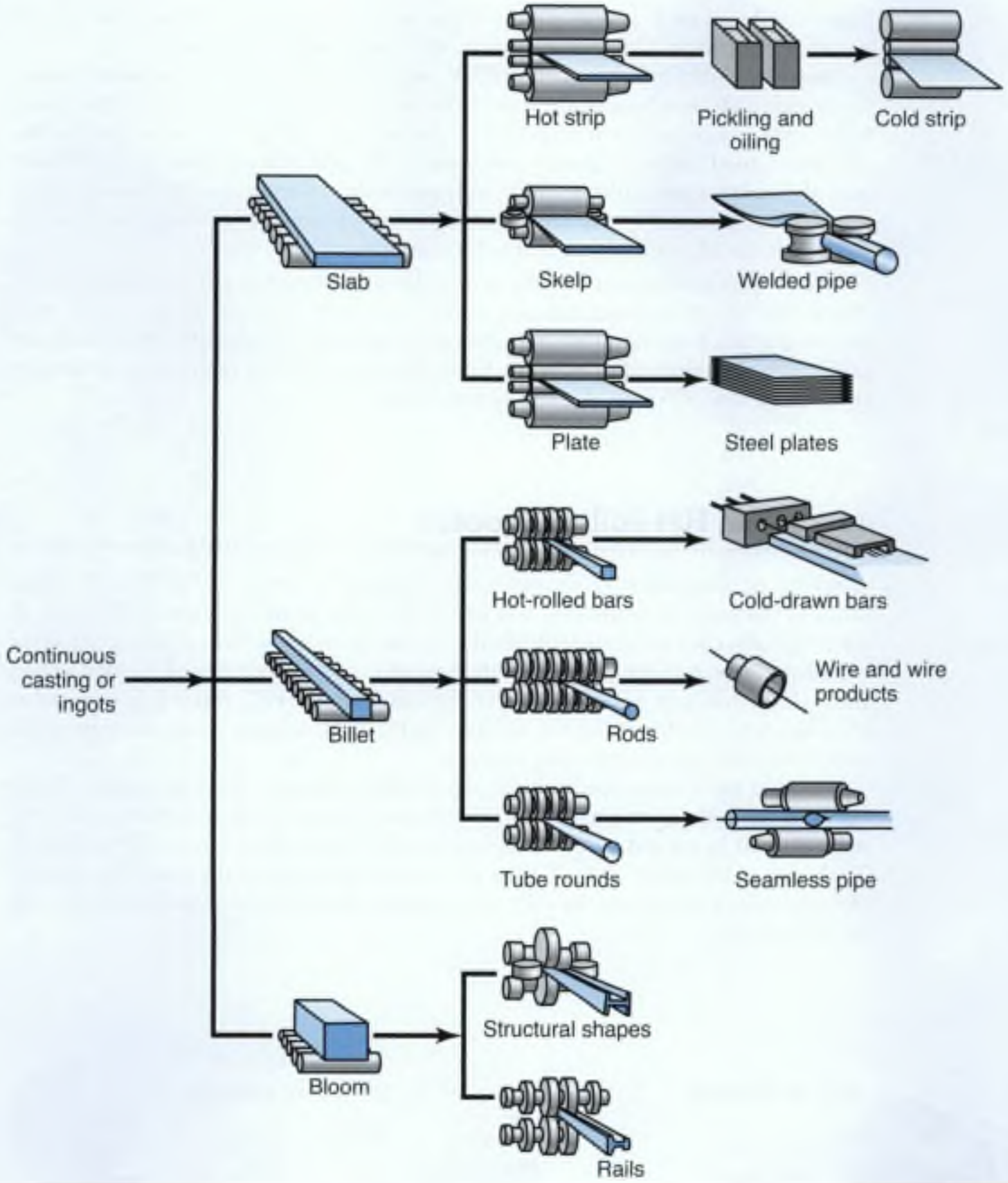


FIGURE 13.1 Schematic outline of various flat-rolling and shape-rolling processes. *Source:* Courtesy of American Iron and Steel Institute.

rolling can be performed at room temperature (*cold rolling*), whereby the rolled sheet has higher strength and hardness, and better surface finish. Cold rolling will, however, result in a product with anisotropic properties, due to preferred orientation or mechanical fibering, described in Section 1.6.

Plates generally have a thickness of more than 6 mm, and are used for structural applications, such as ship hulls, boilers, bridges, and heavy machinery.

QR Code 13.1 Animation of hot rolling of billets. (*Source:* Courtesy of Sandvik Coromant)

Plates can be as thick as 300 mm for large structural supports, 150 mm for reactor vessels, and 100 to 125 mm for machinery frames and warships.

Sheets are generally less than 6 mm thick, and are typically provided to manufacturing facilities as coils, weighing as much as 30,000 kg, or as flat sheets for further processing into a wide variety of sheet-metal products. Sheets are used for trucks and aircraft bodies, appliances, food and beverage containers, and kitchen and office equipment. Commercial aircraft fuselages and trailer bodies usually are made of aluminum–alloy sheets, with a minimum thickness of 1-mm. The skin thickness of a Boeing 747 fuselage, for example, is 1.8 mm; for a Lockheed L1011 it is 1.9 mm.

Steel sheets used for automobile and appliance bodies typically are about 0.7 mm thick. Aluminum beverage cans are made from sheets 0.28 mm thick, which, after processing into a can (Section 16.7), become a cylindrical body with a wall thickness of 0.1 mm. Aluminum **foil** typically has a thickness of 0.008 mm, although thinner foils, down to 0.003 mm, also can be produced.

13.2 The Flat-rolling Process

A schematic illustration of the *flat-rolling* process is shown in Fig. 13.2. A metal strip, of thickness h_o, enters the **roll gap** and is reduced to thickness h_f by a pair of rotating rolls, each powered individually by electric motors. The surface speed of the rolls is V_r. The velocity of the strip increases from its entry value of V_o as it moves through the roll gap, and is highest at the exit from the roll, where it is denoted as V_f. The metal accelerates in the roll gap, in the same manner as an incompressible fluid flows through a converging channel.

Because the surface speed of the rigid roll is constant, there is *relative sliding* between the roll and the strip along the contact length, L. At one point, called the **neutral point** or **no-slip point**, the velocity of the strip is the same as that of the roll. To the left of this point, the roll moves faster than the strip; to the right of this point, the strip moves faster than the roll; consequently, the frictional forces act on the strip as shown in Fig. 13.2b.

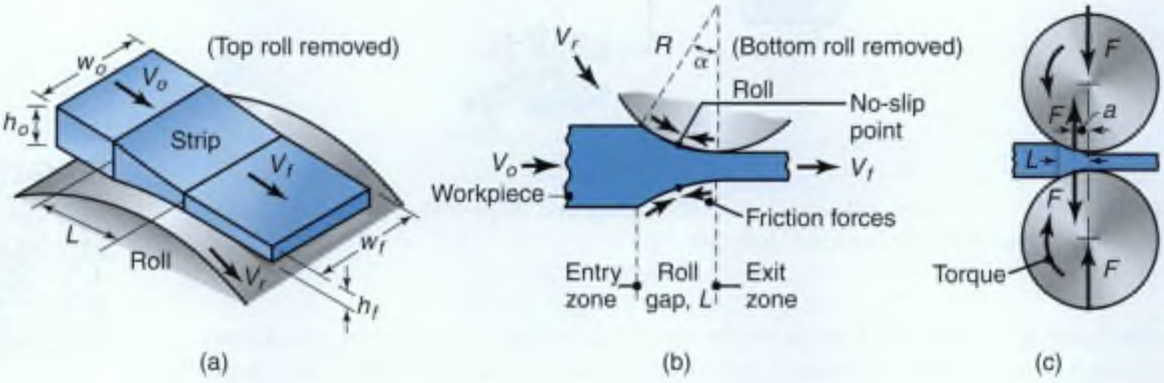


FIGURE 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) Roll force, F, and torque, T, acting on the rolls. The width of the strip, w, usually increases during rolling, as shown in Fig. 13.5.

Forward slip in rolling is defined in terms of the exit velocity of the strip, V_f, and the surface speed of the roll, V_r, as

$$\text{Forward slip} = \frac{V_f - V_r}{V_r}, \tag{13.1}$$

and is a measure of the relative velocities involved in the toll gap. Forward slip can easily be obtained by measuring the roll and workpiece velocities on a rolling mill, and gives a real-time indication of the neutral point location. Forward slip also correlates with the surface finish of the rolled strip, with low values being preferable to high values.

The rolls pull the material into the roll gap through a *frictional force* on the material; thus, a net frictional force must exist and be to the right in Fig. 13.2b; this also means that the frictional force to the left of the neutral point must be higher than the friction force to the right. Although friction is essential to enable rolling (just as it is in driving a car on a road), energy is dissipated in overcoming friction; note that increasing friction also increases rolling forces and power requirements. Furthermore, high friction could damage the surface of the rolled product or cause sticking. A compromise is therefore made in practice through lubricant selection, leading to low and controlled levels of friction.

The maximum possible **draft** is defined as the difference between the initial and final strip thicknesses, or $(h_o - h_f)$; a large draft could cause the rolls to slip. It can be shown that maximum draft is a function of the roll radius, R, and the coefficient of friction, μ, as:

$$h_o - h_f = \mu^2 R. \tag{13.2}$$

Thus, as expected, the higher the friction and the larger the roll radius, the greater the maximum possible draft. This is a situation similar to the use of large tires (high R) and rough treads (high μ) on farm tractors and off-road earthmoving equipment, which allows the vehicles to travel over rough terrain without skidding.

13.2.1 Roll Force, Torque, and Power Requirements

The rolls apply pressure on the flat strip, resolved into a *roll force*, F, as shown in Fig. 13.2c. Note that in the figure this force appears to be perpendicular to the plane of the strip, rather than at an angle; this is because, in practice, the arc of contact is very small compared to the roll radius, thus it can be assumed that the roll force is perpendicular to the strip.

The roll force in flat rolling can be estimated from the expression

$$F = LwY_{\text{avg}}, \tag{13.3}$$

where L is the roll-strip contact length, w is the width of the strip, and Y_{avg} is the average true stress (see Section 2.2.3) of the strip in the roll gap. Equation (13.3) is for a *frictionless* condition; however, an estimate of the *actual roll force*, including friction, may be made by increasing this calculated force by about 20%.

The *torque* on the roll is the product of F and a. The power required per roll can then be estimated by assuming that F acts in the middle of the arc of contact; thus in Fig. 13.2c, $a = L/2$. Therefore, the *total power* (for two rolls), in S.I. units, is

$$\text{Power (kW)} = \frac{2\pi FLN}{60{,}000}, \tag{13.4}$$

Video Solution 13.1 Draft and Force in Metal Rolling where F is in newtons, L is in meters, and N is the revolutions per minute of the roll. In traditional English units, the total power can be expressed as

$$\text{Power (hp)} = \frac{2\pi FLN}{33{,}000}, \tag{13.5}$$

where F is in pounds and L is in feet.

EXAMPLE 13.1 Calculation of Roll Force and Torque in Flat-rolling

An annealed copper strip 228 mm wide and 25 mm thick is rolled to a thickness of 20 mm in one pass. The roll radius is 300 mm, and the rolls rotate at 100 rpm. Calculate the roll force and the power required in this operation.

Solution The roll force is determined from Eq. (13.2), in which L is the roll-strip contact length. It can be shown from simple geometry that this length is given approximately by

$$L = \sqrt{R(h_o - h_f)} = \sqrt{300(25-20)} = 38.7 \text{ mm}.$$

The average true stress, Y_{avg}, for annealed copper is determined as follows: First note that the absolute value of the true strain that the strip undergoes in this operation is

$$\varepsilon = \ln\left(\frac{25}{20}\right) = 0.223.$$

Referring to Fig. 2.6, note that annealed copper has a true stress of about 80 MPa in the unstrained condition, and at a true strain of 0.223, the true stress is 280 MPa. Thus, the average true stress is $(80 + 280)/2 = 180$ MPa. We can now define the roll force as

$$F = LwY_{\text{avg}} = \frac{38.7}{1000} \times \frac{250}{1000} \times 180 \text{ MPa}$$
$$= 1.74 \text{ MN}.$$

The total power is calculated from Eq. (13.4), with $N = 100$ rpm. Thus,

$$\text{Power} = \frac{2\pi FLN}{66{,}000} = 2\pi \times 1.74 \times 10^6 \times \frac{38.7}{1000} \times \frac{100}{66{,}000} = 705 \text{ W}.$$

Exact calculation of the force and the power requirements in rolling is difficult because of the uncertainties involved in (a) determining the exact contact geometry between the roll and the strip and (b) accurately estimating both the coefficient of friction and the strength of the material in the roll gap, particularly for hot rolling because of the sensitivity of the strength of the material to strain rate (see Section 2.2.7.)

Video Solution 13.2 Force and Power in Rolling of Aluminum Foil

Reducing Roll Force. Roll force can cause significant deflection and flattening of the rolls, as it does in a rubber tire. Such changes will, in turn, affect the rolling process, its efficiency, and its ability to produce a uniform thickness in the rolled sheet (known as *gage control*). Also, the columns of the **roll stand** (including the housing, chocks, and bearings, as shown in Fig. 13.3c) would deflect under high roll forces to such an extent that the roll gap may open up significantly. Consequently, the rolls have to be set closer than originally calculated in order to compensate for this deflection and to obtain the desired final thickness.

Roll forces can be reduced by the following means (see Fig. 13.3 and Sections 13.3 and 13.4):

- Using smaller diameter rolls, to reduce the contact area
- Taking smaller reductions per pass, to reduce the contact area

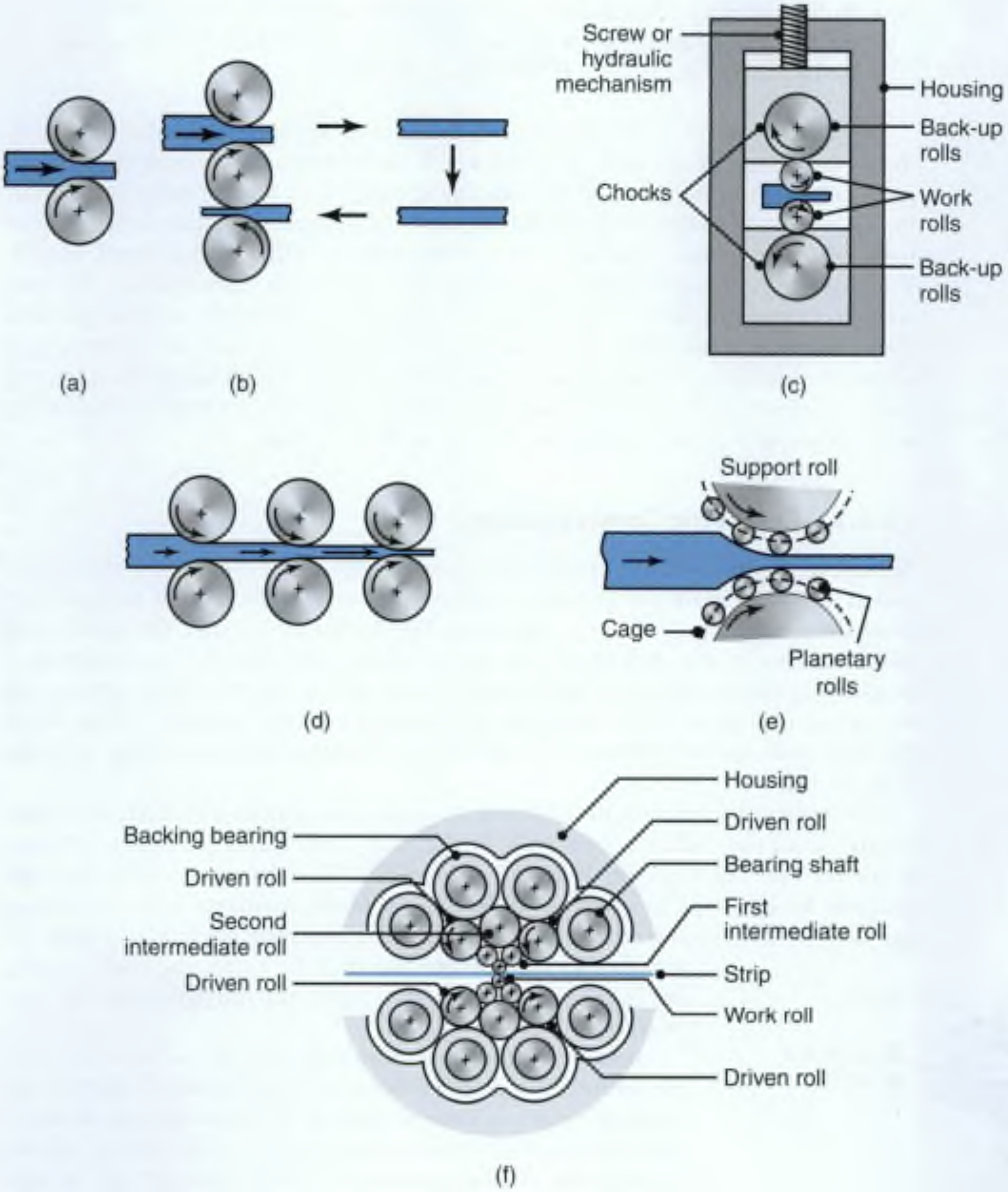


FIGURE 13.3 Schematic illustration of various roll arrangements: (a) Two-high mill; if a two-high mill is used for thick but short workpieces, it will commonly roll a billet back and forth in multiple passes, known as a *reversing mill*. (b) Three-high mill with elevator for multiple passes. (c) Four-high rolling mill showing various features; the stiffness of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip. (d) Tandem rolling, with three stands. (e) Planetary mill, and (f) Cluster mill, also known as a *Sendzimir* or Z-mill.

- Rolling at elevated temperatures, to lower the strength of the material
- Applying back and/or front tensions to the strip, to reduce the roll pressure
- Reducing friction at the roll–workpiece interface

An effective method of reducing roll forces is to apply longitudinal **tension** to the strip during rolling, as a result of which the compressive stresses required to plastically deform the material become lower (known as the apparent decrease in the yield stress of the material; see Bibliography of Chapter 2). Because they require high roll forces, tensions are important, particularly in rolling high-strength metals. Tensions can be applied to the strip at either the entry zone (**back tension**), the exit zone (**front tension**), or both. Back tension is applied to the sheet by a braking action to the reel that supplies the sheet into the roll gap (*pay-off reel*). Front tension is applied by increasing the rotational speed of the *take-up reel*. Although it has limited and specialized applications, rolling also can be carried out by front tension only, with no power supplied to the rolls, known as **Steckel rolling**.

13.2.2 Geometric Considerations

Because of the forces acting on the rolls, they undergo shape changes during rolling. Just as a straight beam deflects under a transverse load, roll forces tend to *elastically* bend the rolls during rolling, as shown in Fig. 13.4a; as a result, the rolled strip will be thicker at its center than at its edges, known as **crown**. A common method of avoiding this problem is to grind the rolls in such a way that their diameter at the center is slightly larger than that at their edges (called **camber**). Thus, when the rolls bend, the strip being rolled will have a constant thickness along its width (Fig. 13.4b).

For rolling sheet metals, the radius of the maximum camber is generally 0.25 mm greater than the radius at the ends of the roll; however, a particular camber is correct only for a certain load and strip width. To reduce deflection, the rolls can also be subjected to external bending, by applying moments at their bearings (as can be demonstrated by simply bending a wooden stick at its ends to simulate camber). Note also that the higher the elastic modulus of the roll material, the smaller the roll deflection (see also Section 13.4).

Because of the heat generated, due to the work of plastic deformation during rolling, rolls can become slightly barrel shaped, known as **thermal camber**. Unless compensated for by some means, this condition can produce strips that are thinner at the center than at their edges. Thermal camber can be controlled by adjusting the location of coolants and their flow rate along the length of the rolls.

Roll forces also tend to *flatten* the rolls elastically, producing an effect much like the flattening of automobile tires. Flattening is undesirable because it results, in effect, in a larger roll radius which, in turn, means a larger contact area for the same draft, and thus the roll force increases because of the now larger contact area.

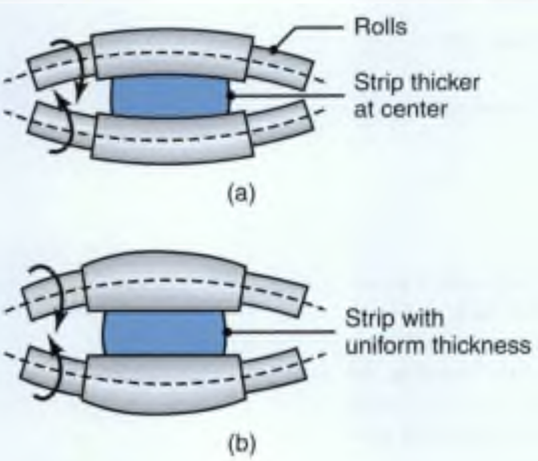


FIGURE 13.4 (a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with camber, producing a strip with uniform thickness through the strip width. (Roll deflections have been exaggerated for clarity.)

Spreading. In rolling plates and sheets with high width-to-thickness ratios, the width of the strip remains effectively constant during rolling. However, with smaller ratios (such as a bar with a square cross-section), its width increases significantly as it passes through the rolls, an effect that can easily be observed in the rolling of dough with a rolling pin. The increase in width is called *spreading* (Fig. 13.5).

It can be shown that spreading increases with (a) decreasing width-to-thickness ratio of the entering strip, because of reduction in the width constraint, (b) increasing friction, and (c) decreasing ratio of roll radius to strip thickness. Spreading can also be prevented by using vertical rolls, in contact with the strip edges; known as *edger mills*, the vertical rolls provide a physical constraint to spreading.

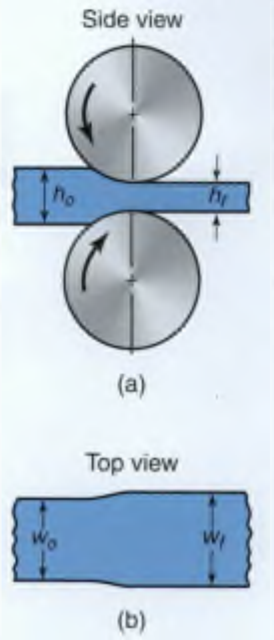


FIGURE 13.5 Spreading in flat rolling; note that similar spreading can be observed when dough is rolled with a rolling pin.

13.2.3 Vibration and Chatter

Vibration and *chatter* can have significant adverse effects on product quality and productivity in manufacturing operations. Generally defined as *self-excited vibration*, chatter in rolling leads to periodic variations in the rolled sheet thickness and surface finish, and may lead to excessive scrap (see Table 40.3). Chatter in rolling is found predominantly in tandem mills (Fig. 13.3d). Chatter is very detrimental to productivity; it has been estimated, for example, that modern rolling mills could operate at up to 50% higher speeds were it not for chatter.

Chatter is a complex phenomenon (see also Section 25.4), and results from interactions between the structural dynamics of the mill stand and the dynamics of the rolling operation. Rolling speed and lubrication are found to be the two most significant parameters. Although not always practical to implement, it also has been suggested that chatter can be reduced by (a) increasing the distance between the stands of the rolling mill, (b) increasing the strip width, (c) decreasing the reduction per pass (draft), (d) increasing the roll radius, (e) increasing the strip-roll friction, and (f) incorporating external dampers in the roll supports.

13.3 Flat-rolling Practice

The initial rolling steps (*breaking down*) of the material is usually done by **hot rolling**, above the recrystallization temperature of the metal (Section 1.7). As described in Section 10.2 and illustrated in Fig. 10.2, a **cast structure** typically is dendritic, consisting of coarse and nonuniform grains; this structure is usually brittle, and may also be porous. Hot rolling converts the cast structure to a **wrought structure** (Fig. 13.6), with finer grains and enhanced ductility, both of which result from the breaking up of brittle grain boundaries and the closing up of internal defects, including porosity. Typical temperature ranges for hot rolling are about 450°C for aluminum alloys, up to 1250°C for alloy steels, and up to 1650°C for refractory alloys (see also Table 14.3).

The rolled product of the first hot-rolling operation is called **bloom**, **slab**, or **billet** (see Fig. 13.1). A bloom usually has a square cross-section, at least 150 mm on the side, whereas a slab is usually rectangular in cross-section. Blooms are further processed by *shape rolling* into structural shapes, such as I-beams and railroad rails (Section 13.5). Slabs are rolled into plates and sheets. Billets usually are square (with a cross-sectional area smaller than that for blooms), and are later rolled into various shapes, such as round rods and bars, using shaped rolls. Hotrolled round rods, called **wire rods**, are used as the starting material for rod- and wire-drawing operations (Chapter 15).

In hot rolling of blooms, billets, and slabs, the surface of the material is usually **conditioned** (prepared for a subsequent operation) prior to rolling them. Conditioning is often done by means of a torch (*scarfing*), which removes heavy

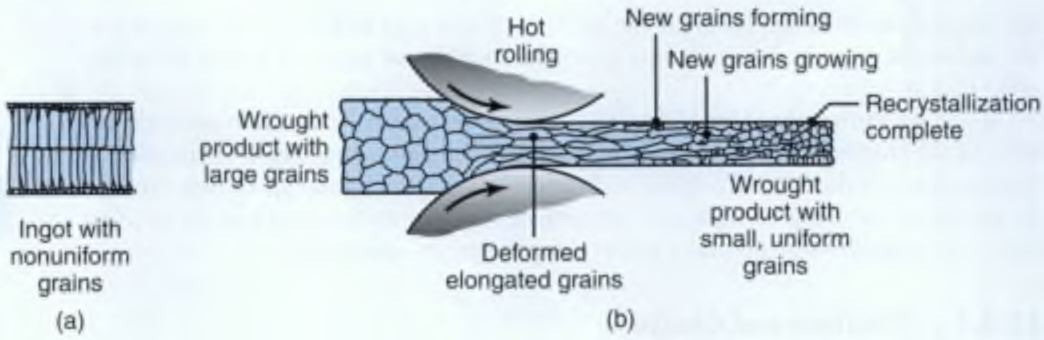


FIGURE 13.6 Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility; cast structures of ingots or continuous casting (Section 5.4) are converted to a wrought structure by hot working.

scale, or by rough grinding, which smoothens surfaces. Prior to cold rolling, the scale developed during hot rolling may be removed by *pickling* with acids (acid etching), and by such mechanical means as blasting with water or by grinding.

Cold rolling is carried out at room temperature and, compared with hot rolling, produces sheets and strips with a much better surface finish, better dimensional tolerances, and enhanced mechanical properties (because of strain hardening).

Pack rolling is a flat-rolling operation in which two or more layers of sheet are rolled together, thus increasing productivity. Aluminum foil, for example, is pack rolled in two layers, thus only the top and bottom outer surfaces are in contact with the rolls. Note that one side of aluminum foil is matte, while the other side is shiny. The foil-to-foil side has a matte and satiny finish, whereas the foil-to-roll side is shiny and bright (because the polished surface is impressed onto the foil during rolling).

Rolled mild steel, when subsequently stretched during sheet-forming operations, undergoes *yield-point elongation* (Section 16.3), a phenomenon that causes surface irregularities, called *stretcher strains* or *Lüder's bands*. To prevent this situation, the sheet metal is subjected to a final light pass of 0.5–1.5% reduction (known as **temper rolling** or **skin pass**) shortly before stretching it in a subsequent forming operation.

A rolled sheet may not be sufficiently flat as it exits the roll gap, due to factors such as variations in the incoming material or in the processing parameters during rolling. To improve *flatness*, the rolled strip typically passes through a series of **leveling rolls**. Several roll arrangements can be used, as shown in Fig. 13.7, in which the sheet is flexed in opposite directions as it passes through the sets of rolls.

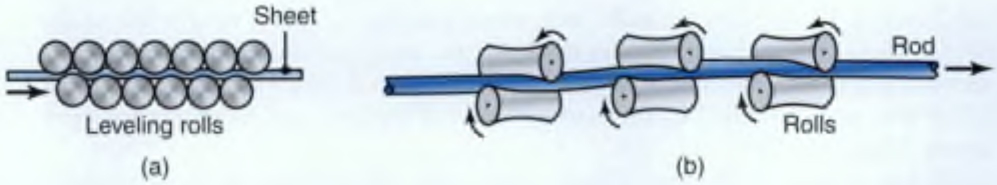


FIGURE 13.7 (a) A method of roller leveling to flatten rolled sheets. (b) Roller leveling to straighten drawn rods.

13.3.1 Defects in Rolled Plates and Sheets

Defects may be present on the surfaces of rolled plates and sheets, or there may be internal structural defects. Defects are undesirable not only because they adversely affect surface appearance, but also because they may affect strength, formability, and other manufacturing characteristics of the rolled sheets. Several surface defects (scale, rust, scratches, gouges, pits, and cracks) have been identified in sheet metals. These defects may be caused by inclusions and impurities in the original cast material or by various other conditions related to material preparation and to the rolling operation.

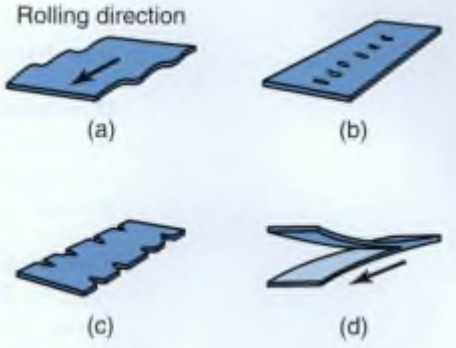


FIGURE 13.8 Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.

Wavy edges on sheets (Fig. 13.8a) are due to roll bending. The strip becomes thinner along its edges than at its center (see Fig. 13.4a), thus, because of volume constancy in plastic deformation, the edges have to elongate more than the material at the center. Consequently, the edges buckle because they are constrained by the central region from expanding freely in the longitudinal (rolling) direction.

The **cracks** shown in Figs. 13.8b and c are usually the result of low material ductility at the rolling temperature. Because the quality of the edges of the sheet is important in subsequent forming operations, edge defects in rolled sheets may have to be removed by shearing and slitting operations (Section 16.2). **Alligatoring** (Fig. 13.8d) is typically caused by nonuniform bulk deformation of the billet during rolling or by the presence of defects in the original cast material.

13.3.2 Other Characteristics of Rolled Metals

Residual Stresses. Because of nonuniform deformation of the material in the roll gap, residual stresses can develop in rolled plates and sheets, especially in cold rolling. Small-diameter rolls or small thickness reductions per pass tend to plastically deform the metal to a higher degree at its surfaces than in its bulk (Fig. 13.9a). This situation results in compressive residual stresses on the surfaces and tensile stresses in the bulk. Conversely, large-diameter rolls or high reductions per pass tend to deform the bulk more than its surfaces (Fig. 13.9b). This is due to the higher frictional constraint

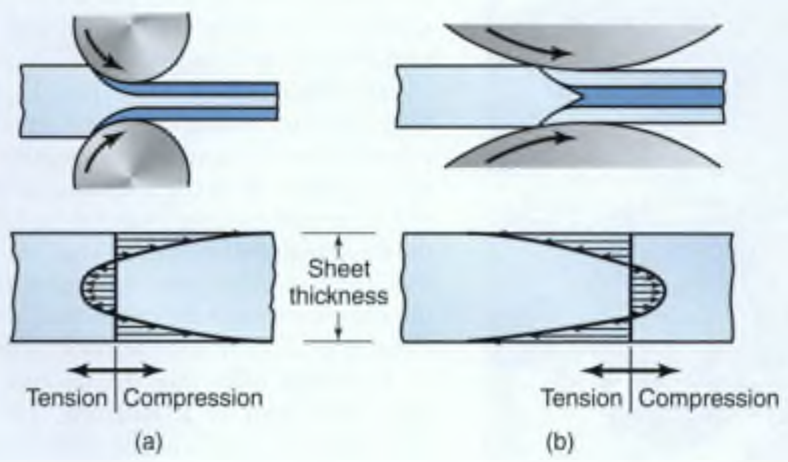


FIGURE 13.9 (a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions per pass; note the reversal of the residual stress patterns.

at the surfaces along the arc of contact, a situation that produces residual stress distributions that are the opposite of those with small-diameter rolls.

Dimensional Tolerances. Thickness tolerances for cold-rolled sheets usually range from ±0.01 to 0.05 mm; tolerances are much greater for hot-rolled plates. *Flatness tolerances* are usually within ±15 mm/m for cold rolling and ±55 mm/m for hot rolling.

Surface Roughness. The ranges of surface roughness in cold and hot rolling are given in Fig. 23.14, which, for comparison, also includes other manufacturing processes. Note that cold rolling can produce a very fine surface finish; thus, products made of cold-rolled sheets may not require additional finishing operations. Note also in the figure that hot rolling and sand casting produce the same range of surface roughness.

Gage Numbers. The thickness of a sheet is usually identified by a *gage number*: the smaller the number, the thicker the sheet. Several numbering systems are used in industry, depending on the type of sheet metal. Rolled sheets of copper and brass are generally identified by thickness changes during rolling, such as 14 hard, 12 hard, and so on.

13.4 Rolling Mills

Several types of *rolling mills* and equipment are available, with a range of sizes and diverse roll arrangements. Although the designs of equipment for hot and cold rolling are essentially the same, there are important differences in the roll materials, process parameters, lubricants, and cooling systems. The design, construction, and operation of rolling mills (Fig. 13.10) require major investments. Highly automated mills now produce close-tolerance, high-quality plates and sheets, at high production rates and at low cost per unit weight, particularly when integrated with continuous casting (Section 5.4). The width of rolled products may range up to 5 m, and rolling speeds are up to 40 m/s.

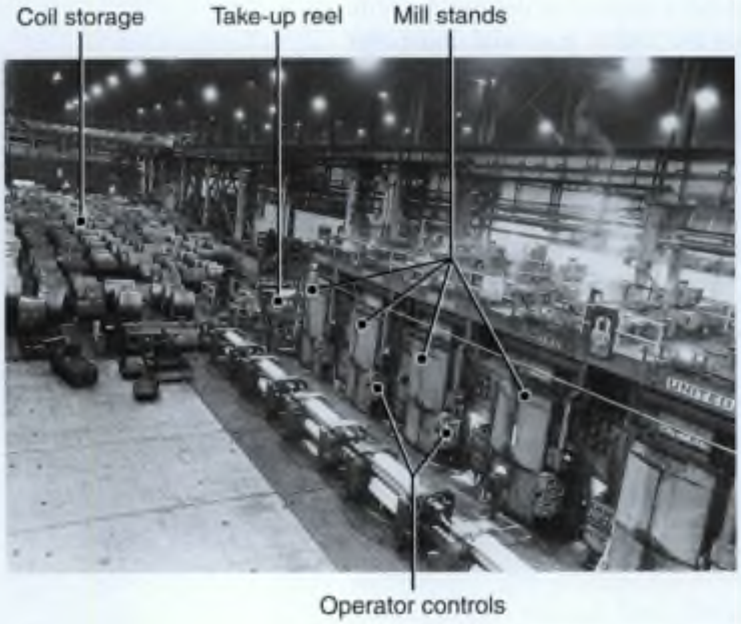


FIGURE 13.10 View of a rolling mill. *Source:* Courtesy of Ispat Inland.

Two-high rolling mills (Fig. 13.3a) are used for hot rolling in initial breakdown passes (*primary roughing* or **cogging mills**) on cast ingots or in continuous casting, with roll diameters ranging from 0.6 to 1.4 m. In the **three-high mill** (*reversing mill*, Fig. 13.3b) the direction of material movement through the rolls is reversed after each pass, using an elevator mechanism and various manipulators.

Four-high mills (Fig. 13.3c) and **cluster mills** (**Sendzimir** or **Z mill**, Fig. 13.3f) use small-diameter work rolls to lower roll forces (because of smaller roll-strip contact area), and thus lower power requirements and reduced spreading. Moreover, when worn or broken, small rolls can be replaced at lower cost than can large ones. On the other hand, small rolls deflect more under roll forces, and thus have to be supported by other larger—diameter rolls. Although the cost of a Sendzimir mill facility is very high, it is particularly suitable for cold rolling thin sheets of high-strength metals and alloys. Common rolled widths in this mill are 0.66 m, with a maximum of 1.5 m.

In **tandem rolling**, the strip is rolled continuously, through a number of **stands**, to thinner gages with each pass (Fig. 13.11). Each stand consists of a set of rolls, with its own housing and controls; a group of stands is called a *train*. The control of the strip thickness and the speed at which the strip travels through each roll gap is critical. Extensive electronic and computer controls are used in these operations, particularly in precision rolling at high speeds.

Roll Materials. The basic requirements for roll materials are strength and resistance to wear (see also Table 5.8). Common roll materials are cast iron, cast steel, and forged steel; tungsten carbide is also used for small-diameter rolls, such as the work roll in the cluster mill (Fig. 13.3f). Forged-steel rolls, although more costly than cast rolls, have higher strength, stiffness, and toughness than cast-iron rolls. Rolls for cold rolling are ground to a fine finish, and for special applications, they are also polished. Rolls made for cold rolling should not be used for hot rolling, because they may crack due to thermal cycling (*heat checking*) or *spall* (cracking or flaking of surface layers).

Lubricants. Hot rolling of ferrous alloys is usually carried out without lubricants, although graphite may be used to reduce friction. Water-based solutions may be used to cool the rolls and to break up the scale on the rolled material. Nonferrous

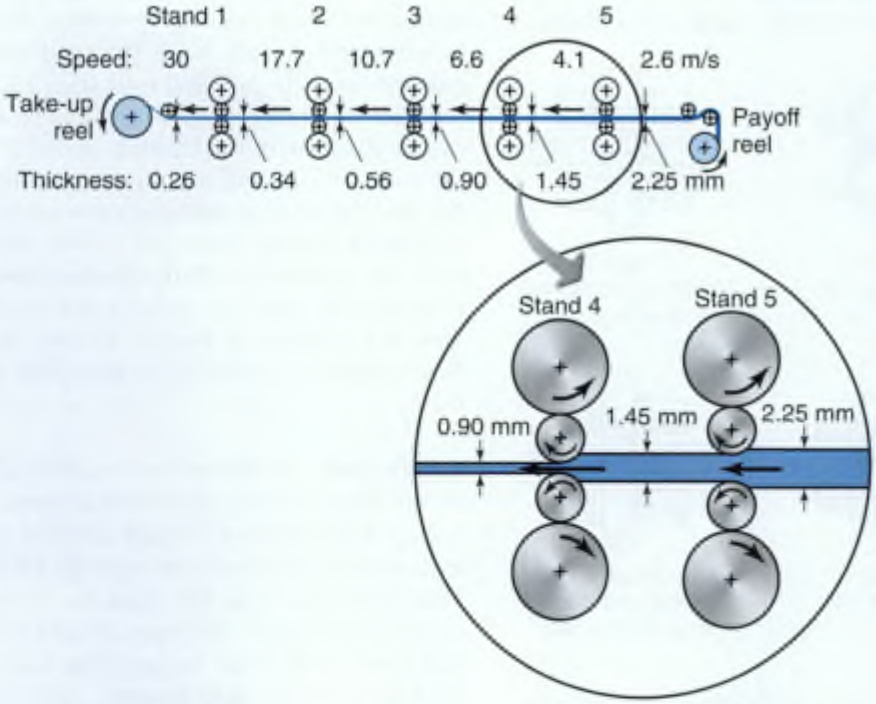


FIGURE 13.11 An example of a tandem-rolling operation.

alloys are hot rolled using a variety of compounded oils, emulsions, and fatty acids. Cold rolling is carried out with water-soluble oils or low-viscosity lubricants, such as mineral oils, emulsions, paraffin, and fatty oils. (See also Section 33.7.)

13.4.1 Integrated Mills and Minimills

Integrated Mills. These mills are large facilities that involve complete integration of the activities, from the production of hot metal in a blast furnace to the casting and rolling of finished products, ready to be shipped to the customer.

Minimills. Competition in the steel industry has led to the development of *minimills*, in which scrap metal is (a) melted in electric-arc furnaces, (b) cast continuously, and (c) rolled directly into specific lines of products. Each minimill produces essentially one type of rolled product (rod, bar, or structural sections such as angle iron), from basically one type of metal or alloy. The scrap metal, obtained locally to reduce transportation costs, is typically old machinery, cars, and farm equipment. Minimills have the economic advantage of lower capital equipment costs for each type of metal and product line, with low labor and energy costs. The products typically are aimed at markets in the mill's particular geographic location.

QR Code 13.2 Animation of shape rolling. (*Source:* Courtesy of Sandvik Coromant)

13.5 Various Rolling Processes and Mills

Several rolling processes and mills have been developed to produce a variety of product shapes.

Shape Rolling. Straight and long structural shapes (such as channels, I-beams, railroad rails, and solid bars) are formed by *shape rolling* (*profile rolling*), in which the heated stock passes through pairs of specially designed rolls (Fig. 13.12; see also Fig. 13.1). *Cold shape rolling* also can be done, with the starting materials in the shape of rod, with various cross-sections. Because the entering material's cross-section is reduced nonuniformly, the proper design of a roll sequence, called **roll-pass design,** is critical in order to prevent the formation of external and internal defects, hold dimensional tolerances, and to reduce roll wear.

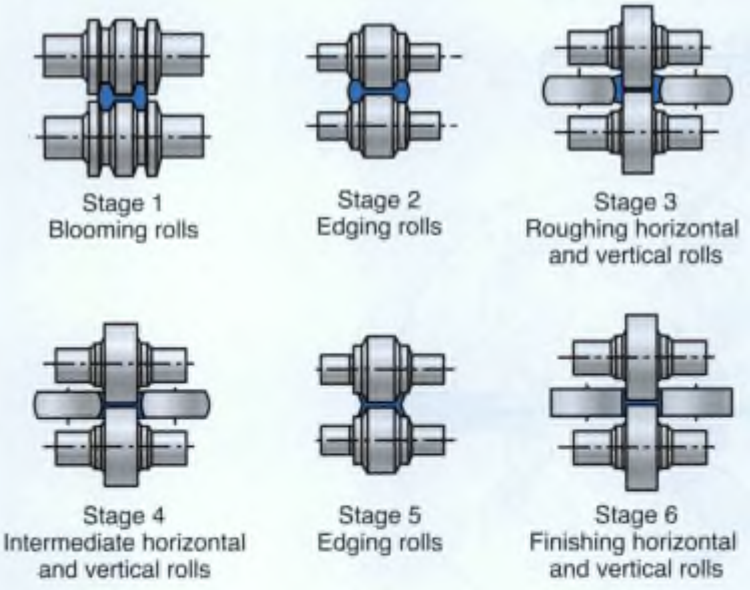


FIGURE 13.12 Steps in the shape rolling of an I-beam. Various other structural sections, such as channels and rails, also are rolled by this process.

Roll Forging. In this operation, also called *cross rolling*, the cross-section of a round bar is shaped by passing it through a pair of rolls with specially profiled grooves (Fig. 13.13). This process is typically used to produce tapered shafts and leaf springs, table knives, and hand tools. Roll forging also may be used as a preliminary forming operation, to be followed by other forging processes (Chapter 14).

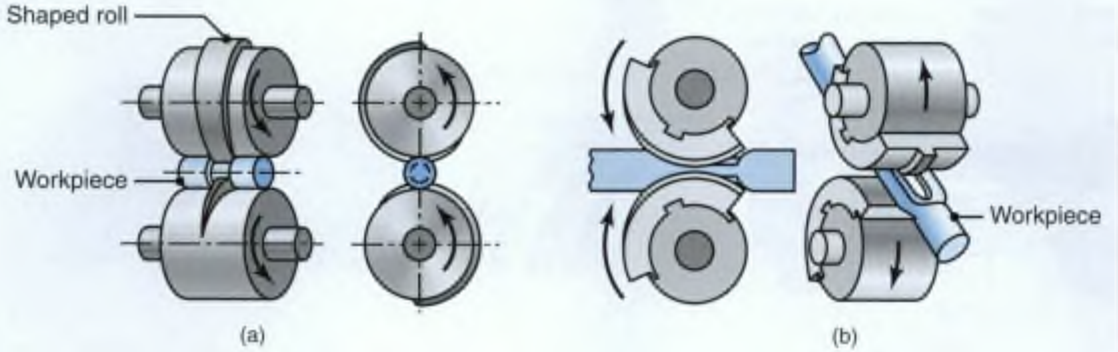


FIGURE 13.13 Two examples of the roll-forging operation, also known as cross rolling; tapered leaf springs and knives can be made by this process. *Source:* After J. Holub.

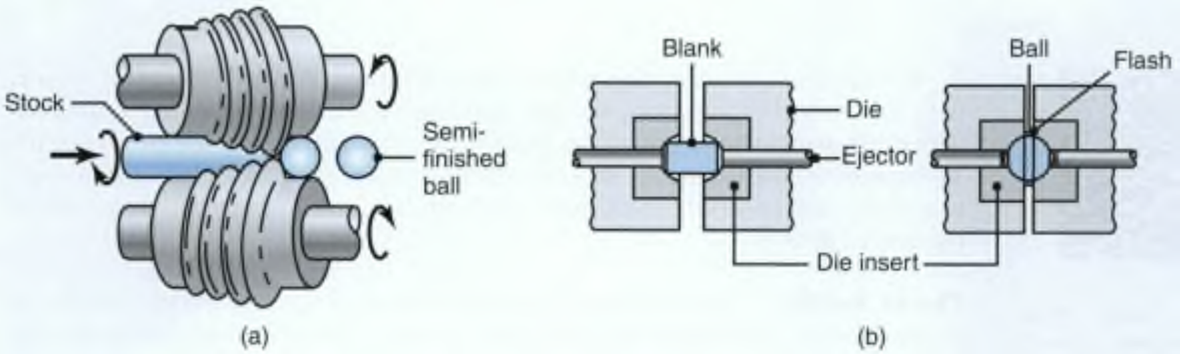


FIGURE 13.14 (a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank: note the formation of flash. The balls made by these processes are subsequently ground and polished for use in ball bearings.

Skew Rolling. A process similar to roll forging is *skew rolling*, typically used for making ball bearings (Fig. 13.14a). Round wire or rod is fed into the roll gap, and spherical blanks are formed continuously by the action of the rotating rolls. (Another method of forming ball bearings is illustrated in Fig. 13.14b, which is basically a forging operation, described in Fig. 14.12.) The balls, which require further finishing, are subsequently ground and polished in special machinery (see Fig. 26.15).

Ring Rolling. In *ring rolling*, a ring-shaped blank is placed between two rolls, one of which is driven while the other idles (Fig. 13.15a). The thickness of the ring is reduced by bringing the rolls closer together as they rotate. Since the volume of the ring remains constant during deformation (volume constancy), the reduction in ring thickness results in its increase in diameter. The process can be carried out at room temperature or at an elevated temperature, depending on the size (which can be up to 3 m in diameter), and strength and ductility of the material.

Depending on its size, the blank may be produced by such means as cutting from a plate, piercing, or sawing or shearing a thick-walled pipe. Various shapes can be ring rolled using shaped rolls (Figs. 13.15b–d). The thickness of rings also can be reduced by an open-die forging process, as illustrated in Fig. 14.4c; however, dimensional control and surface finish will not be as good as in ring rolling.

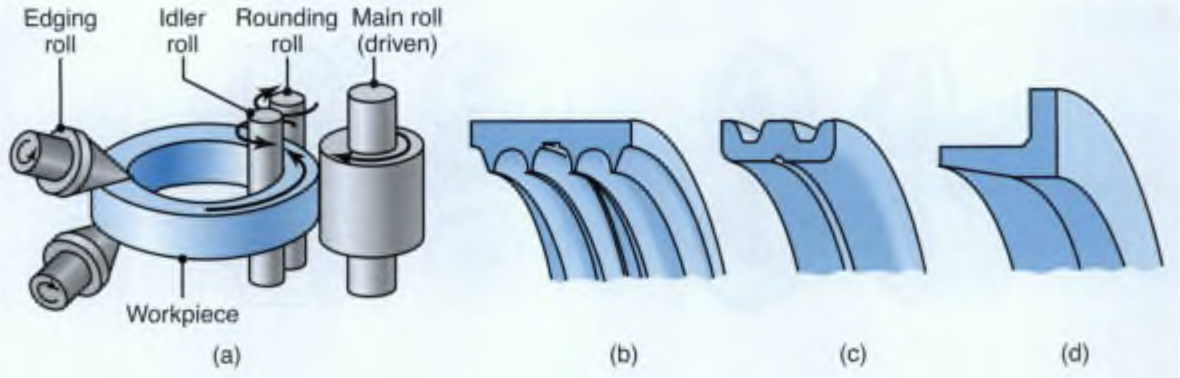


FIGURE 13.15 (a) Schematic illustration of a ring-rolling operation: thickness reduction results in an increase in the part diameter. (b) through (d) Examples of cross-sections that can be formed by ring rolling.

QR Code 13.3 Ring-rolling operations. (*Source:* Courtesy of the Forging Industry Association, www.forging.org)

Typical applications of ring rolling are body casings for rockets and jet-engine, ball- and roller-bearing races, flanges, and reinforcing rings for pipes. Compared with other manufacturing processes that are capable of producing the same part, the advantages of ring rolling are short production times, low scrap, close dimensional tolerances, and favorable grain flow in the product, thus enhancing its strength in the desired direction.

Thread Rolling. *Thread rolling* is a cold-forming process by which straight or tapered threads are formed on round rods or wire. The threads are formed on the rod or wire with each stroke of a pair of flat reciprocating dies (Fig. 13.16a). In another method, threads are formed using two rolls (Fig. 13.16b) or *rotary* or *planetary dies* (Fig. 13.16c), at production rates as high as 80 pieces per second. Typical parts made are screws, bolts, and similar threaded parts. Depending on die design, the major diameter of a rolled thread may or may not be larger than a machined thread (Fig. 13.17a), that is, the same as the blank diameter.

The thread-rolling process has the advantages of generating threads at high production rates and without any scrap. The surface finish produced is very smooth, and the process induces compressive residual stresses on the surfaces, thus improving fatigue life. Thread rolling is superior to other methods of thread manufacture (notably thread cutting, as illustrated in Fig. 23.1k), because machining the threads cuts through the grain-flow lines of the material, whereas rolling the threads results in a grain-flow pattern that improves thread strength (Figs. 13.17b and c). **Internal thread rolling** can be carried out with a fluteless **forming tap** (Section 23.7). This is an operation that is similar to external thread rolling, and it produces accurate internal threads and with good strength.

Spur and helical gears can be produced by a cold-rolling process similar to thread rolling (see also Section 24.7); the operation may be carried out on solid cylindrical blanks or on precut gears. Cold rolling of gears has extensive applications in automatic transmissions and in power tools.

Lubrication is important in thread-rolling operations in order to obtain good surface finish and surface integrity and to minimize defects. Lubrication affects the manner in which the material deforms during deformation, an important consideration because of the possibility of internal defects being developed. Typically made of hardened steel, rolling dies are expensive because of their complex shape. The

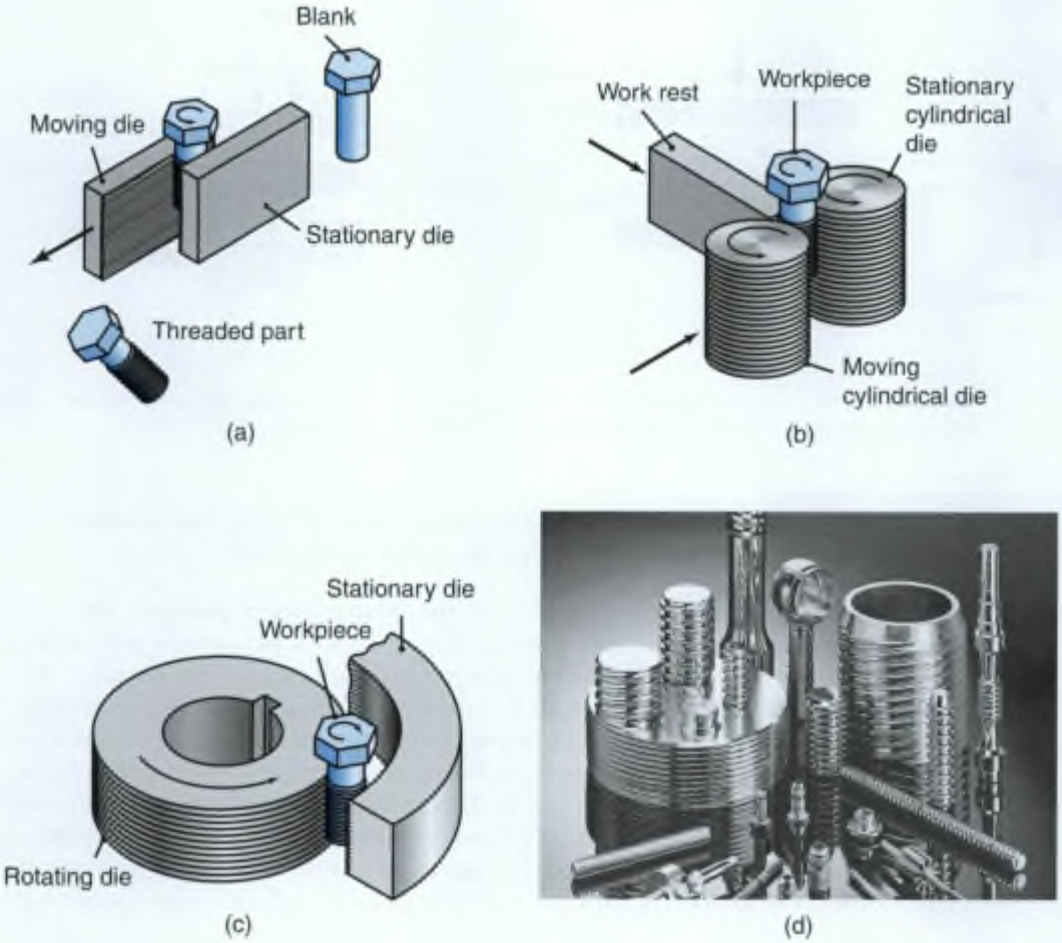
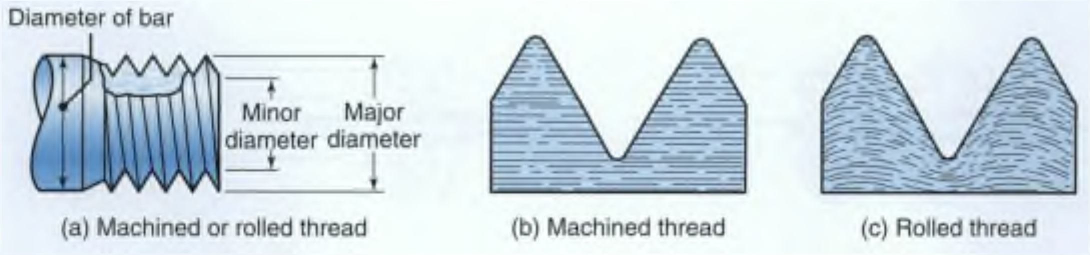


FIGURE 13.16 Thread-rolling processes: (a) reciprocating flat dies used to produce a threaded fastener; (b) two-roll dies; (c) rotary or planetary die set; and (d) a collection of thread-rolled parts made economically at high production rates. *Source:* (d) courtesy of Tesker Manufacturing Corp., Saukville, Wisconsin.



(a) Machined or rolled thread (b) Machined thread (c) Rolled thread

FIGURE 13.17 (a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.

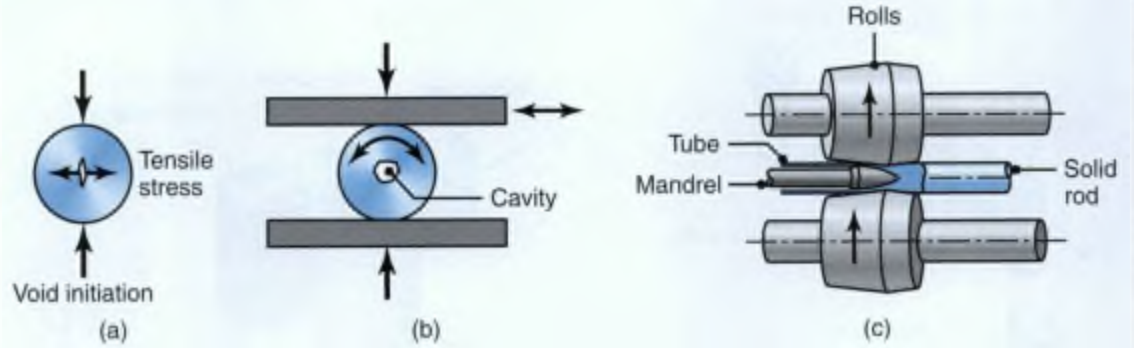


FIGURE 13.18 Cavity formation in a solid, round bar and its utilization in the rotary tube piercing process for making seamless pipe and tubing. (See also Fig. 2.9.)

dies usually cannot be reground after they are worn. With proper die materials and preparation, however, die life may range up to millions of pieces.

Rotary Tube Piercing. Also known as the **Mannesmann process**, this is a hot-working operation for making long, thick-walled *seamless pipe and tubing* (Fig. 13.18). Developed in the 1880s, this process is based on the principle that when a round bar is subjected to radial compressive forces, tensile stresses develop at its center (see Fig. 2.9). When continuously subjected to these cyclic compressive stresses (Fig. 13.18b), the bar begins to develop a small cavity at its center, which then begins to grow. This phenomenon can be demonstrated with a short piece of round eraser, by rolling it back and forth on a hard flat surface, as shown in Fig. 13.18b.

Rotary tube piercing is carried out using an arrangement of rotating rolls (Fig. 13.18c). The axes of the rolls are *skewed* in order to pull the round bar through

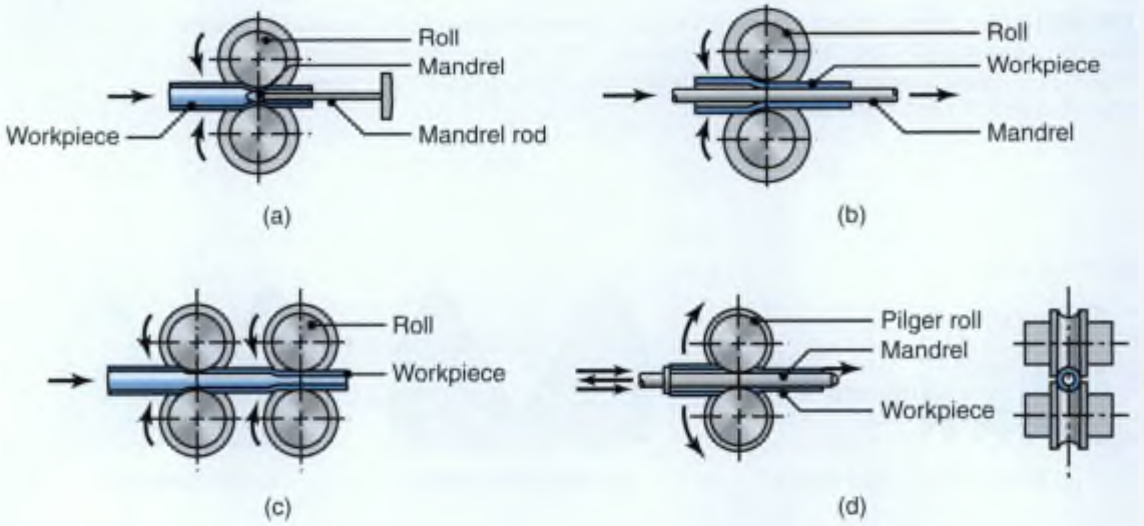


FIGURE 13.19 Schematic illustration of various tube-rolling processes: (a) with a fixed mandrel; (b) with a floating mandrel; (c) without a mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses also can be changed by other processes, such as drawing, extrusion, and spinning.

the rolls, by the axial component of the rotary motion. An internal mandrel assists the operation by expanding the hole and sizing the inside diameter of the tube. The mandrel may be held in place by a long rod or it may be a floating mandrel, without a support (see Fig. 15.21c for a similar floating mandrel, used in drawing). Because of the severe deformation that the bar undergoes, the round blank must be of high quality and free of inclusions.

Tube Rolling. The diameter and thickness of pipes and tubing can be reduced by *tube rolling*, which utilizes shaped rolls, arranged in various configurations (Fig. 13.19). These operations can be carried out either with or without an internal mandrel. In the *pilger mill*, the tube and an internal mandrel undergo a reciprocating motion; the rolls are specially shaped and are rotated continuously. During the gap cycle on the roll, the tube is advanced and rotated, starting another cycle of tube reduction, whereby the tube undergoes a reduction in both diameter and wall thickness. Steel tubing 265 mm in diameter has been produced by this process. Other operations for tube manufacturing are described in Chapter 15.

SUMMARY

- Rolling is the process of reducing the thickness or changing the cross-section of a long strip by compressive forces applied through a set of rolls. Shape rolling is used to make products with various cross-sections. Other rolling operations include ring rolling and thread rolling.
- Rolling may be carried out at room temperature (cold rolling) or at elevated temperatures (hot rolling). The process involves several material and process variables, including roll diameter (relative to material thickness), reduction per pass, speed, lubrication, and temperature. Spreading, bending, and flattening are important considerations for controlling the dimensional accuracy of the rolled stock.
- Rolling mills have a variety of roll configurations, such as two-high, three-high, four-high, cluster (Sendzimir), and tandem. Front and/or back tension may be applied to the material to reduce roll forces.
- Continuous casting and rolling of ferrous and nonferrous metals into semifinished products are now in common practice because of the economic benefits.
- Integrated mills are large facilities involving the complete sequence of activities, from the production of hot metal in a blast furnace to the casting and the rolling of finished products ready to be shipped to the customer. On a much smaller scale, minimills utilize scrap metal that is melted in electric-arc furnaces, cast, and continuously rolled into specific lines of products.

KEY TERMS

Alligatoring
Back tension
Billet
Bloom
Camber
Cast structure
Chatter
Cogging mill
Cold rolling
Crown
Draft
Flat rolling
Foil
Front tension
Gage number
Hot rolling
Mannesmann process
Minimill
Neutral point
Pack rolling
Pilger mill
Plate
Ring rolling
Roll

Roll forging
Roll stand
Rolling
Rolling mill
Rotary tube piercing
Sendzimir mill
Shape rolling
Sheet
Skew rolling
Slab
Spreading
Stand
Steckel rolling
Tandem rolling
Temper rolling
Thread rolling
Tube rolling
Wrought structure

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REVIEW QUESTIONS

13.1 What is the difference between a plate and a sheet?

13.2 Define roll gap, neutral point, and draft.

13.3 What factors contribute to spreading in flat rolling?

13.4 What is forward slip? Why is it important?

13.5 Describe the types of deflections that rolls undergo.

13.6 Describe the difference between a bloom, a slab, and a billet.

13.7 Why may roller leveling be a necessary operation?

13.8 List the defects commonly observed in flat rolling.

13.9 What are the advantages of tandem rolling? Pack rolling?

13.10 How are seamless tubes produced?

13.11 Why is the surface finish of a rolled product better in cold rolling than in hot rolling?

13.12 What is a Sendzimir mill? What are its important features?

13.13 What is the Mannesmann process? How is it different from tube rolling?

13.14 Describe ring rolling. Is there a neutral plane in ring rolling?

13.15 How is back tension generated?

QUALITATIVE PROBLEMS

13.16 Explain why the rolling process was invented and developed.

13.17 Flat rolling reduces the thickness of plates and sheets. It is possible, instead, to reduce their thickness simply by stretching the material? Would this be a feasible process? Explain.

13.18 Explain how the residual stress patterns shown in Fig. 13.9 become reversed when the roll radius or reduction-per-pass is changed.

13.19 Explain whether it would be practical to apply the roller-leveling technique shown in Fig. 13.7a to thick plates.

13.20 Describe the factors that influence the magnitude of the roll force, F, in Fig. 13.2c.

13.21 Explain how you would go about applying front and back tensions to sheet metals during rolling. How would you go about controlling these tensions?

13.22 What typically is done to make sure that the product in flat rolling is not crowned?

13.23 Make a list of parts that can be made by (a) shape rolling and (b) thread rolling.

13.24 Describe the methods by which roll flattening can be reduced. Which property or properties of the roll material can be increased to reduce roll flattening?

13.25 It was stated that spreading in flat rolling increases with (a) a decreasing width-to-thickness ratio of the entering material, (b) decreasing friction, and (c) a decreasing ratio of the roll radius to the strip thickness. Explain why.

13.26 Flat rolling can be carried out by front tension only, using idling rolls (Steckel rolling). Since the torque on the rolls is now zero, where, then, is the energy coming from to supply the work of deformation in rolling?

13.27 Explain the consequence of applying too high a back tension in rolling.

13.28 Note in Fig. 13.3f that the driven rolls (powered rolls) are the third set from the work roll. Why isn't power supplied through the work roll itself? Is it even possible? Explain.

13.29 Describe the importance of controlling roll speeds, roll gaps, temperature, and other process variables in a tandem-rolling operation, as shown in Fig. 13.11. Explain how you would go about determining the optimum distance between the stands.

13.30 In Fig. 13.9a, if you remove the top compressive layer by, say, grinding, will the strip remain flat? If not, which way will it curve and why?

13.31 Name several products that can be made by each of the operations shown in Fig. 13.1.

13.32 List the possible consequences of rolling at (a) too high of a speed and (b) too low of a speed.

13.33 It is known that in thread rolling, as illustrated in Fig. 13.16, a workpiece must make roughly six revolutions to form the thread. Under what conditions (process parameters, thread geometry or workpiece properties) can deviation from this rule take place?

13.34 If a rolling mill encounters chatter, what process parameters would you change, and in what order? Explain.

13.35 Can the forward slip ever become negative? Why or why not?

QUANTITATIVE PROBLEMS

13.36 In Example 13.1, calculate the roll force and the power for the case in which the workpiece material is 1100-O aluminum and the roll radius, R, is 200mm

13.37 Calculate the individual drafts in each of the stands in the tandem-rolling operation shown in Fig. 13.11.

13.38 Estimate the roll force, F, and the torque for an AISI 1020 carbon-steel strip that is 200 mm wide, 10 mm thick, and rolled to a thickness of 7 mm. The roll radius is 200 mm, and it rotates at 200 rpm.

13.39 A rolling operation takes place under the conditions shown in Fig. P13.39. What is the position, x_n, of the neutral point? Note that there are front and back tensions that have not been specified. Additional data are as follows: Material is 5052-O aluminum; hardened steel rolls; surface roughness of the rolls = 0.02 μm; rolling temperature = 210°C.

13.40 Estimate the roll force and power for annealed low-carbon steel strip 200 mm wide and 10 mm thick, rolled to a thickness of 6 mm. The roll radius is 200 mm, and the roll rotates at 200 rpm; use $\mu = 0.1$.

13.41 A flat-rolling operation is being carried out where $h_o = 5$ mm, $h_f = 3.75$ mm, $w_o = 250$ mm, $R = 200$ mm, $\mu = 0.25$, and the average flow stress of the material is 275 MPa. Estimate the roll force and the torque; include the effects of roll flattening.

13.42 It can be shown that it is possible to determine μ in flat rolling without measuring torque or forces. By inspecting the equations for rolling, describe an experimental procedure to do so. Note that you are allowed to measure any quantity other than torque or forces.

13.43 Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

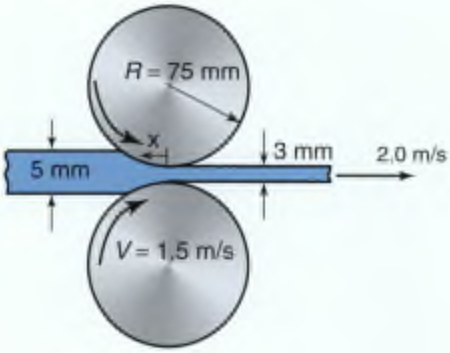


FIGURE P13.39

SYNTHESIS, DESIGN, AND PROJECTS

13.44 A simple sketch of a four-high mill stand is shown in Fig. 13.3c. Make a survey of the technical literature and present a more detailed sketch for such a stand, showing the major components.

13.45 Obtain a piece of soft, round rubber eraser, such as that at the end of a pencil, and duplicate the process shown in Fig. 13.18b. Note how the central portion of the eraser will begin to disintegrate, producing a rough hole.

13.46 If you repeat the experiment in Problem 13.45 with a harder eraser, such as that used for erasing ink, you will note that the whole eraser will begin to crack and crumble. Explain why.

13.47 Design a set of rolls to produce cross-sections other than those shown in Fig. 13.12.

13.48 Design an experimental procedure for determining the neutral point in a flat rolling operation.

13.49 Using a rolling pin and any available dough (bread, cookie, etc), measuring 100 mm by 100 mm by 8 mm, quantify the spreading in flat rolling for different reductions in thickness.

13.50 Derive an expression for the thickest workpiece that can be drawn between two rolls as a function of roll gap, roll radius, and coefficient of friction.

Metal-forging Processes and Equipment

CHAPTER 14

- This chapter describes the fundamentals of forging and related processes, including design and economic considerations.
- Open-die forging operations for producing simple shapes are discussed first, followed by impression-die and closed-die forging operations for producing more intricate shapes.
- Various forging operations, such as heading, piercing, coining, swaging, and cold extrusion, are then introduced.
- Factors involved in forging defects and die failures are explained.
- The economics of forging, as it relates to process selection, is also discussed.
- The chapter ends with a review of the design of parts to be forged, guidelines for die design and manufacturing, and selection of die materials and lubricants in forging operations.

Typical parts made by forging and related processes: Shafts, gears, bolts, turbine blades, hand tools, dies, and components for machinery, transportation, and farm equipment.

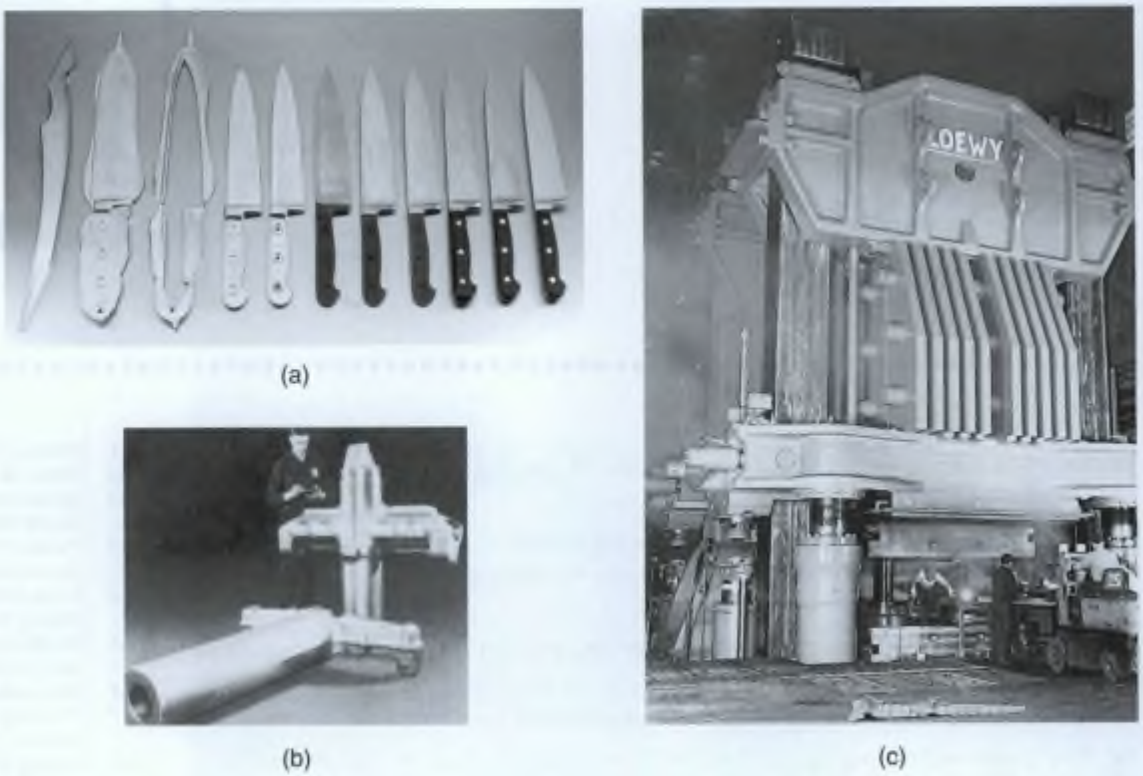
Alternative processes: Casting, powder metallurgy, machining, and fabrication.

14.1 Introduction

Forging is a basic process in which the workpiece is shaped by compressive forces applied through various dies and tooling. One of the oldest and most important metalworking operations, dating back at least to 4000 B.C., forging was first used to make jewelry, coins, and various implements, by hammering metal with tools made of stone. Forged parts now include large rotors for turbines, gears, cutlery (Fig. 14.1a), hand tools, components for machinery, aircraft (Fig. 14.1b), railroads, and transportation equipment.

Unlike rolling operations, described in Chapter 13, that generally produce continuous plates, sheets, strips, and various structural cross-sections, forging operations produce discrete parts. Because the metal flow in a die and the material's grain structure can be controlled, forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications (Fig. 14.2). Simple forging operations can be performed with a heavy hammer and an anvil, as has been done traditionally by blacksmiths. Most forgings require a set of dies and such equipment as press or powered hammers.

QR Code 14.1 What is Forging. (*Source:* Courtesy of the Forging Industry Association, www.forging.org)

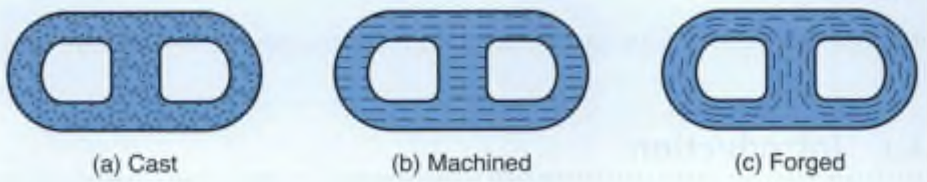


(a)

(b)

(c)

FIGURE 14.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear components for the C5A and C5B transport aircraft, made by forging. (c) General view of a 445-MN hydraulic press. *Source:* (a) Courtesy of Mundial, LLC. (b) and (c) Courtesy of Wyman-Gordon Company.



(a) Cast

(b) Machined

(c) Forged

FIGURE 14.2 Schematic illustration of a part (dragline chain link, approximately 2 m long) made by three different processes and showing grain flow. Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production. *Source:* Courtesy of the Forging Industry Association.

Forging may be carried out at room temperature (*cold forging*) or at elevated temperatures (*warm* or *hot forging*), depending on the homologous temperature, described in Section 1.8. Cold forging requires higher forces, because of the higher strength of the workpiece material, which also must possess sufficient ductility at room temperature to be able to undergo the required deformation without cracking. Cold-forged parts have good surface finish and dimensional accuracy. Hot forging requires lower forces, but the dimensional accuracy and surface finish of the parts are not as good as those in cold forging.

Forgings generally are subjected to additional finishing operations, such as heat treating to modify properties and machining for accuracy in final dimensions and good surface finish. The finishing operations can be minimized by *precision forging*, which is an important example of *net-shape* or *near-net-shape* forming processes. As described throughout this book, parts that can be forged successfully also may be manufactured economically by other methods, such as casting (Chapter 11), powder metallurgy (Chapter 17), or machining (Part IV). Each of these methods will produce a part having different characteristics, particularly with regard to strength, toughness, dimensional accuracy, surface finish, and the possibility of internal or external defects.

14.2 Open-die Forging

Open-die forging is the simplest forging operation (Table 14.1). Although most opendie forgings generally weigh 15 to 500 kg, forgings as heavy as 275 metric tons have been made. Part sizes may range from very small (such as pins, nails, and bolts) to very large [up to 23 m long shafts for ship propellers]. Open-die forging can be simply described by a metal workpiece (blank), placed between two flat dies, and reduced in height by compressing it (Fig. 14.3), a process called **upsetting** or **flat-die forging**. The die surfaces may have shallow cavities or features to produce relatively simple shapes.

The deformation of a workpiece under *frictionless* conditions is shown in Fig. 14.3b. Because constancy of volume is maintained, any reduction in height increases the diameter of the forged part. Note in the figure that the workpiece is deformed uniformly; in actual operations, however, there is friction at the die–workpiece interfaces, and the part develops a barrel shape (Fig. 14.3c), a deformation mode also called *pancaking*.

Barreling is caused primarily by frictional forces that oppose the outward flow of the workpiece at the die interfaces; thus, it can be minimized by using an effective

QR Code 14.2 Open-die forging operations. (*Source:* Courtesy of the Forging Industry Association, www.forging.org)

QR Code 14.3 Animation of open-die forging. (*Source:* Courtesy of Sandvik Coromant)

TABLE 14.1

General Characteristics of Forging Processes

Process	Advantages	Limitations
Open die	Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost, not economical for small quantities; machining often necessary
Blocker	Low die costs; high production rates	Machining to final shape necessary; parts with thick webs and large fillets
Conventional	Requires much less machining than blocker type; high production rates; good utilization of material	Higher die cost than blocker type
Precision	Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization	High forging forces, intricate dies, and provision for removing forging from dies

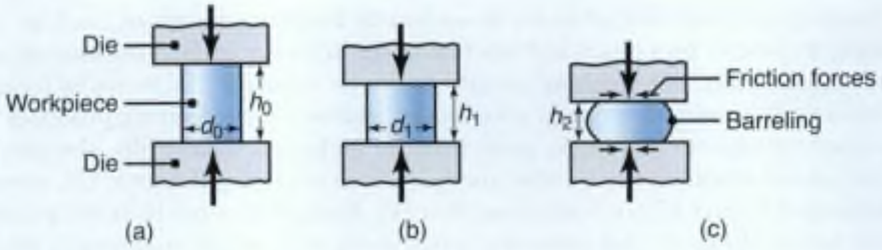


FIGURE 14.3 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction; note barreling of the billet caused by friction forces at the billet–die interfaces.

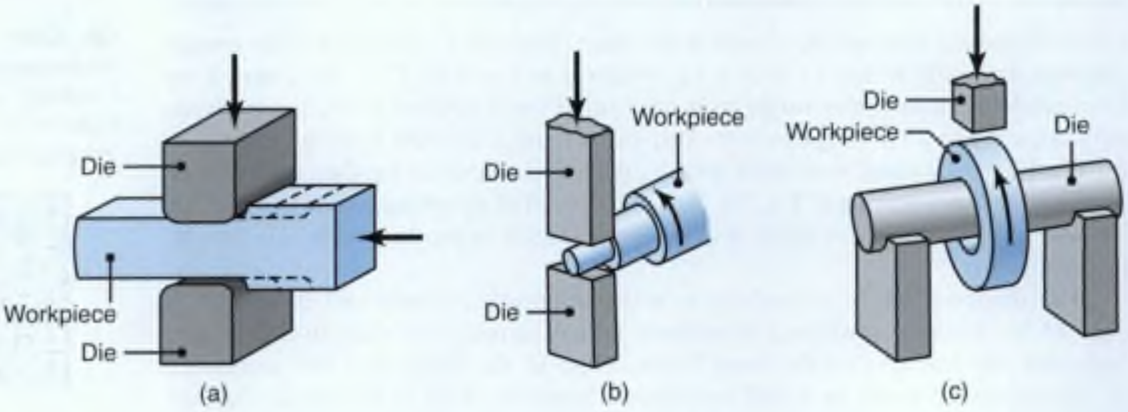


FIGURE 14.4 (a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil; reduction in thickness is accompanied by barreling. (b) Reducing the diameter of a bar by open-die forging; note the movements of the dies and the workpiece. (c) The thickness of a ring being reduced by open-die forging.

lubricant. Barreling also can develop in upsetting hot workpieces between cold dies. The material at the die surfaces cools rapidly, while the rest remains relatively hot; consequently, the material at the top and bottom of the workpiece has higher resistance to deformation than the material at the center. As a result, the central portion of the workpiece expands laterally to a greater extent than do the ends. Barreling from thermal effects can be reduced or eliminated by using heated dies. Thermal barriers, such as glass cloth at the die–workpiece interfaces also can be used for this purpose.

Cogging, also called *drawing out*, is an open-die forging operation in which the thickness of a bar is reduced by successive forging steps (*bites*) at specific intervals (Fig. 14.4a). The thickness of bars and rings also can be reduced by similar open-die forging techniques, as illustrated in Figs. 14.4b and c. Because the contact area between the die and the workpiece is small, a long section of a bar can thus be reduced in thickness without requiring large forces or heavy machinery. Note that blacksmiths have been performing such operations for centuries on hot workpieces, using a hammer and an anvil. Cogging of larger workpieces is usually done using mechanized equipment and computer controls, in which lateral and vertical movements of the dies are coordinated to produce the desired part shape.

Forging Force. The *forging force, F*, in an *open-die forging operation* on a solid cylindrical workpiece can be estimated from the formula

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right), \tag{14.1}$$

where Y_f is the *flow stress* of the material (see Example 14.1), μ is the coefficient of friction between the workpiece and the die, and r and h are, respectively, the instantaneous radius and height of the workpiece.

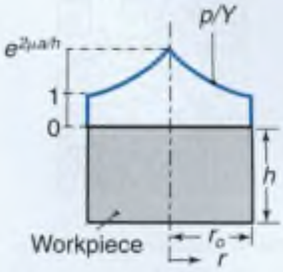


FIGURE 14.5 Distribution of die pressure in upsetting with sliding friction. Note that the pressure at the outer radius is equal to the flow stress, Y, of the material. Sliding friction means that the frictional stress is directly proportional to the normal stress.

Friction Hill. Consider the upsetting of a solid cylinder, as depicted in Fig. 14.3. If the workpiece-die interface is frictionless, then the die pressure is equal to the flow stress of the material. If friction is present, as is the case in actual forging operations, then calculating the die pressure is more involved. For upsetting of a cylinder with outer radius r_o, height, h, and coefficient of friction, μ, the die pressure at any radius can be expressed as

$$p = Ye^{2\mu(r_o - r)/h}. \tag{14.2}$$

The die-pressure distribution is plotted in Fig. 14.5. Note that the pressure is maximum at the center of the workpiece, and can be very high, especially if the diameter-to-height ratio of the workpiece is large. Because of its shape, the pressure-distribution curve in Fig. 14.5 is referred to as the *friction hill*.

EXAMPLE 14.1 Calculation of Forging Force in Upsetting

Given: A solid cylindrical workpiece made of 304 stainless steel is 150 mm in diameter and 100 mm high. It is reduced in height by 50%, at room temperature, by open-die forging with flat dies. Assume that the coefficient of friction is 0.2.

Find: Calculate the forging force at the end of the stroke.

Solution: The forging force at the end of the stroke is calculated using Eq. (14.1), in which the dimensions pertain to the final dimensions of the forging. The final height is $h = 100/2 = 50$ mm, and the final radius, r, is determined from volume constancy by equating the volumes before and after deformation. Hence,

$$(\pi)(75)^2(100) = (\pi)(r)^2(50).$$

Thus, $r = 106$ mm.

The quantity Y_f in Eq. (14.1) is the flow stress of the material, which is the stress required to continue plastic deformation of the workpiece at a particular true strain. The absolute value of the true strain that the workpiece has undergone at the end of the stroke in this operation is

$$\epsilon = \ln\left(\frac{100}{50}\right) = 0.69.$$

The flow stress can be determined by referring to Eq. (2.8) and noting from Table 2.3 that, for 304 stainless steel, $K = 1275$ MPa and $n = 0.45$. Thus, for a true strain of 0.69, the flow stress is calculated to be 1100 MPa. Another method is to refer to Fig. 2.5 and note that the flow stress for 304 stainless steel at a true strain of 0.69 is about 1000 MPa. The small difference between the two values is due to the fact that the data in Table 2.3 and Fig. 2.5 are from different sources.

Taking the latter value for flow stress, the forging force can now be calculated, noting that in this problem the units in Eq. (14.1) must be in N and m. Thus,

$$F = \left(1000 \times 10^6\right)(\pi)(0.106)^2(1) + \frac{(2)(0.2)(0.106)}{(3)(0.050)}$$
$$= 4.5 \times 10^7 \text{ N} = 45 \text{ MN}.$$

14.3 Impression-die and Closed-die Forging

In *impression-die forging*, the workpiece takes the shape of the die cavity while being forged between two shaped dies (Figs. 14.6a–c). This process is usually carried out at elevated temperatures, in order to lower the forging forces and develop enhanced ductility of the workpiece. Note in Fig. 14.6c that, during deformation, some of the material flows outward and forms a **flash**.

The flash has an important role in impression-die forging: The high pressure, and the resulting high frictional resistance in the flash, presents a severe constraint on any radially outward flow of the material in the die. This is due to the friction hill effect,

Video Solution 14.1 Construction of the Load-stroke Curve in Forging

Video Solution 14.2 Calculation of Forging Force

QR Code 14.4 Video of impression-die forging. (*Source:* Courtesy of the Forging Industry Association, www.forging.org)

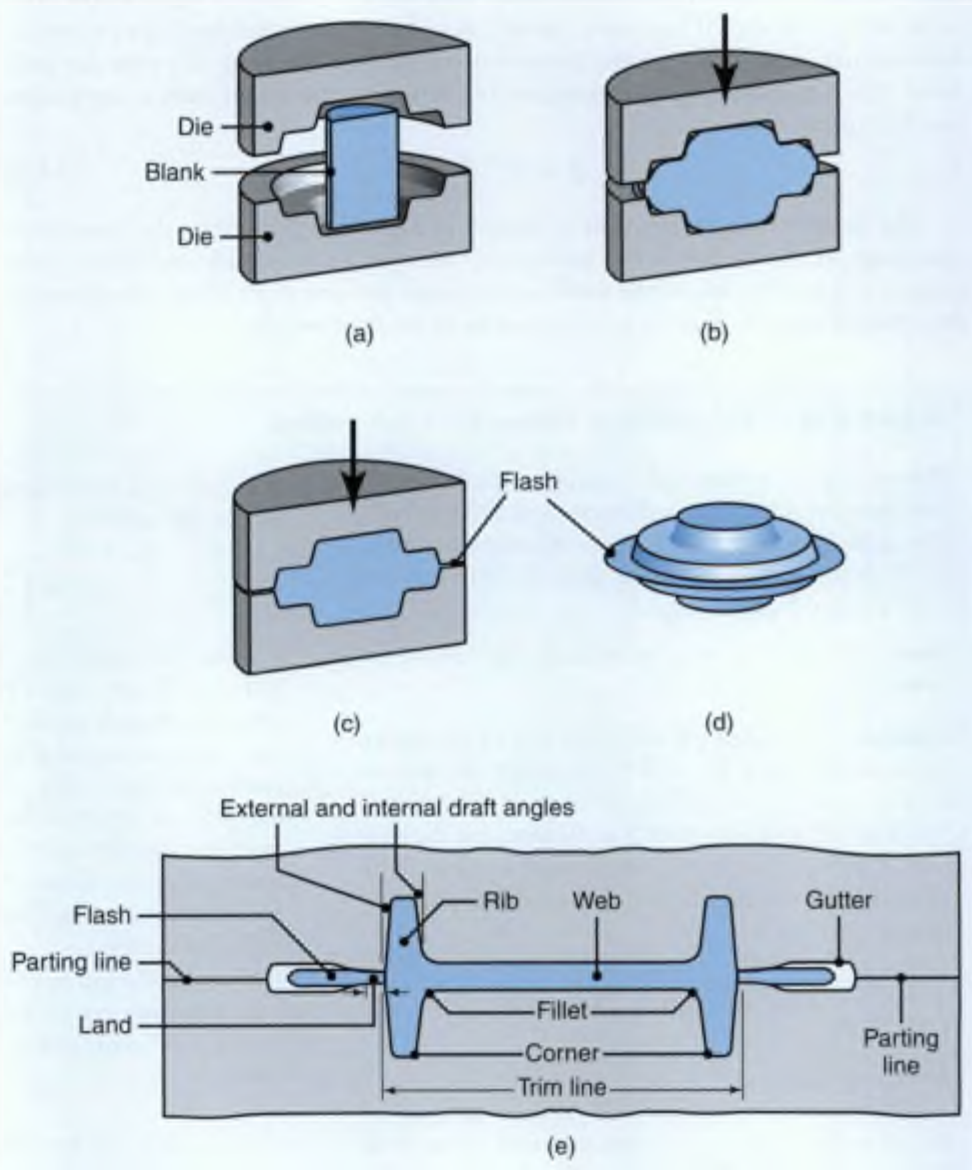


FIGURE 14.6 (a) through (d) Stages in impression-die forging of a solid round billet; note the formation of flash, which is excess metal that is subsequently trimmed off. (e) Standard terminology for various features of a forging die.

described in Section 14.2. Thus, based on the principle that, in plastic deformation, the material flows in the direction of least resistance (because it requires less energy), the material flows preferentially into the die cavity, eventually filling it completely.

The standard terminology for a typical forging die is shown in Fig. 14.6e. Instead of being made as one piece, dies may be made of several pieces (segmented), including die inserts (Fig. 14.7), and particularly for complex part shapes. The inserts can easily be replaced in the case of wear or failure in a particular region of the die, and are usually made of stronger and harder materials.

The blank to be forged is prepared by (a) *cropping* (shearing, Section 16.2) from an extruded or drawn bar stock; (b) *powder metallurgy* or *casting*; or (c) a preformed blank from a prior forging operation. The blank is placed on the lower die, and as the upper die begins to descend, its shape gradually changes (Fig. 14.8a).

Preforming operations (Figs. 14.8b and c) are typically used to enhance the distribution of the material into various regions of the blank, using simple dies of various contours. In **fullering**, material is distributed away from a region in the dies. In **edging**, it is gathered into a localized region. The part is then formed into a rough shape by a process called **blocking**, using *blocker dies*. The final operation is the finishing of the forging in *impression dies*, which give the forging its final shape; the flash is later removed by a trimming operation (Fig. 14.9).

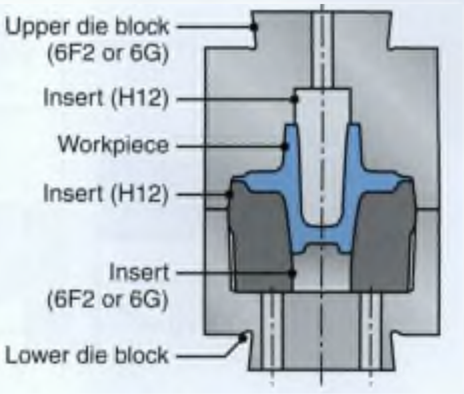


FIGURE 14.7 Die inserts used in forging an automotive axle housing. (See Section 5.7 for die materials.)

Forging Force. The *forging force*, F, required in an *impression-die forging* operation can be estimated from the formula

$$F = kY_f A, \tag{14.3}$$

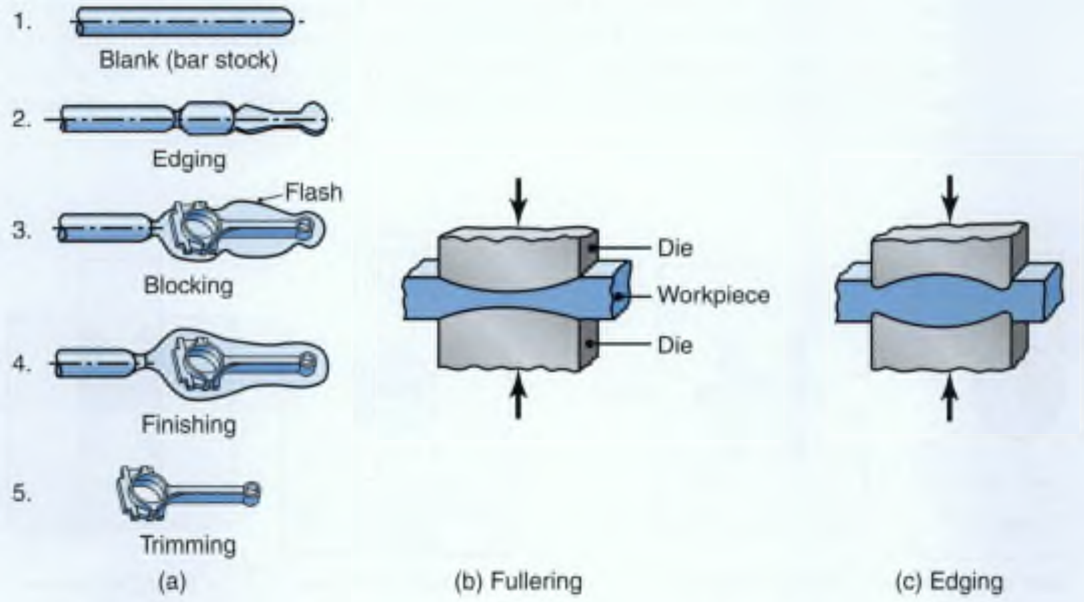


FIGURE 14.8 (a) Stages in forging a connecting rod for an internal combustion engine; note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering and (c) edging operations to distribute the material properly when preshaping the blank for forging.

where k is a multiplying factor, obtained from Table 14.2, Y_f is the flow stress of the material at the forging temperature, and A is the projected area of the forging, including the flash area.

In hot-forging operations, the actual forging pressure for most metals typically ranges from 550 to 1000 MPa. As an example, assume that the flow stress of a material at the forging temperature is 700 MPa, and a part (such as that shown in Fig. 14.8a) has a projected area (with flash) of 38,000 mm^2. Taking a value of $k = 10$ from Table 14.2, the forging force would be $F = (10)(700)(38{,}000) = 266$ MN.

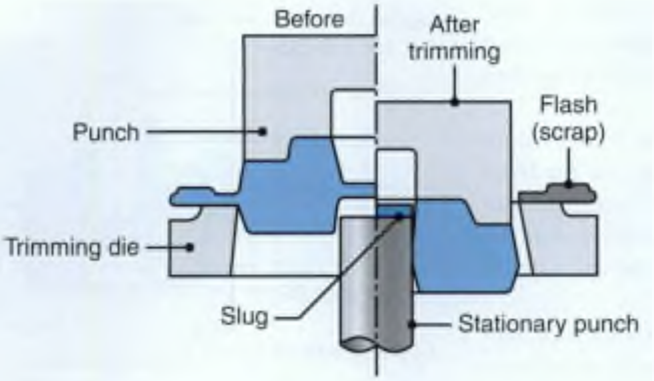


FIGURE 14.9 Trimming flash from a forged part; note that the thin material at the center (slug) is removed by punching.

TABLE 14.2

Range of *k* Values for Eq. (14.3)

Shape	*k*
Simple shapes, without flash	3–5
Simple shapes, with flash	5–8
Complex shapes, with flash	8–12

Closed-die Forging. The process shown in Fig. 14.6 is also referred to as *closed-die forging*. In true closed-die forging, however, a flash does not form (hence the term *flashless forging*), and the workpiece completely fills the die cavity (see right side of Fig. 14.10b). The accurate control of the blank volume and proper die design are essential to producing a forging with the required dimensional tolerances. Undersized blanks prevent the complete filling of the die cavity; conversely, oversized blanks generate excessive pressures and may cause dies to fail prematurely or the machine to jam.

Precision Forging. In order to reduce the number of additional finishing operations (hence cost), the trend continues toward greater precision in forged products (net-shape forming). Typical precision-forged products are gears, connecting rods, and turbine blades. Precision forging requires (a) special and more complex dies, (b) precise control of the blank's volume and shape, and (c) accurate positioning of the blank in the die cavity. Also, because of the higher forces required to obtain fine details on the part, precision forging requires higher capacity equipment. Although steel and titanium also can be precision forged, aluminum and magnesium alloys are particularly suitable, because of the relatively low forging loads and temperatures that they require; however, steels and titanium also can be precision forged.

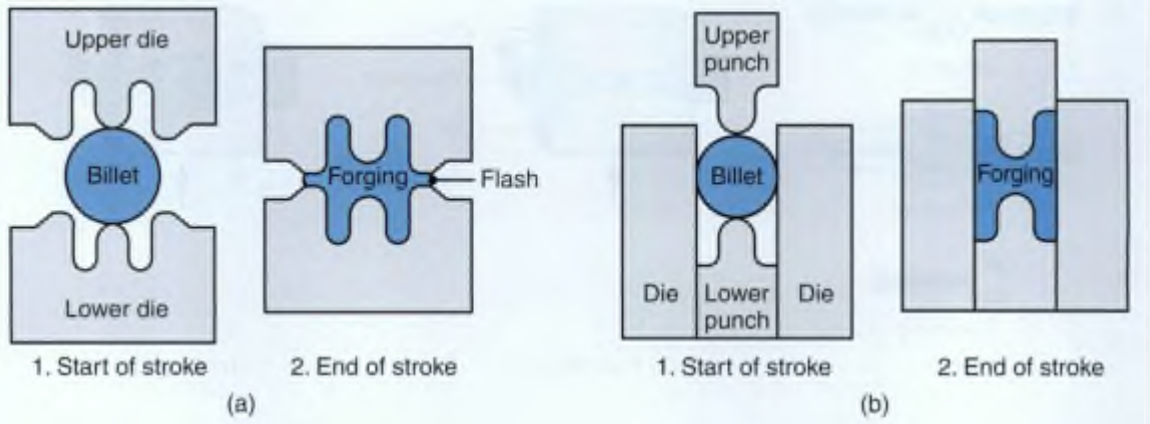


FIGURE 14.10 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet. *Source:* After H. Takemasu, V. Vazquez, B. Painter, and T. Altan.

Forging Practice and Product Quality. A forging operation typically involves the following sequence of steps:

1. A slug, billet, or preform is prepared; if necessary, cleaned by such means as shot blasting.
2. For hot forging, the workpiece is heated in a suitable furnace and then, if necessary, descaled with a wire brush, water jet, steam, or by scraping. Some descaling also may occur during the initial stages of forging, when the thick, brittle scale falls off during forging.
3. For hot forging, the dies are preheated and lubricated; for cold forging, the blank is lubricated.
4. The billet is forged in appropriate dies and in the proper sequence. If necessary, any excess material is removed (especially flash) by trimming, machining, or grinding.
5. The forging is cleaned, checked for dimensions and, if necessary, machined or ground to final dimensions and specified tolerances and surface finish.
6. Additional operations are performed, such as straightening and heat treating (for improved mechanical properties). Any additional finishing operations that may be required are performed.
7. The forging is inspected for any external and internal defects.

The quality, dimensional tolerance, and surface finish of a forging depend on how well these operations have been performed. Generally, dimensional tolerances range between ±0.5% and ±1% of the dimensions of the forging. In good practice, tolerances for hot forging of steel are usually less than ±6 mm in precision forging, they can be as low as ±0.25 mm. Other factors that contribute to dimensional inaccuracies are draft angles, radii, fillets, die wear, die closure (whether the dies have closed properly), and mismatching of the dies.

14.4 Various Forging Operations

Several other operations related to the basic forging process are described below.

Coining. A closed-die forging process, *coining* was originally used in the minting of coins, medallions, and jewelry (Fig. 14.11), but currently is used to produce a wide range of parts with high accuracy, such as gears, industrial seals, and medical devices. The blank or slug is coined in a completely closed-die cavity, in order to produce fine details, such as in coins; the pressures required can be as high as five or six times the strength of the material. On some parts, several coining operations may be required. Lubricants should not be applied in coining, because they can become entrapped in the die cavities and, being incompressible, prevent the full reproduction of die-surface details and surface finish.

Marking parts with letters and numbers also can be done rapidly through coining. **Sizing** is a process used in forging, and other processes, to improve surface finish and to impart the desired dimensional accuracy with little or no change in part size.

Heading. Also called **upset forging**, *heading* is essentially an upsetting operation, performed on the end of a rod or wire in order to increase the cross-section. Typical products are nails, bolt heads, screws, rivets, and various other fasteners (Fig. 14.12). Heading can be carried out cold, warm, or hot. An important consideration in heading is the tendency for the bar to *buckle* if its unsupported length-to-diameter ratio is too high. This ratio usually is limited to less than 3:1, but with appropriate dies,

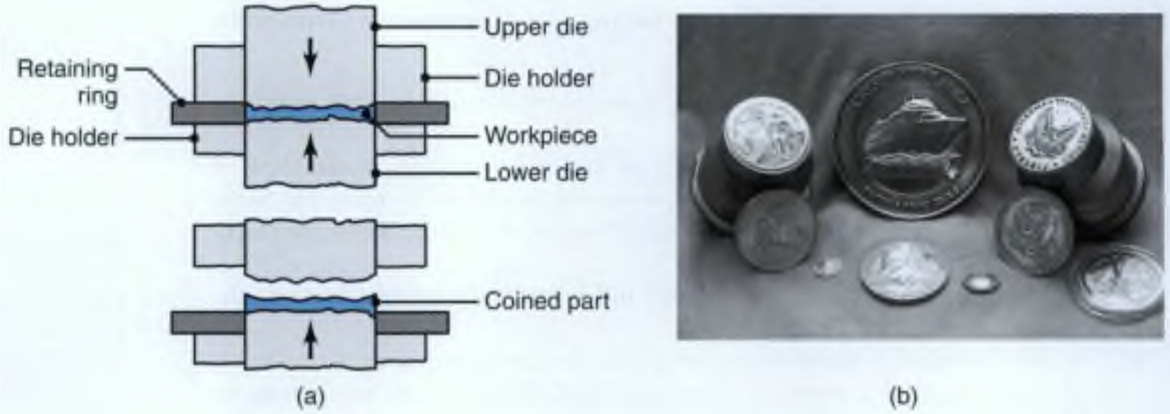


FIGURE 14.11 (a) Schematic illustration of the coining process; the earliest coins (see Table I.2) were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the coins and tooling; note the detail and superior surface finish that can be achieved in this process. *Source*: Courtesy of C & W Steel Stamp Company Inc.

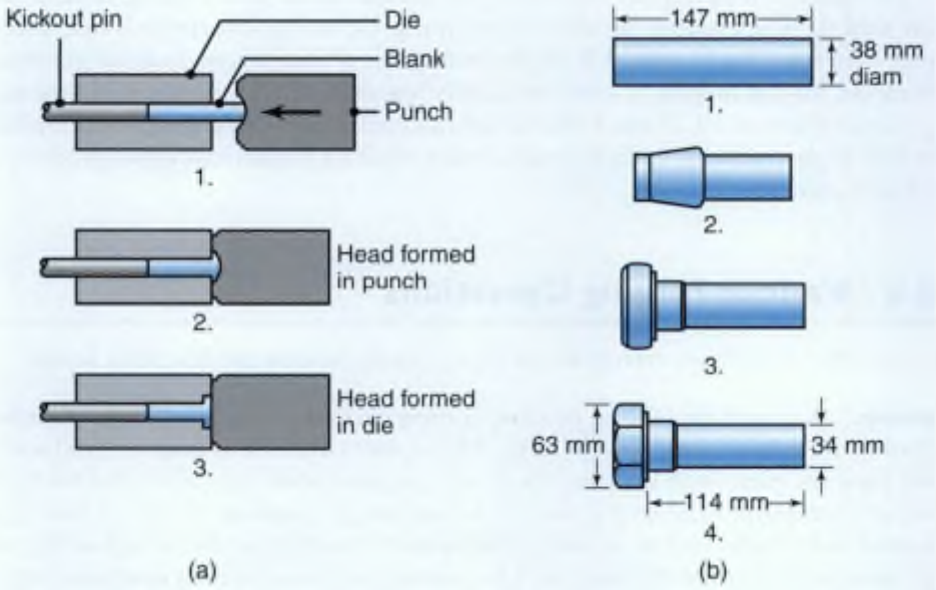


FIGURE 14.12 (a) Heading operation to form heads on fasteners, such as nails and rivets. (b) Sequence of operations in producing a typical bolt head by heading.

it can be higher; for example, higher ratios can be accommodated if the diameter of the die cavity is not more than 1.5 times the bar diameter.

Heading operations are performed on machines called **headers**, which usually are highly automated, with production rates of hundreds of pieces per minute for small parts. Hot heading on larger parts typically are performed on **horizontal upsetters**. Heading operations can be combined with cold-extrusion processes to make various parts, as described in Section 15.4.

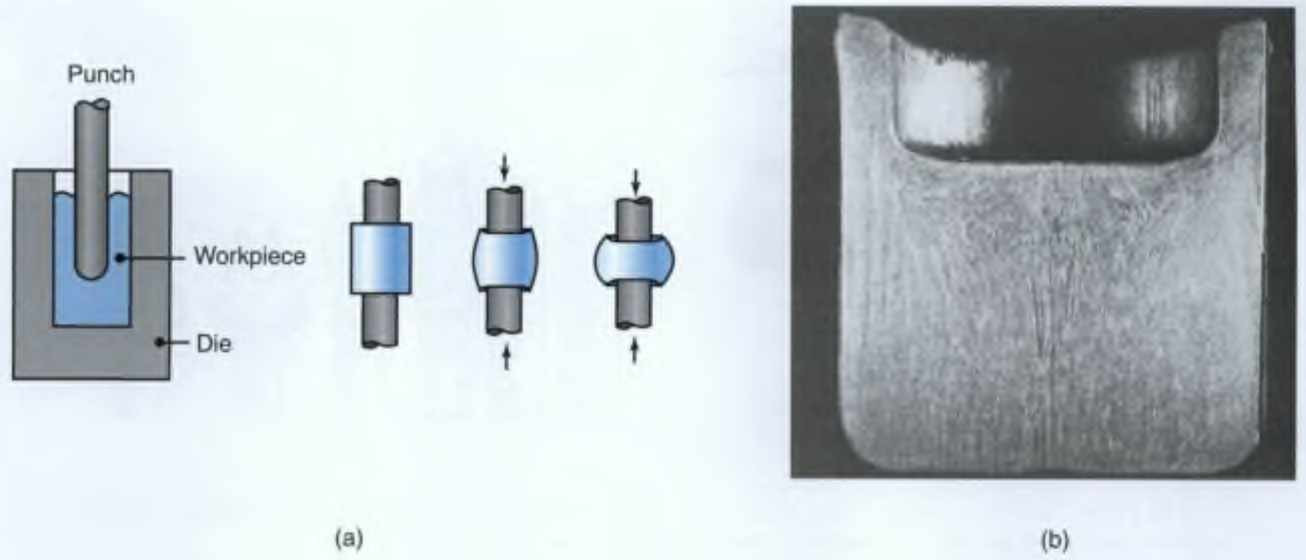


FIGURE 14.13 (a) Examples of piercing operations. (b) A pierced round billet showing grain-flow pattern (see also Fig. 14.2c). *Source:* Courtesy of Ladish Co., Inc.

Piercing. This is a process of indenting (but not breaking through) the surface of a workpiece with a punch, in order to produce a cavity or an impression (Fig. 14.13). The workpiece may be confined in a container, such as a die cavity or may be unconstrained. The extent of surface deformation of the workpiece depends on how much it is constrained from flowing freely as the punch descends. A common example of piercing is the indentation of the hexagonal cavity in bolt heads. Piercing may be followed by punching to produce a hole in the part. (For a similar depiction of this situation, see the slug above the stationary punch in the central portion of Fig. 14.9.) Piercing also is performed to produce hollow regions in forgings, using side-acting auxiliary equipment.

The *piercing force* depends on (a) the cross-sectional area and the tip geometry of the punch, (b) the strength of the workpiece, and (c) friction at the punch–workpiece interfaces. The pressure may range from three to five times the strength of the material, which is about the same level of stress required to make an indentation in hardness testing (Section 2.6).

CASE STUDY 14.1 Manufacture of a Stepped Pin by Heading and Piercing Operations

Figure 14.14a shows a stepped pin made from SAE 1008 steel, and used as a portion of a roller assembly to adjust the position of a car seat. The part is fairly complex and must be produced in a progressive manner, in order to produce the required details and fill the die completely.

The cold-forging steps used to produce this part are shown in Fig. 14.14b. First, a solid, cylindrical blank is extruded (Chapter 15) in two operations, followed by upsetting. The upsetting operation uses a conical cross-section in the die to produce the preform, and is oriented such that material is concentrated at the top of the part in order to ensure proper die filling. After impression-die forming, a piercing operation is performed which forms the bore.

(*continued*)

FIGURE 14.14 (a) The stepped pin used in Case Study 14.1. (b) Illustration of the manufacturing steps used to produce the stepped pin. *Source:* Courtesy of National Machinery, LLC.

Hubbing. This process consists of pressing a hardened punch, with a particular tip geometry, into the surface of a block of metal. The cavity produced is subsequently used as a die for forming operations, such as those employed in making tableware. The die cavity usually is shallow, but for deeper cavities, some material may first be removed from the surface of the block by machining prior to hubbing (see Figs. 24.2c and d). The *hubbing force* can be estimated from the equation

$$\text{Hubbing force} = 3(\text{UTS})(A), \tag{14.4}$$

where UTS is obtained from Table 2.2, and A is the projected area of the impression. For example, for high-strength steel with UTS = 1500 MPa and a part with a projected area of 400 mm^2, the hubbing force is (3)(1500 N/mm^2)(400 mm^2) = 1.8 MN.

Orbital Forging. In this process, the upper die moves along an orbital path and forms the part *incrementally*, an operation that is similar to the action of a mortar and pestle, used for crushing herbs and seeds. Typical components that may be forged by this process are disk-shaped and conical parts, such as bevel gears and gear blanks. The forging force is relatively small, because at any particular instant, the die contact is concentrated onto a small area of the workpiece (see also *incremental forging* below). The operation is relatively quiet, and parts can be formed within 10–20 cycles of the orbiting die.

Incremental Forging. In this process, a tool forges a blank into a particular shape in several small steps. The operation is somewhat similar to cogging (Fig. 14.4a), in which the die deforms the blank to a different extent at different positions. Because of the smaller area of contact with the die, the process requires much lower forces as compared with conventional impression-die forging, and the tools are simpler and less costly.

Isothermal Forging. Also known as **hot-die forging**, the dies in this process are heated to the same temperature as that of the hot workpiece (see also Table 14.3). Because the workpiece remains hot (essentially no heat is lost to the dies), its flow strength and high ductility are maintained during forging; thus, the forging load is low, and the material flow within the die cavity is improved. Complex parts can be isothermally forged, with good dimensional accuracy and to near-net shape by one stroke in a hydraulic press. The dies for hot forging usually are made of nickel or molybdenum alloys (because of their resistance to high temperature), but steel dies can be used for aluminum alloys.

The process is expensive and the production rate is low. It can, however, be economical for specialized, intricate forgings, made of such materials as aluminum, titanium, and superalloys, provided that the quantity of forgings to be made is sufficiently high to justify high die costs.

TABLE 14.3

Forgeability of Metals, in Decreasing Order (See also Table 15.1)

Metal or alloy	Approximate range of hot-forging temperatures (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon- and low-alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-based superalloys	1050–1180
Cobalt-based superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-based superalloys	1050–1200
Tungsten alloys	1200–1300

Rotary Swaging. In this process, also known as *radial forging*, *rotary forging*, or simply *swaging*, a solid rod or tube is subjected to radial impact forces using a set of reciprocating dies (Figs. 14.15a and b). The dies are activated by means of a set of rollers within a cage, in an action similar to that of a roller bearing. The workpiece is stationary and the dies rotate (while moving radially in their slots), striking the workpiece at rates as high as 20 strokes per second. In **die-closing swaging machines**, die movements are through the reciprocating motion of wedges (Fig. 14.15c). The dies can be opened wider than those in rotary swagers, thereby accommodating large-diameter or variable-diameter parts. In another type of machine, the dies do not rotate but move radially in and out. Typical products made by this machine are screwdriver blades and soldering-iron tips.

Swaging also can be used to *assemble* fittings over cables and wire; in such cases, the tubular fitting is swaged directly onto the cable. The process also is used for operations such as pointing (tapering the tip of a cylindrical part) and *sizing* (finalizing the dimensions of a part).

Swaging generally is limited to a maximum workpiece diameter of about 150 mm and parts as small as 0.5 mm have been swaged; dimensional tolerances range from ±0.05 to ±0.5 mm. The process is suitable for medium-to-high rates of production, with rates as high as 50 parts per minute possible, depending on part complexity. Swaging is a versatile process and is limited in length only by the length of the bar supporting the mandrel, if one is needed (see Fig. 14.15b).

Tube Swaging. In this process, the internal diameter and/or the thickness of the tube is reduced, with or without the use of *internal mandrels* (Figs. 14.16a and b). For small-diameter tubing, high-strength wire can be used as a mandrel. Mandrels also can be made with longitudinal grooves, to allow swaging of internally shaped tubes (Fig. 14.16c). For example, the *rifling* in gun barrels (internal spiral grooves to give gyroscopic effect to bullets) can be produced by swaging a tube over a mandrel with spiral grooves. Special machinery can swage gun barrels, and other tubular parts, with starting diameters as large as 350 mm.

14.5 Forgeability of Metals; Forging Defects

Forgeability is generally defined as the capability of a material to undergo deformation in forging without cracking. Various tests have been developed to quantify forgeability; however, because of their complex nature, only two simple tests have had general acceptance: upsetting and hot twist.

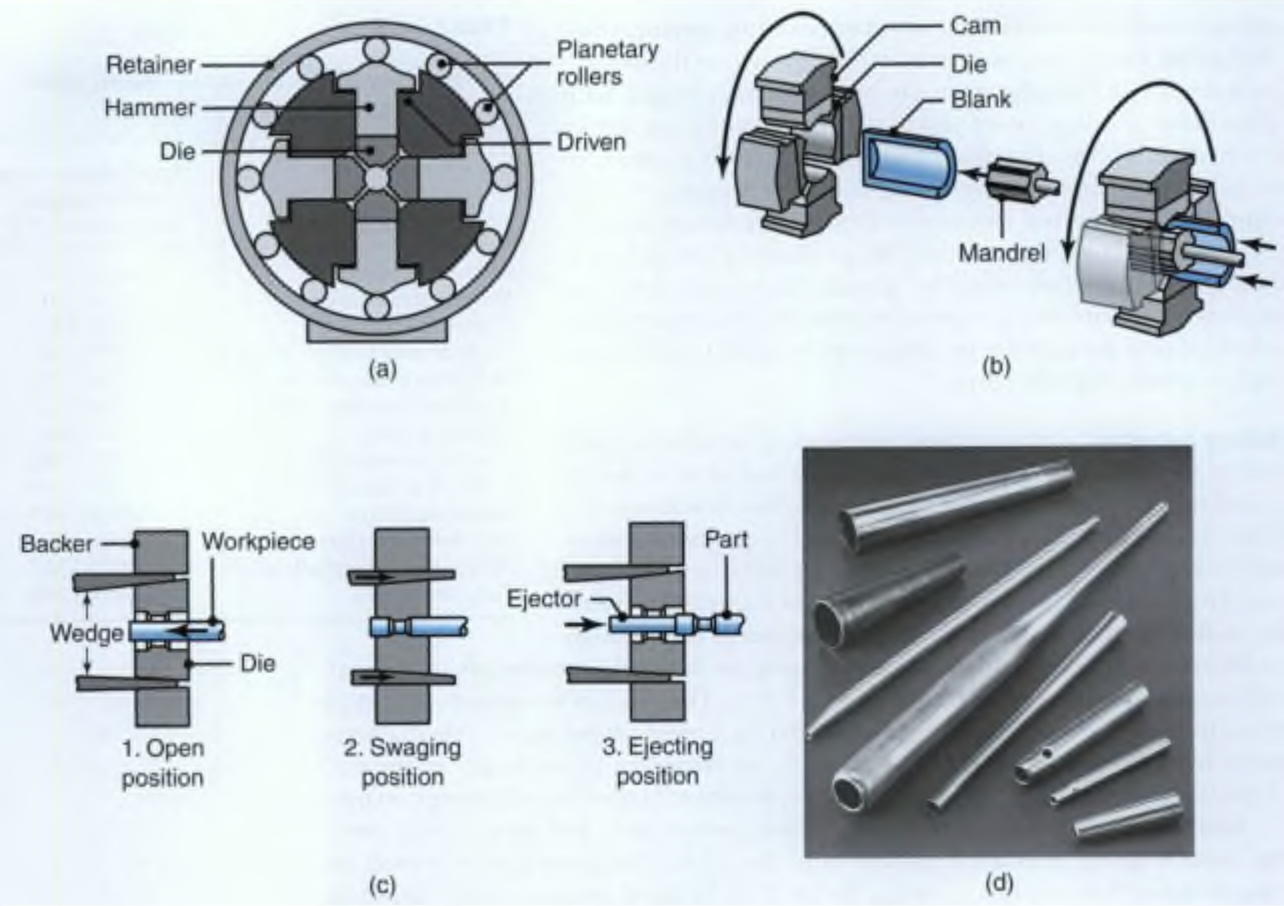


FIGURE 14.15 (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging. *Source:* (d) Courtesy of J. Richard Industries.

In the **upsetting test**, a solid, cylindrical specimen is upset between flat dies, and the reduction in height at which cracks on the barreled surfaces begin to develop (see also Fig. 2.20d); the greater the deformation prior to cracking, the greater the forgeability of the metal. The second method is the **hot-twist test**, in which a round specimen is twisted continuously and in the same direction until it fails. This test is performed on a number of specimens and at different temperatures; the number of complete turns that each specimen undergoes before failure at each temperature is then plotted. The temperature at which the maximum number of turns occurs becomes the forging temperature for maximum forgeability. This test has been found to be useful particularly for steels.

The forgeability of various metals and alloys is given in Table 14.3, in decreasing order. More comprehensively, forgeability is rated on considerations such as (a) ductility and strength of the material, (b) forging temperature required, (c) frictional behavior between die and workpiece, and (d) the quality of the forgings produced. The ratings should be regarded only as general guidelines. Typical *hot-forging temperature* ranges for various metals and alloys are included in Table 14.3; for *warm* forging, temperatures range from 200° to 300°C for aluminum alloys, and 550° to 750°C for steels.

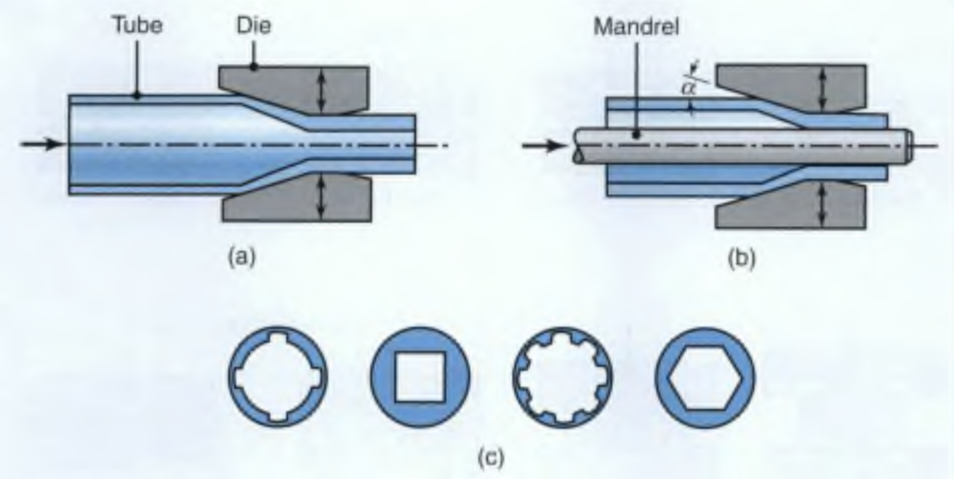


FIGURE 14.16 (a) Swaging of tubes without a mandrel; note the increase in wall thickness in the die gap. (b) Swaging with a mandrel; note that the final wall thickness of the tube depends on the mandrel diameter. (c) Examples of cross-sections of tubes produced by swaging on shaped mandrels; rifling (internal spiral grooves) in small gun barrels can be made by this process.

Forging Defects. In addition to surface cracking, other defects can develop during forging as a result of the material flow pattern in the die, as described next in Section 14.6 regarding die design. For example, if there is an insufficient volume of material to fill the die cavity completely, the web may buckle during forging and develop laps (Fig. 14.17a). Conversely, if the web is too thick, the excess material flows past the already formed portions of the forging and develops internal cracks (Fig. 14.17b).

The various radii in the forging-die cavity can significantly influence the formation of such defects. Internal defects also may develop from (a) nonuniform deformation of the material in the die cavity, (b) temperature gradients developed throughout the workpiece during forging, and (c) microstructural changes caused by phase transformations. The *grain-flow pattern* of the material in forging also is important. The flow lines may reach a surface perpendicularly, as shown in Fig. 14.13b, known as **end grains**; the grain boundaries become directly exposed to the environment and can be attacked by it, developing a rough surface and acting as stress raisers.

Forging defects can cause fatigue failures, corrosion, and wear during the service life of the forging. The importance of inspecting forgings prior to their placement in service, particularly in critical applications, is obvious. Inspection techniques for manufactured parts are described in Chapter 36.

14.6 Die Design, Die Materials, and Lubrication

The design of forging dies requires considerations of (a) the shape and complexity of the workpiece, (b) forgeability, (c) strength and its sensitivity to deformation rate, (d) temperature, (e) frictional characteristics at the die–workpiece interfaces, and (f) die distortion under the forging loads. The most important rule in die design is

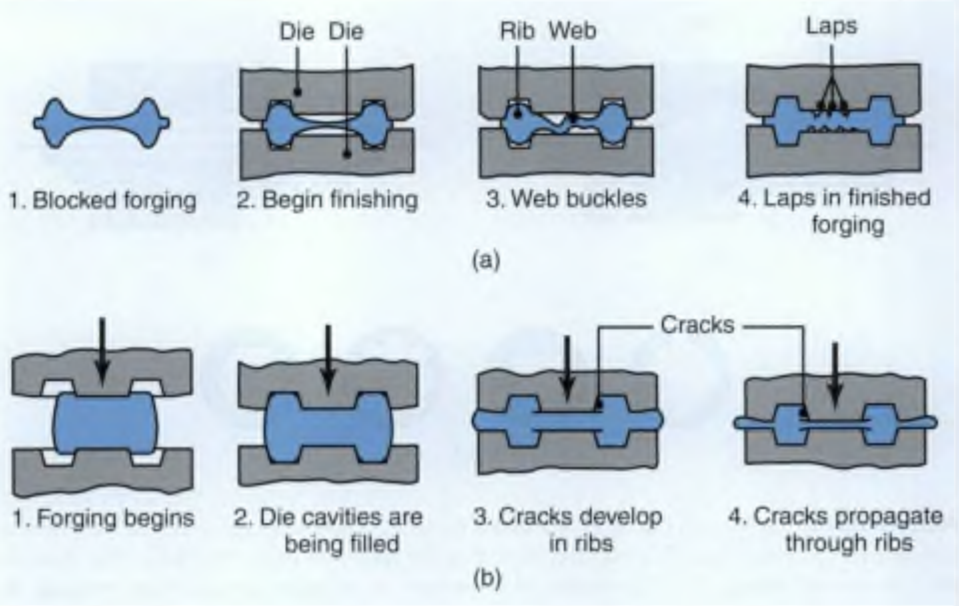


FIGURE 14.17 Examples of defects in forged parts. (a) Laps due to web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by an oversized billet; die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

the fact that the part will flow in the direction of least resistance. Workpiece *intermediate shapes* should be considered so that die cavities are filled properly, and without defects; an example of the intermediate shapes for a connecting rod is given in Fig. 14.8a.

With continuing advances in reliable simulation of all types of metalworking operations, software is available to help predict material flow in forging-die cavities (see Fig. 14.18). The simulation incorporates various conditions, such as workpiece temperature and heat transfer to dies, frictional conditions at die–workpiece contact surfaces, and forging speed. Such software has become essential in die design, especially in eliminating defective forgings (see also Section 38.7).

Preshaping. The requirements for preshaping a workpiece are: (a) the material should not flow easily into the flash area, as otherwise die filling will be incomplete, (b) the grain flow pattern should be favorable for the products' strength and reliability, and (c) sliding at the die–workpiece interface should be minimized in order to reduce die wear. The selection of preshapes involves calculations of cross-sectional areas at each location in the forging; computer modeling and simulation techniques are very useful in such calculations.

Die Features. The terminology for forging dies is shown in Fig. 14.6e. For most forgings, the **parting line** is located at the largest cross-section of the part. For simple symmetrical shapes, the parting line is usually a single plane and at the center of the forging; for more complex shapes, the line may not lie in a single plane. The dies are then designed in such a way that they make proper contact with the workpiece, while avoiding side thrust forces and maintaining die alignment during forging.

After sufficiently constraining lateral flow to ensure proper die filling, the flash material is allowed to flow into a **gutter**, so that the extra flash does not increase the forging load excessively. A general guideline for flash thickness is 3% of the maximum thickness (vertical dimension) of the forging. The length of the **land** is usually two to five times the flash thickness.

Draft angles are necessary in almost all forging dies in order to facilitate removal of the forging. Upon cooling, the forging shrinks both radially and longitudinally; internal draft angles (about 7°–10°) are therefore made larger than external ones (about 3°–5°).

Selection of the proper radii for corners and fillets is important in ensuring smooth flow of the metal into the die cavity and improving die life. Small radii generally are undesirable, because of their adverse effect on metal flow and their tendency to wear rapidly (as a result of stress concentration and thermal cycling). Small fillet radii also can cause fatigue cracking of the dies. As a general rule, these radii should be as large as can be permitted by the design of the forging. As with the patterns used in casting (Section 12.2.1), *allowances* are provided in forging-die design, when machining or grinding of the forging is necessary in order to impart final desired dimensions and surface finish. Machining allowance should be provided at flanges, holes, and mating surfaces.

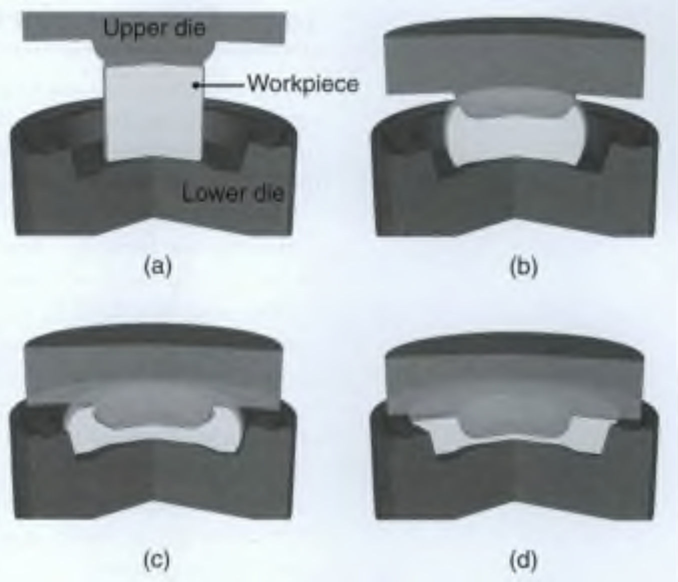


FIGURE 14.18 Deformation of a blank during forging as predicted by the software program DEFORM, based on the finite-element method of analysis. *Source:* Courtesy of Scientific Forming Technologies Corporation.

Die Materials. General requirements for die materials are:

- Strength and toughness, especially at elevated temperatures
- Hardenability and ability to harden uniformly
- Resistance to mechanical and thermal shock
- Wear resistance, particularly resistance to abrasive wear, because of the presence of scale in hot forging

Common die materials are tool and die steels containing chromium, nickel, molybdenum, and vanadium (see Tables 5.7–5.9). Dies are made from die blocks, which themselves are forged from castings, and then machined and finished to the desired shape and surface finish.

Lubrication. A wide variety of metalworking fluids are available for use in forging, as described in Section 33.7. Lubricants greatly influence friction and wear, in turn affecting the forces required [see Eq. (14.1)], die life, and the manner in which the material flows into the die cavities. Lubricants can also act as a *thermal barrier* between the hot workpiece and the relatively cool dies, thus slowing the rate of cooling of the workpiece and improving metal flow. Another important function of the lubricant is to act as a *parting agent*, preventing the forging from sticking to the dies and helping release it from the die.

14.7 Die-manufacturing Methods and Die Failure

Dies have an important impact on the overall economics in forging, because of the significant cost and the lead time required to produce them, as some dies can take months to make. Equally important are the proper maintenance of dies and their modifications as parts are first produced and evaluated.

Several manufacturing methods, either singly or in combination, can be used to make dies for forging. These methods include casting, forging, machining, grinding, electrical and electrochemical methods [particularly electrical-discharge machining (EDM) and wire EDM], and laser beams for making small dies. An important and continuing trend is the production of tools and dies by **rapid tooling**, using rapid-prototyping techniques, described in Section 20.6.

Producing a die cavity in a die block is called **die sinking**. Recall that the process of **hubbing** (Section 14.4), either cold or hot, also may be used to make small dies with shallow cavities. Usually, dies are subsequently heat treated, for higher hardness and wear resistance (Chapter 33). If necessary, their surface profile and finish are further improved by finish grinding and polishing, usually using computer numerically controlled machines.

The choice of a die manufacturing method depends on die size and shape, and the particular operation in which the die is to be used, such as casting, forging, extrusion, powder metallurgy, or plastics molding. As in all manufacturing operations, cost often dictates the process selected, because tool and die costs can be significant in manufacturing operations. Dies of various sizes and shapes can be cast from steels, cast irons, and nonferrous alloys; the processes used for preparing them may range from sand casting (for large dies, weighing several metric tons) to shell molding (for casting small dies). Cast steels generally are preferred for large dies, because of their strength and toughness as well as the ease with which the steel composition, grain size, and other properties can be controlled and modified.

Most commonly, dies are *machined* from forged die blocks, using processes such as high-speed milling, turning, grinding, and electrical discharge and electrochemical machining (see Part IV). Such an operation is shown in Fig. I.10b for making molds for eyeglass frames. For high-strength and wear-resistant die materials that are hard or are heat treated (and thus difficult to machine), processes such as hard machining and electrical and electrochemical machining are in common practice.

Typically, a die is machined by milling on computer-controlled machine tools, using various software packages that have the capability of optimizing the cutting-tool path; thus, for example, the best surface finish can be obtained in the least possible machining time. Equally important is the setup for machining, because dies should be machined as much as possible in one setup, without having to remove them from their fixtures and reorient them for subsequent machining operations.

After heat treating, to achieve the desired mechanical properties, dies usually are subjected to *finishing operations* (Section 26.7), such as grinding, polishing, and chemical and electrical processes, to obtain the desired surface finish and dimensional accuracy. This also may include *laser surface treatments* and *coatings* (Chapter 34) to improve die life. Laser beams also may be used for die repair and reconfiguration of the worn regions of dies (see also Fig. 33.11).

Die Costs. From the preceding discussion, it is evident that the cost of a die depends greatly on its size, shape complexity, and surface finish required, as well as the die material and manufacturing, heat treating, and finishing methods employed. Some qualitative ranges of tool and die costs are given throughout this book, such as in Table 12.6. Even small and relatively simple dies can cost hundreds of dollars to make, and the cost of a set of dies for automotive body panels can be on the order of $2 million. On the other hand, because a large number of parts usually are made from one set of dies, *die cost per piece made* is generally a small portion of a part's manufacturing cost (see also Section 40.9). The *lead time* required to produce dies also can have a significant impact on the overall manufacturing cost of parts made.

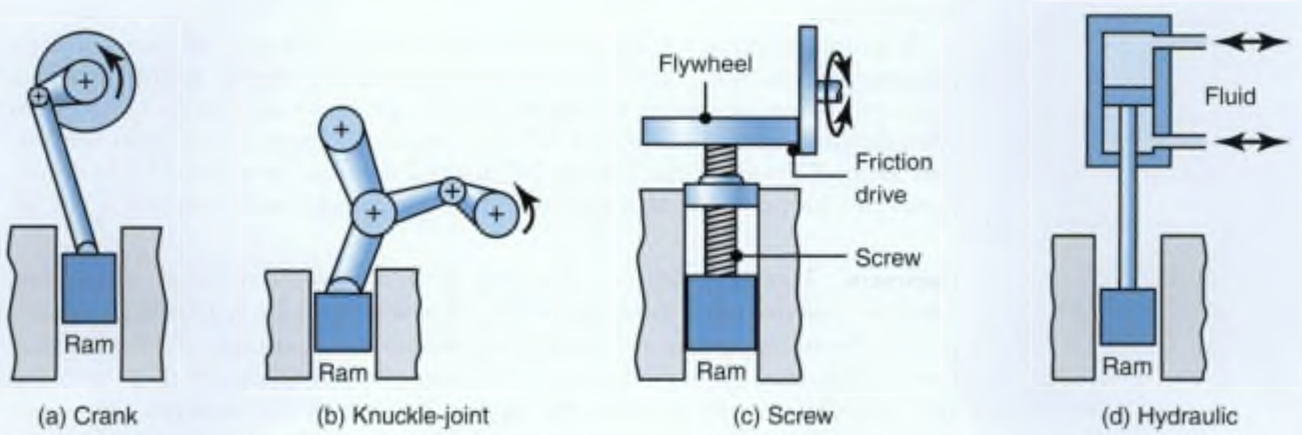
Die Failures. Failure generally results from one or more of the following causes:

- Improper die design
- Improper selection of die material
- Improper manufacturing, heat treatment, and finishing operations
- Overheating and heat checking (cracking caused by temperature cycling)
- Excessive die wear
- Overloading (excessive force on the die)
- Improper alignment of die components or segments
- Misuse
- Improper handling of the die

Other Considerations. In order to withstand the forces involved, a die must have sufficiently large cross-sections and clearances (to prevent jamming). Abrupt changes in cross-section, sharp corners, radii, fillets, and a coarse surface finish (including grinding marks and their orientation on die surfaces) act as stress raisers, and thus reduce die life. For improved strength and to reduce the tendency for cracking, dies may be made in segments and assembled into a complete die, with rings that prestress the dies. Proper handling, installation, assembly, and alignment of dies are essential. Overloading of tools and dies can cause premature failure. A common cause of damage to dies is the failure of the operator, or of a programmable robot, to remove a formed part from the die before another blank is placed (loaded) into the die.

14.8 Forging Machines

Various types of forging machines are available, with a wide range of capacities (tonnage), speeds, and speed–stroke characteristics (Fig. 14.19 and Table 14.4).



(a) Crank (b) Knuckle-joint (c) Screw (d) Hydraulic

FIGURE 14.19 Schematic illustration of the principles of various forging machines. (a) Crank press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram. (b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.

TABLE 14.4

Typical Speed Ranges of Forging Equipment

Equipment	m/s
Hydraulic press	0.06–0.30
Mechanical press	0.06–1.5
Screw press	0.6–1.2
Gravity drop hammer	3.6–4.8
Power drop hammer	3.0–9.0
Counterblow hammer	4.5–9.0

Mechanical Presses. These presses are basically of either the *crank* or the *eccentric* type (Fig. 14.19a). The speed varies from a maximum at the center of the stroke to zero at the bottom of the stroke, thus mechanical presses are *stroke limited*. The energy in a mechanical press is generated by a large flywheel powered by an electric motor. A clutch engages the flywheel to an eccentric shaft; a connecting rod then translates the rotary motion into a reciprocating linear motion. A *knuckle-joint* mechanical press is shown in Fig. 14.19b; because of the linkage design, very high forces can be applied in this type of press (see also Fig. 11.21).

The force available in a mechanical press depends on the stroke position, and becomes extremely high at the end of the stroke; thus, proper setup is essential to avoid breaking the dies or equipment components. Mechanical presses have high production rates, are easier to automate, and require less operator skill than do other types of machines. Press capacities generally range from 2.7 to 107 MN. Mechanical presses are preferred for forging parts requiring high precision.

Screw Presses. These presses (Fig. 14.19c) derive their energy from a flywheel, hence they are *energy limited*. The forging load is transmitted through a large vertical screw, and the ram comes to a stop when the flywheel energy has been dissipated. If the dies do not close at the end of the cycle, the operation is repeated until the forging is completed. Screw presses are used for various open-die and closed-die forging operations. They are particularly suitable for small production quantities and for thin parts with high precision, such as turbine blades. Press capacities range from 1.4 to 280 MN.

Hydraulic Presses. These presses (Fig. 14. 19d) operate at constant speeds and are *load limited* (load restricted), whereby the press stops if the load required exceeds its capacity. Large amounts of energy can be transmitted from the press to the workpiece by a constant load throughout the stroke, the speed of which can be controlled. Because forging in a hydraulic press takes longer than in the other types of forging machines, described next, the workpiece may cool rapidly unless the dies are heated (see *isothermal forging*, Section 14.4). Compared with mechanical presses, hydraulic presses are slower and involve higher initial costs, but they require less maintenance.

A hydraulic press typically consists of a frame with two or four columns, pistons,cylinders, rams, and hydraulic pumps driven by electric motors. The ram speed can be varied during the stroke. Press capacities range up to 125 MN for open-die forging, and up to 730 MN for closed–die forging. The main landing-gear support beam for the Boeing 747 aircraft is forged in a 450-MN hydraulic press; this part is made of a titanium alloy and weighs approximately 1350 kg.

Hammers. Hammers derive their energy from the potential energy of the ram, which is converted into kinetic energy; thus they are *energy limited*. Unlike hydraulic presses, hammers operate at high speeds, minimizing the cooling of a hot forging. Low cooling rates allow the forging of complex shapes, particularly those with thin and deep recesses. To complete the forging, several successive blows are usually made in the same die. Hammers are available in a variety of designs, and are the most versatile and the least expensive type of forging equipment.

Drop Hammers. In *power drop hammers*, the ram's downstroke is accelerated by steam, air, or hydraulic pressure. Ram weights range from 225 to 22,500 kg, with energy capacities reaching 1150 kJ. In the operation of *gravity drop hammers*, a process called **drop forging**, the energy is derived from the free-falling ram. The available energy is the product of the ram's weight and the height of its drop. Ram weights range from 180 to 4500 kg, with energy capacities ranging up to 120 kJ.

Counterblow Hammers. These hammers have two rams that simultaneously approach each other horizontally or vertically to forge the part. As in open-die forging operations, the workpiece may be rotated between blows in shaping the workpiece during forging. Counterblow hammers operate at high speeds and transmit less vibration to their bases; capacities range up to 1200 kJ.

High-energy-rate Forging Machines. In these machines, the ram is accelerated rapidly by inert gas at high pressure, and the part is forged in one blow at a very high speed. Although there are several types of these machines, various problems associated with their operation and maintenance, as well as die breakage and safety considerations, have greatly limited their use in industry.

Servo Presses. A recent development is the use of servo presses for forging and stamping applications (Fig. 14.20). These presses utilize servo drives along with

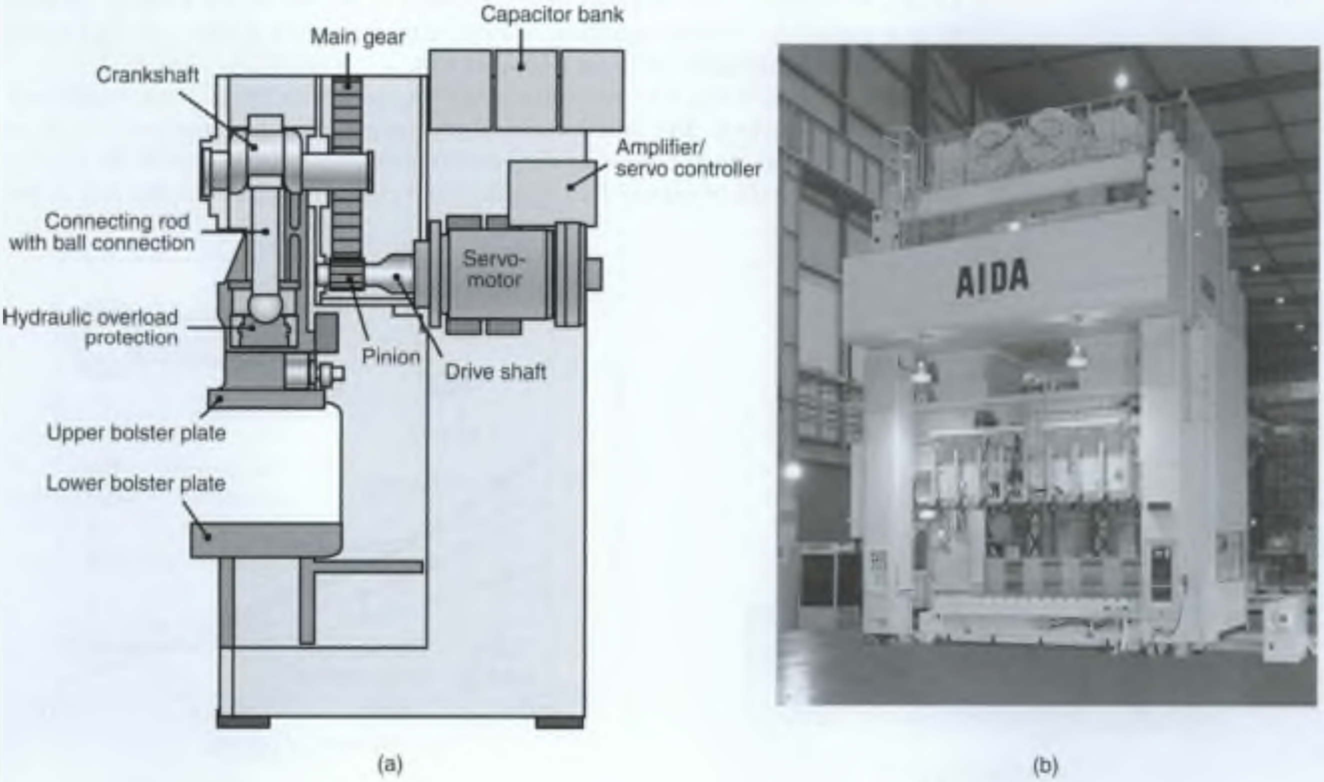


FIGURE 14.20 (a) Schematic illustration of a servo press, with the power source and transmission components highlighted. (b) An example of a servo press, with a 23,000 kN capacity.
Source: Courtesy of Aida Engineering, Inc.

linkage mechanisms, as in mechanical, knuckle joint, or screw presses. There are no clutches or brakes; instead, the desired velocity profile is achieved through a servo motor controller. The servo drive thus allows considerable flexibility regarding speeds and stroke heights, which simplifies setup and allows an optimized velocity profile for forging difficult materials or products; in addition, servo presses can produce parts with as little as 10% of the energy consumption of other presses, attributable mainly to their low energy costs when not producing parts (see Section 40.4). Servo presses can develop forces up to 25,000 kN; larger forces can be developed by hybrid machines that combine servo drives with energy storage in a flywheel.

14.9 Economics of Forging

QR Code 14.5 The Forging Advantage. (*Source:* Courtesy of the Forging Industry Association, www.forging.org)

Several factors are involved in the cost of forgings, depending on the complexity of the forging and tool and die costs, which range from moderate to high. As in other manufacturing operations, these costs are spread out over the number of parts forged with that particular die set. Thus, referring to Fig. 14.21, even though the cost of workpiece material per forging is constant, setup and tooling costs per piece decrease as the number of pieces forged increases.

The ratio of the cost of the die material to the total cost of forging the part increases with the weight of forgings: The more expensive the material, the higher the cost of the material relative to the total cost. Because dies must be made and forging operations must be performed regardless of the size of the forging, the cost of dies and of the forging operation relative to material cost is high for small parts; by contrast, die material costs are relatively low.

The size of forgings also has some effect on cost. Sizes range from small forgings (such as utensils and small automotive components) to large ones (such as gears, crankshafts, and connecting rods for large engines). As the size of the forging increases, the share of material cost in the total cost also increases, but at a lower

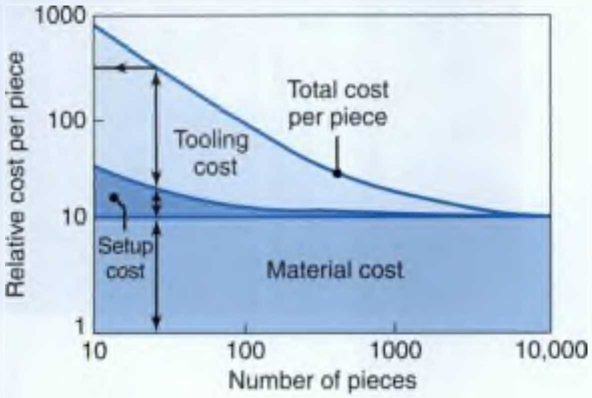


FIGURE 14.21 Typical cost per piece (*unit cost*) in forging; note how the setup and the tooling costs per piece decrease as the number of pieces forged increases (if all pieces use the same die).

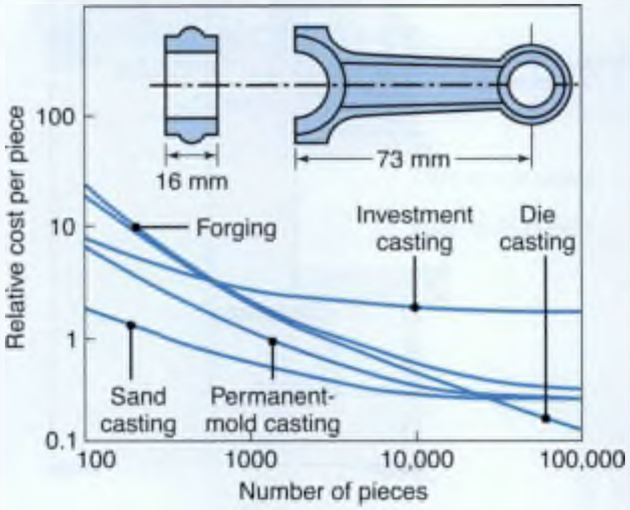


FIGURE 14.22 Relative costs per piece of a small connecting rod made by various forging and casting processes; note that, for large quantities, forging is more economical, and sand casting is the most economical process for fewer than about 20,000 pieces.

rate. This is because (a) the incremental increase in die cost for larger dies is relatively small, (b) the machinery and operations involved are essentially the same, regardless of forging size, and (c) the labor involved per piece made is not that much higher.

The total cost involved in a forging operation is not influenced to any major extent by the type of materials forged. Because they now have been reduced significantly by automated and computer-controlled operations, labor costs in forging generally are moderate. Moreover, die design and manufacturing are now mostly performed by computer-aided design and manufacturing techniques (Chapter 38), resulting in major savings in time and effort.

The cost of forging a part, compared to that of producing it by various processes such as casting, powder metallurgy, machining, or other methods, is an important consideration. For example, for shorter production runs and all other factors being the same, manufacturing a certain part by, say, expendable-mold casting may well be more economical than producing it by forging (Fig. 14.22). Recall that this casting method does not require expensive molds and tooling, whereas forging typically requires expensive dies. The competitive aspects of manufacturing and process selection are discussed in greater detail in Chapter 40.

CASE STUDY 14.2 Suspension Components for the Lotus Elise Automobile

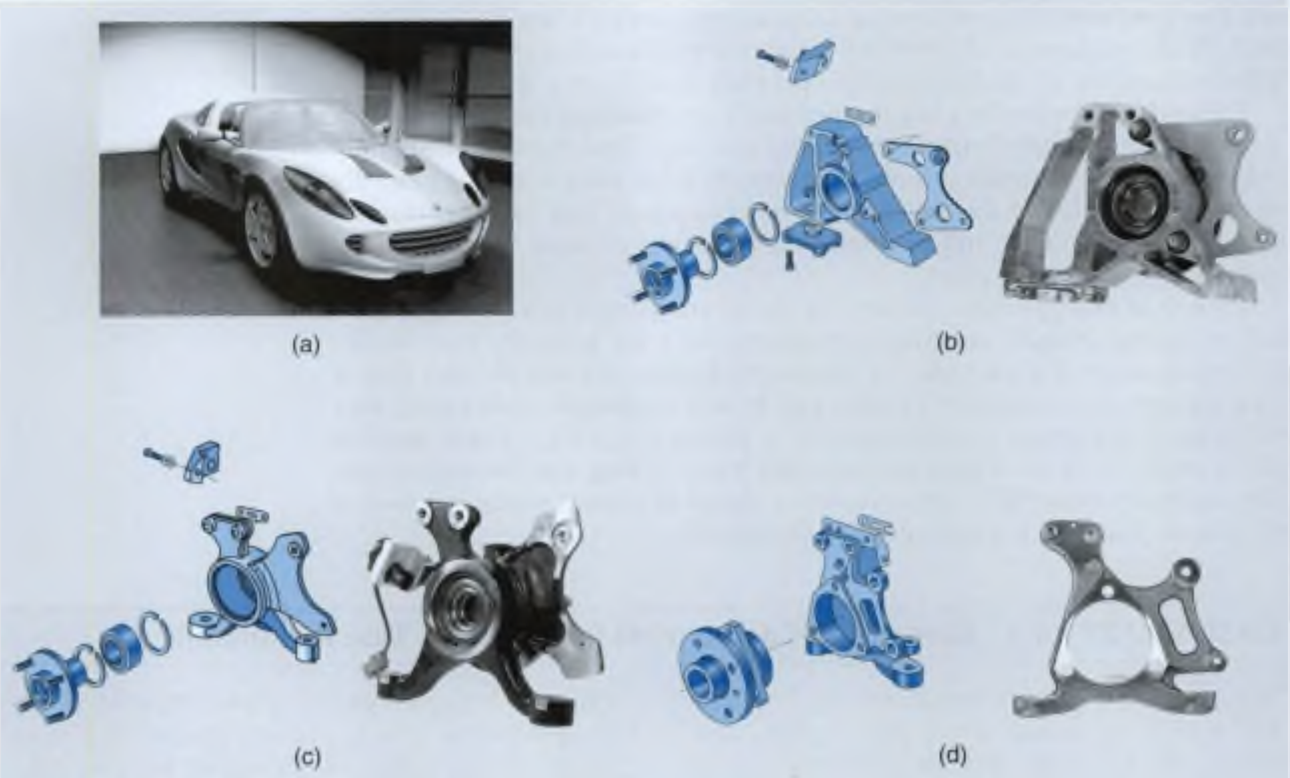
The automotive industry increasingly has been subjected to a demanding set of performance, cost, safety, fuel efficiency, and environmental regulations. One of the main strategies in improving vehicle design with respect to all of these possibly conflicting constraints is to reduce vehicle weight while using advanced materials and manufacturing processes. Previous design optimization for this car has shown that weight savings of up to 34% can be realized on suspension system components, a significant savings since suspensions make up approximately 12% of a car's mass.

Weight savings could be achieved largely by developing optimum designs, utilizing advanced analytical tools, and using net-shape or near-net-shape steel forgings, instead of cast-iron components. In addition, it has been demonstrated that significant cost savings can be achieved for many parts when using steel forgings, as opposed to aluminum castings and extrusions.

The Lotus Elise is a high-performance sports car (Fig. 14.23a), designed for superior ride and handling. The Lotus group investigated the use of steel forgings, instead of extruded-aluminum suspension uprights, in order to reduce cost and improve reliability and performance. Their development efforts consisted of two phases, shown in Figs. 14.23b and c. The first phase involved the development of a forged-steel component that could be used on the existing Elise sports car; the second phase involved the production of a suspension upright for a new model. A new design was developed using an iterative process, with advanced software tools, to reduce the number of components and to determine the optimum geometry. The material selected for the upright was an air-cooled forged steel, which gives uniform grain size and microstructure, and uniform high strength, without the need for heat treatment. These materials also have approximately 20% higher fatigue strengths than traditional carbon steels, such as AISI 1548-HT used for similar applications.

The revised designs are summarized in Table 14.5. As can be seen, the optimized new forging design (Fig. 14.23d) resulted in significant cost savings. Although it also resulted in a small weight increase, when compared to the aluminum-extrusion design, the weight penalty is recognized as quite small. Furthermore, the use of forged steel for such components is especially advantageous in fatigue-loading conditions, constantly encountered by suspension components. The new design also had certain performance advantages, in that the component stiffness is now higher, which registered as improved customer satisfaction and better "feel" during driving. The new design also reduced the number of parts required, thus satisfying another fundamental principle in design.

(*continued*)


(a)

(b)

(c)

(d)

FIGURE 14.23 (a) The Lotus Elise Series 2 automobile; (b) illustration of the original design for the vertical suspension uprights, using an aluminum extrusion; (c) retrofit design, using a steel forging; and (d) optimized steel forging design for new car models. *Source:* (a) Courtesy of Fox Valley Motorcars; (b) through (d) Courtesy of American Iron and Steel Institute.

TABLE 14.5

Comparison of Suspension Upright Designs for the Lotus Elise Automobile

Fig. 14.23 sketch	Material	Application	Mass (kg)	Cost ($)
(b)	Aluminum extrusion, steel bracket, steel bushing, housing	Original design	2.105	85
(c)	Forged steel	Phase I	2.685 (+28%)	27.7 (–67%)
(d)	Forged steel	Phase II	2.493 (+18%)	30.8 (–64%)

Source: Courtesy of American Iron and Steel Institute

SUMMARY

- Forging denotes a family of metalworking processes in which deformation of the workpiece is carried out by compressive forces applied through a set of dies. Forging is capable of producing a wide variety of structural parts, with favorable characteristics such as higher strength, improved toughness, dimensional accuracy, and reliability in service.

- The forging process can be carried out at room, warm, or high temperatures. Workpiece material behavior during deformation, friction, heat transfer, and material-flow characteristics in the die cavity are important considerations, as are the proper selection of die materials, lubricants, workpiece and die temperatures, forging speeds, and equipment.
- Various defects can develop if the process is not designed or controlled properly. Computer-aided design and manufacturing techniques are now used extensively in die design and manufacturing, preform design, predicting material flow, and avoiding the possibility of internal and external defects during forging.
- A variety of forging machines is available, each with its own capabilities and characteristics. Forging operations are now highly automated, using industrial robots and computer controls.
- Swaging is a type of rotary forging in which a solid rod or a tube is reduced in diameter by the reciprocating radial movement of a set of two or four dies. The process is suitable for producing short or long lengths of bar or tubing, with various internal or external profiles.
- Because die failure has a major economic impact, die design, material selection, and production method are of great importance. A variety of die materials and manufacturing methods is available, including advanced material-removal and finishing processes.

KEY TERMS

Barreling
Closed-die forging
Cogging
Coining
Edging
End grain
Flash
Forgeability
Forging
Fullering
Hammers
Heading
Hot-twist test
Hubbing
Impression-die forging
Incremental forging
Isothermal forging
Net-shape forging
Open-die forging
Orbital forging
Piercing
Precision forging
Presses
Sizing
Swaging
Upsetting

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REVIEW QUESTIONS

14.1 What is the difference between cold, warm, and hot forging?

14.2 Explain the difference between open-die and impression-die forging.

14.3 Explain the difference between fullering, edging, and blocking.

14.4 What is flash? What is its function?

14.5 Why is the intermediate shape of a part important in forging operations?

14.6 Describe the features of a typical forging die.

14.7 Explain what is meant by "load limited," "energy limited," and "stroke limited" as these terms pertain to forging machines.

14.8 What type of parts can be produced by rotary swaging?

14.9 Why is hubbing an attractive alternative to producing simple dies?

14.10 What is the difference between piercing and punching?

14.11 What is a hammer? What are the different kinds of hammers?

14.12 Why is there barreling in upsetting?

14.13 What are the advantages and disadvantages of isothermal forging?

14.14 Why are draft angles required in forging dies?

14.15 Is a mandrel needed in swaging?

QUALITATIVE PROBLEMS

14.16 Describe and explain the factors that influence spread in cogging operations on long square billets.

14.17 How can you tell whether a certain part is forged or cast? Explain the features that you would investigate.

14.18 Identify casting design rules, described in Section 12.2, that also can be applied to forging.

14.19 Describe the factors involved in precision forging.

14.20 Why is control of the volume of the blank important in closed-die forging?

14.21 Why are there so many types of forging machines available? Describe the capabilities and limitations of each.

14.22 What are the advantages and limitations of cogging operations? Should cogging be performed hot or cold? Explain.

14.23 What are the advantages and limitations of using die inserts? Give some examples.

14.24 Review Fig. 14.6e and explain why internal draft angles are larger than external draft angles. Is this also true for permanent-mold casting?

14.25 Comment on your observations regarding the grain-flow pattern in Fig. 14.13b.

14.26 Describe your observations concerning the control of the final tube thickness in Fig. 14.16a.

14.27 By inspecting some forged products, such as hand tools, you will note that the lettering on them is raised rather than sunk. Offer an explanation as to why they are made that way.

14.28 Describe the difficulties involved in defining the term "forgeability" precisely.

14.29 Describe the advantages of servo presses for forging and stamping.

14.30 List the general recommendations you would make for forging materials with limited ductility.

14.31 Which would you recommend, (a) hot forging and heat treating a workpiece or (b) cold forging it and relying upon strain hardening for strengthening? Explain.

QUANTITATIVE PROBLEMS

14.32 Take two solid, cylindrical specimens of equal diameter, but different heights, and compress them (frictionless) to the same percent reduction in height. Show that the final diameters will be the same.

14.33 Calculate the room-temperature forging force for a solid, cylindrical workpiece made of 5052-O aluminum that is 90 mm high and 125 mm in diameter and is to be reduced in height by 30%. Let the coefficient of friction be 0.15.

14.34 Using Eq. (14.2), estimate the forging force for the workpiece in Problem 14.33, assuming that it is a complex forging and that the projected area of the flash is 30% greater than the projected area of the forged workpiece.

14.35 To what thickness can a solid cylinder of 1020 steel that is 25 mm in diameter and 50 mm high be forged in a press that can generate 445 kN?

14.36 In Example 14.1, calculate the forging force, assuming that the material is 1100-O aluminum and that the coefficient of friction is 0.10.

14.37 Using Eq. (14.1), make a plot of the forging force, F, as a function of the radius, r, of the workpiece. Assume that the flow stress, Y_f, of the material is constant. Recall that the volume of the material remains constant during forging; thus, as h decreases, r increases.

14.38 How would you go about estimating the punch force required in a hubbing operation, assuming that the material is mild steel and the projected area of the impression is 320 mm^2. Explain clearly. (*Hint:* See Section 2.6 on hardness.)

14.39 A mechanical press is powered by a 23-kW motor and operates at 40 strokes per minute. It uses a flywheel, so that the crankshaft speed does not vary appreciably during the stroke. If the stroke is 150 mm, what is the maximum constant force that can be exerted over the entire stroke length?

14.40 A solid cylindrical specimen, made of a perfectly plastic material, is being upset between flat dies with no friction. The process is being carried out by a falling weight, as in a drop hammer. The downward velocity of the hammer is at a maximum when it first contacts the workpiece, and becomes zero when the hammer stops at a certain height of the specimen. Establish quantitative relationships between workpiece height and velocity, and make a qualitative sketch of the velocity profile of the hammer. (*Hint:* The loss in the kinetic energy of the hammer is the plastic work of deformation; thus, there is a direct relationship between workpiece height and velocity.)

14.41 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

SYNTHESIS, DESIGN, AND PROJECTS

14.42 Devise an experimental method whereby you can measure only the force required for forging the flash in impression-die forging.

14.43 Assume that you represent the forging industry and that you are facing a representative of the casting industry. What would you tell that person about the merits of forging processes?

14.44 Figure P14.44 shows a round impression-die forging made from a cylindrical blank, as illustrated on the left. As described in this chapter, such parts are made in a sequence of forging operations. Suggest a sequence of intermediate forging steps to make the part on the right, and sketch the shape of the dies needed.

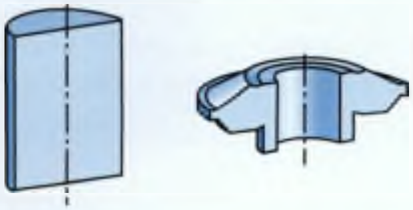


FIGURE P14.44

14.45 In comparing forged parts with cast parts, we have noted that the same part may be made by either process. Comment on the pros and cons of each process, considering such factors as part size, shape complexity, design flexibility, mechanical properties developed, and performance in service.

14.46 From the data given in Table 14.3, obtain the approximate value of the yield strength of the materials listed at their hot-forging temperatures.

14.47 Review the sequence of operations in the production of the stepped pin shown in Fig. 14.14. If the conical-upsetting step is not performed, how would the final part be affected?

14.48 Using a flat piece of wood, perform simple cogging operations on pieces of clay, and make observations regarding the spread of the pieces as a function of the original cross-sections (for example, square or rectangular with different thickness-to-width ratios).

14.49 Discuss the possible environmental concerns regarding the operations described in this chapter.

14.50 List the advantages and disadvantages in using a lubricant in forging operations.

CHAPTER

15

Metal Extrusion and Drawing Processes and Equipment

EXAMPLE:

CASE STUDIES:

- Extrusion and drawing involve, respectively, pushing or pulling a material through a die, for the purpose of modifying its cross-section.
- The chapter begins by describing the basic types of extrusion processes, and how the extrusion force can be estimated from material and processing parameters.
- Hot and cold extrusion are then discussed, including die design, and describing how cold extrusion is often done in combination with forging to produce specific shapes of parts.
- Extrusion practices and die designs that avoid common defects also are presented.
- The drawing of rod, wire, and tubing is then examined in a similar manner, along with die design considerations.
- The equipment characteristics for these processes also are described.

Typical parts made by extrusion and drawing: Long pieces having a wide variety of constant cross-sections, rods, shafts, bars for machinery and automotive power-train applications, aluminum ladders, collapsible tubes, and wires for numerous electrical and mechanical applications and musical instruments.

Alternative processes: Machining, powder metallurgy, shape rolling, roll forming, pultrusion, and continuous casting.

15.1 Introduction

Extrusion and drawing have numerous applications in manufacturing continuous as well as discrete products from a wide variety of metals and alloys. In extrusion, a usually cylindrical billet is forced through a die (Fig. 15.1), in a manner similar to squeezing toothpaste from a tube. A wide variety of solid or hollow cross-sections can be produced by extrusion, which essentially are semifinished products.

A characteristic of extrusion (from the Latin *extrudere*, meaning "to force out") is that large deformations can take place without fracture (see Section 2.2.8), because the material is under high triaxial compressive stresses. Since the die geometry remains unchanged throughout the process, extruded products typically have a constant cross-section.

Typical products made by extrusion are railings for sliding doors, window frames, tubing, aluminum ladder frames, and structural and architectural shapes. Extrusions can be cut into desired lengths, which then become discrete parts, such as brackets, gears, and coat hangers (Fig. 15.2). Commonly extruded metals are aluminum, copper, steel, magnesium, and lead; other metals and alloys also can be extruded, with various levels of difficulty.

Each billet is extruded individually, thus extrusion is a batch or semicontinuous operation. The process can be economical for large as well as short production runs. Tool costs generally are low, particularly for producing simple, solid cross-sections. Depending on the required ductility of the material, the process is carried out at room or at elevated temperatures. Extrusion at room temperature is often combined with forging operations, in which case it is generally called **cold extrusion** (see also Section 14.4), with numerous applications, such as fasteners and components for automobiles, bicycles, motorcycles, heavy machinery, and transportation equipment.

In **drawing**, developed between 1000 and 1500 A.D., the cross-section of a solid rod, wire, or tubing is reduced or changed in shape by pulling it through a die. Drawn rods are used for shafts, spindles, and small pistons, and as the raw material for fasteners such as rivets, bolts, and screws. In addition to round rods, various profiles also can be drawn.

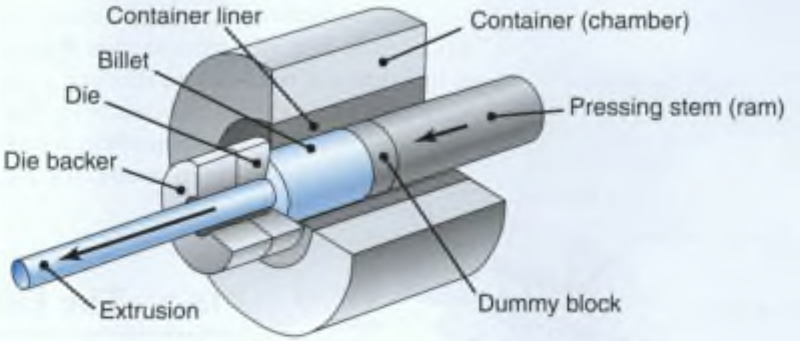


FIGURE 15.1 Schematic illustration of the direct-extrusion process.

QR Code 15.1 Aluminum Extrusion. (*Source:* Courtesy of PBC Linear, a Pacific Bearing Company)

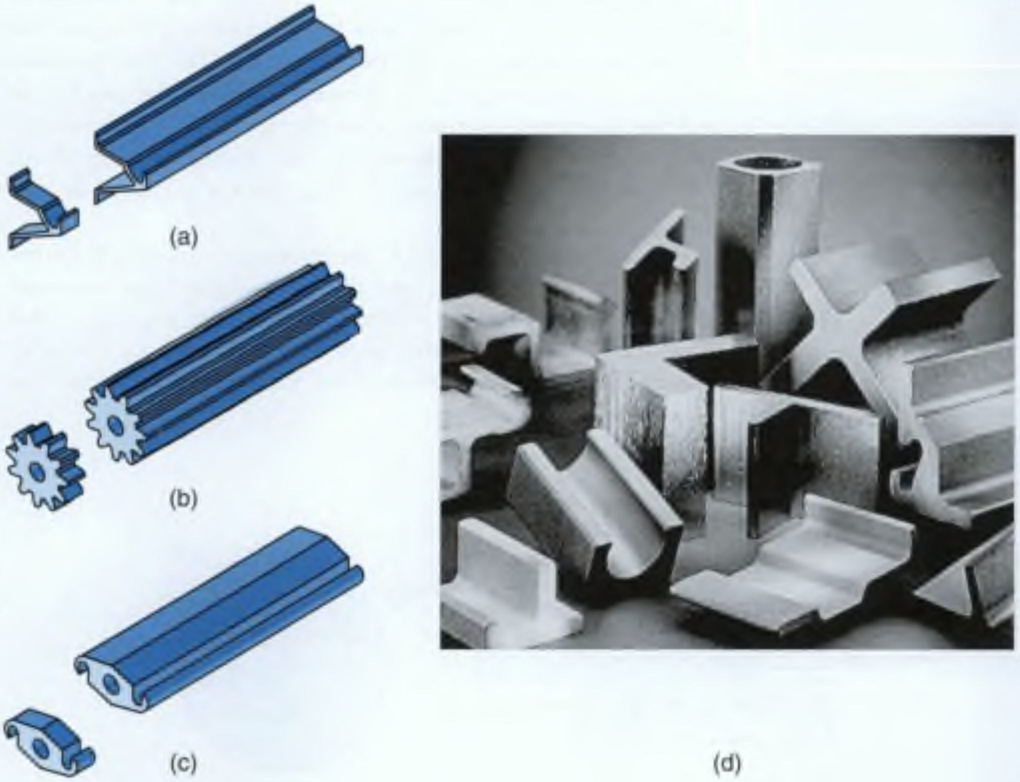


FIGURE 15.2 Extrusions and examples of products made by sectioning off extrusions. *Source:* (d) Courtesy of Plymouth Extruded Shapes. (For extruding plastics, see Section 19.2.)

The distinction between the terms **rod** and **wire** is somewhat arbitrary, with rod taken to be larger in cross-section than wire. In industry, wire is generally defined as a rod that has been drawn through a die at least once, or that its diameter is small enough so that it can be coiled. Wire drawing involves much smaller diameters than rod drawing, with sizes down to 0.01 mm for magnet wire, and even smaller for use in very low current fuses.

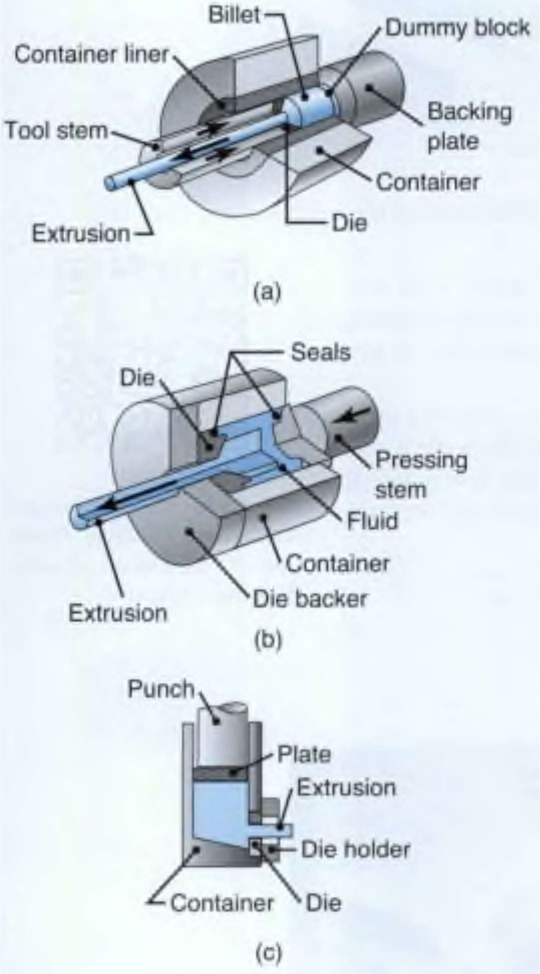


FIGURE 15.3 Types of extrusion: (a) indirect; (b) hydrostatic; and (c) lateral.

15.2 The Extrusion Process

There are three basic types of extrusion. In **direct** or **forward extrusion**, a billet is placed in a container (*chamber*) and forced through a die, as shown in Fig. 15.1. The die opening may be round, or it may have various shapes, depending on the desired profile. The function of the dummy block, shown in the figure, is to protect the tip of the pressing stem (punch), particularly in hot extrusion.

In **indirect** extrusion, also called *reverse, inverted,* or *backward extrusion*, the die moves toward the unextruded billet (Fig. 15.3a). Indirect extrusion has the advantage of having no billet–container friction, since there is no relative motion; thus, it is used on materials with very high friction, such as hot extrusion of high strength and stainless steels.

In **hydrostatic extrusion** (Fig. 15.3b), the billet is smaller in diameter than the container (which is filled with a fluid), and the pressure is transmitted to the fluid by a ram. The fluid pressure imparts triaxial compressive stresses acting on the workpiece and thus has improved formability (Section 2.10). Furthermore, there is much less workpiece–container friction than in direct extrusion. A less common type of extrusion is *lateral* or *side extrusion* (Fig. 15.3c).

As can be seen in Fig. 15.4, the geometric variables in extrusion are the die angle, α, and the ratio of the cross-sectional area of the billet to that of the extruded part, A_o/A_f, called the **extrusion ratio,** R. Other processing variables are the billet temperature, the speed at which the ram travels, and the type of lubricant used.

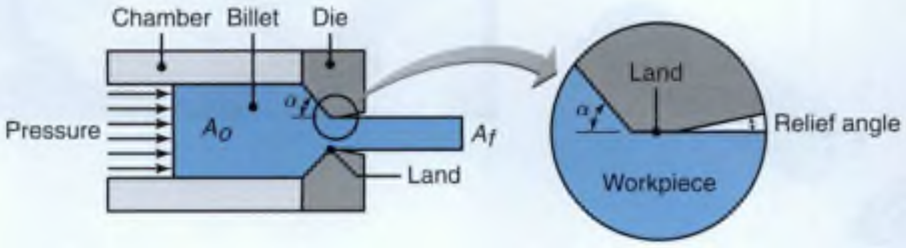


FIGURE 15.4 Process variables in direct extrusion; the die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Extrusion Force. The force required for extrusion depends on (a) the strength of the billet material, (b) extrusion ratio, (c) friction between the billet, container, and die surfaces, and (d) process variables. For a small die angle, α, it has been shown that the extrusion pressure can be approximated as

$$p = Y\left(1 + \frac{\tan\alpha}{\mu}\right)\left(R^{\mu\cot\alpha} - 1\right), \qquad (15.1)$$

where μ is the coefficient of friction, Y is the yield stress of the billet material, and R is the extrusion ratio. The extrusion force can then be obtained by multiplying the pressure by the billet area, and can be simplified as

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right), \qquad (15.2)$$

where k is the extrusion constant, determined experimentally; thus, k is a measure of the strength of the material being extruded and the frictional conditions. Figure 15.5 gives the values of k for several metals for a range of extrusion temperatures.

Video Solution 15.1 Forces in Extrusion

EXAMPLE 15.1 Calculation of Force in Hot Extrusion

Given: A round billet made of 70–30 brass is extruded at a temperature of 675°C. The billet diameter is 125 mm, and the diameter of the extrusion is 50 mm.

Find: Calculate the extrusion force required.

Solution: The extrusion force is calculated using Eq. (15.2), in which the extrusion constant, k, is obtained from Fig. 15.5. For 70–30 brass, k = 250 MPa at the given extrusion temperature. Thus,

$$F = \frac{\pi(125)^2}{4}(250)\ln\left[\frac{\pi(125)^2}{\pi(50)^2}\right] = 4$$

$$= 5.6 \text{ MN}.$$

Metal Flow in Extrusion. The metal flow pattern in extrusion, as in other forming processes, is important because of its influence on the quality and the properties of the extruded product. The material flows longitudinally, much like an incompressible fluid flow in a channel; thus, extruded products have an elongated grain structure (*preferred orientation*, Section 1.6). Improper metal flow during extrusion can produce various defects in the extruded product, as described in Section 15.5.

A common technique for investigating the flow pattern is to cut the round billet lengthwise in half and mark one face with a square grid pattern. The two halves are placed in the chamber together and are extruded. Figure 15.6 shows typical flow patterns obtained by this technique, for the case of direct extrusion with square dies (90° die angle). The conditions under which these different flow patterns occur are described in the caption of Figs. 15.6. Note the **dead-metal zone** in Figs. 15.6b and c, where the metal at the corners is essentially stationary; a situation similar to the stagnation of fluid flow in channels that have sharp angles or turns.

Process Parameters. In practice, extrusion ratios, R, usually range from about 10 to 100. They may be higher for special applications (400 for softer nonferrous metals)

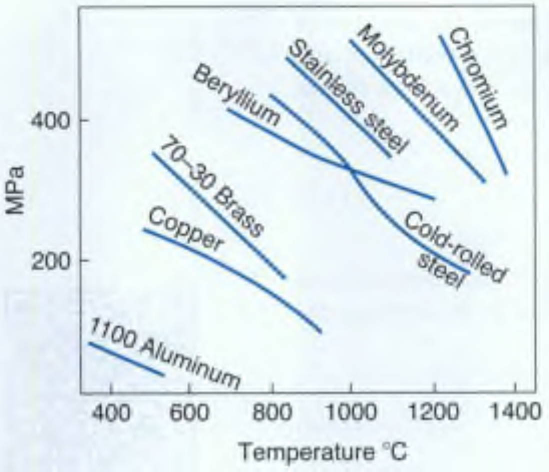


FIGURE 15.5 Extrusion constant k for various metals at different temperatures, as determined experimentally. *Source:* After P. Loewenstein.

or lower for less ductile materials, although the ratio usually has to be at least 4 to deform the material plastically through the bulk of the workpiece. Extruded products are usually less than 7.5 m long, because of the difficulty in handling greater lengths, but they can be as long as 30 m. Ram speeds range up to 0.5 m/s. Generally, lower speeds are preferred for aluminum, magnesium, and copper, higher speeds for steels, titanium, and refractory alloys. Dimensional tolerances in extrusion are usually in the range from ±0.25 to 2.5 mm and they increase with increasing cross-section.

Because they have high ductility, aluminum, copper, and magnesium and their alloys, as well as steels and stainless steels, are extruded with relative ease into numerous shapes. Other metals, such as titanium and refractory metals, also can be extruded, but only with some difficulty and significant die wear. Most extruded products, particularly those with small cross-sections, require straightening and twisting. This is typically done by stretching and twisting the extruded product, usually in a hydraulic stretcher equipped with jaws.

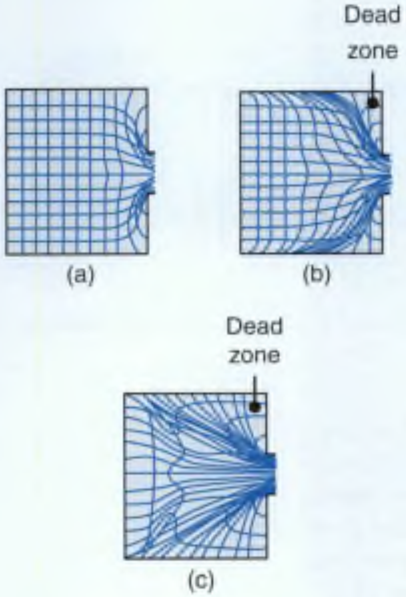


FIGURE 15.6 Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction or in indirect extrusion. (b) Pattern obtained with high friction at the billet–chamber interfaces. (c) Pattern obtained at high friction or with cooling of the outer regions of the hot billet in the chamber; this type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe (or extrusion) defect.

The presence of a die angle causes a small portion of the end of the billet to remain in the chamber after the stroke of the ram. This portion, called *scrap* or the *butt end*, is later removed by cutting it off. Alternatively, another billet or a graphite block may be placed in the chamber to extrude the piece remaining from the previous extrusion.

In **coaxial extrusion**, or **cladding**, coaxial billets are extruded together, provided that the strength and ductility of the two metals are compatible. An example is copper clad with silver. *Stepped extrusions* also are produced, by extruding the billet partially in one die and then in successively larger dies (see also *cold extrusion*, Section 15.4). *Lateral extrusion* (Fig. 15.3c) is used for the sheathing of wire and the coating of electric wire with plastic.

15.3 Hot Extrusion

For metals and alloys that do not have sufficient ductility at room temperature, or in order to reduce the forces required, extrusion can be carried out at elevated temperatures (Table 15.1). As in all other elevated-temperature operations, hot extrusion has special requirements, because of the high operating temperatures involved. For example, die wear can be excessive, and cooling of the hot-billet surfaces (in the cooler container) and the die can result in highly nonuniform deformation of the billet, as shown in Fig. 15.6c. Thus, extrusion dies may be preheated, as is done in hot-forging operations (Chapter 14).

Because the billet is hot, it develops an oxide film, unless it is heated in an inert atmosphere. Oxide films can be abrasive (see

Section 33.2), and can affect the flow pattern of the material. Their presence also results in an extruded product that may be unacceptable when good surface finish is required. In order to avoid the formation of oxide films on the hot extruded product, the dummy block placed ahead of the ram (Fig. 15.1) is made a little smaller in diameter than the container. As a result, a thin shell (*skull*), consisting mainly of the outer oxidized layer of the billet, is left in the container. The skull is later removed from the chamber.

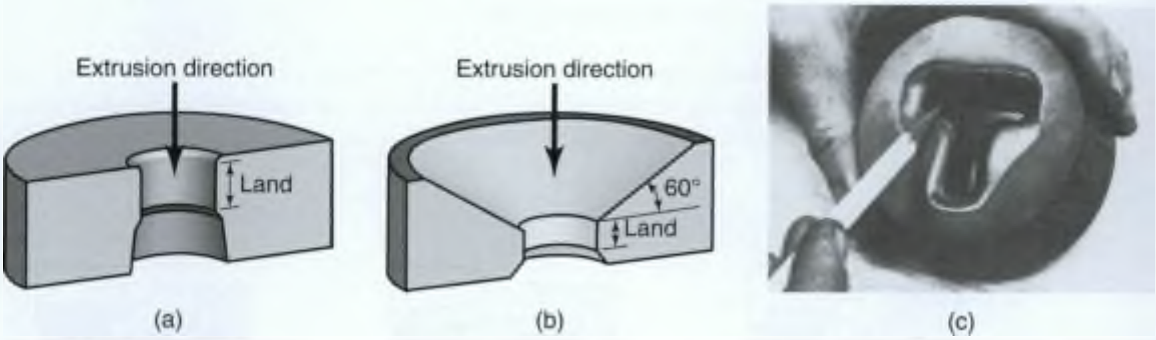
Die Design. Die design requires considerable experience, as can be appreciated by reviewing Fig. 15.7. *Square dies*, also called *shear dies*, are used in extruding nonferrous metals, especially aluminum. These dies develop *dead-metal zones*, which in turn form a "die angle" (see Figs. 15.6b and c) along which the material flows. These zones produce extrusions with bright finishes, because of the burnishing (Section 16.2) that takes places as the material flows past the "die angle" surface and land in the die.

Tubing can be extruded from a solid or hollow billet (Fig. 15.8). Wall thickness is usually limited to 1 mm for aluminum, 3 mm for carbon steels, and 5 mm for stainless steels. When solid billets are used, the ram is fitted with a mandrel that pierces a hole into the billet. Billets with a previously pierced hole also may be extruded in

TABLE 15.1

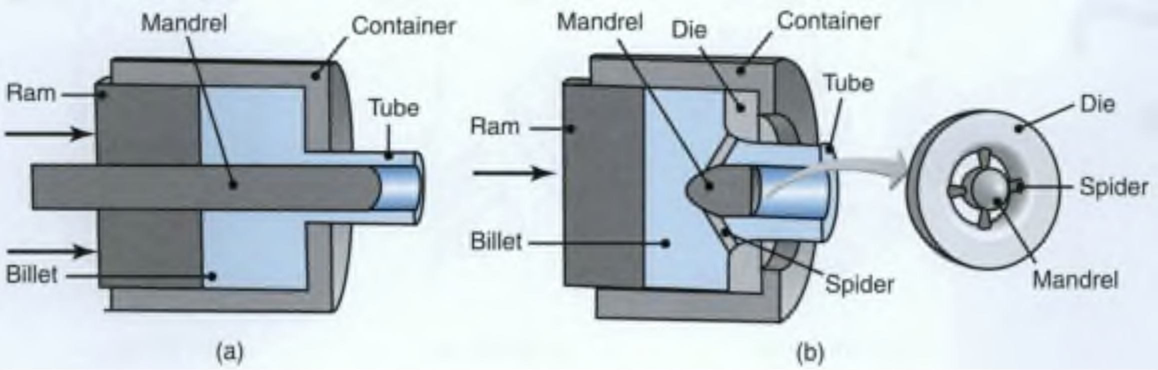
Typical Extrusion Temperature Ranges for Various Metals and Alloys. (See also Table 14.3.)

Material	Extrusion temperature (°C)
Lead	200–250
Aluminum and its alloys	375–475
Copper and its alloys	650–975
Steels	875–1300
Refractory alloys	975–2200



(a)
(b)
(c)

FIGURE 15.7 Typical extrusion die shapes: (a) die for nonferrous metals; (b) die for ferrous metals; and (c) die for a T-shaped extrusion made of hot-work die steel and used with molten glass as a lubricant. *Source:* (c) Courtesy of LTV Steel Company.



(a)
(b)

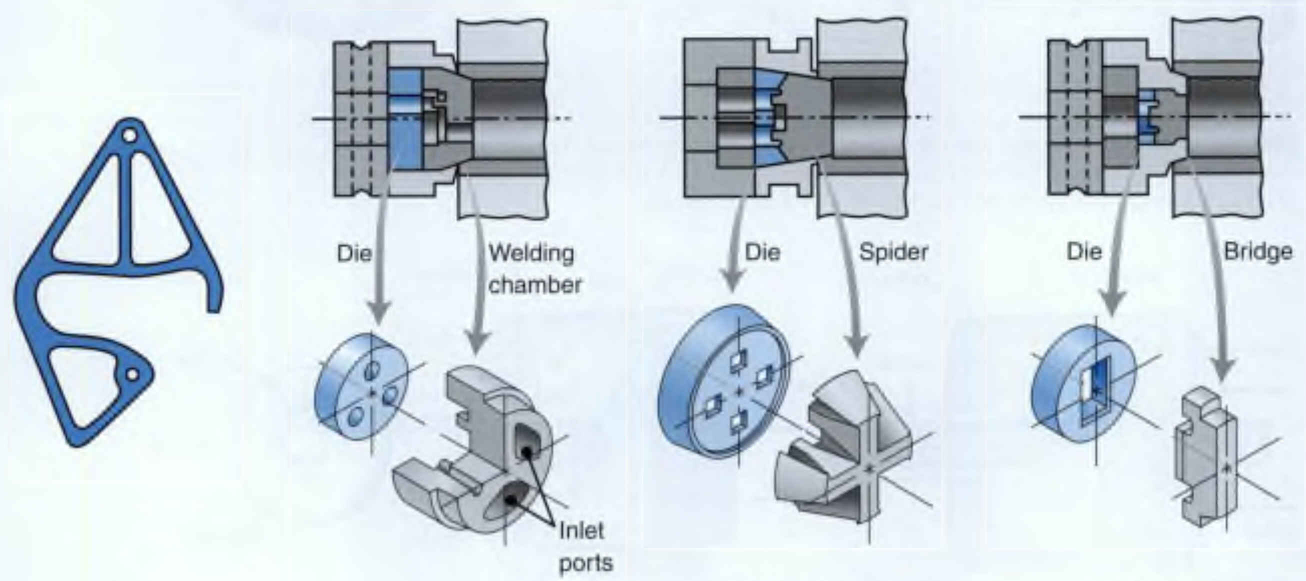
FIGURE 15.8 Extrusion of a seamless tube (a) using an internal mandrel that moves independently of the ram: an alternative arrangement has the mandrel integral with the ram and (b) using a spider die (see Fig. 15.9) to produce seamless tubing.

this manner. Because of friction and the severity of deformation, thin-walled extrusions are more difficult to produce than those with thick walls.

Hollow cross-sections (Fig. 15.9a) can be extruded by *welding-chamber* methods and using various dies known as a **porthole die, spider die,** and **bridge die** (Figs. 15.9b to d). During extrusion, the metal divides and flows around the supports for the internal mandrel into strands; this is a condition much like that of air flowing around a moving car and rejoining downstream, or water flowing around large rocks in a river and rejoining. The strands being extruded then become rewelded, under the high pressure in the welding chamber, before exiting the die. The rewelded surfaces have good strength, because they have not been exposed to the environment; as otherwise, they would develop oxides on their surfaces, thereby inhibiting good welding. The welding-chamber process is suitable only for aluminum and some of its alloys, because they can develop a strong weld under pressure, as described in Section 31.2. Lubricants cannot be used, because they prevent rewelding of the metal surfaces in the die.

Die Materials. Die materials for hot extrusion usually are hot-work die steels (Section 5.7). Coatings, such as partially stabilized zirconia (PSZ), may be applied to the dies to extend their life. Dies made of PSZ (Section 8.2.2) also are used for hot extrusion of tubes and rods. However, they are not suitable for dies for extruding complex shapes, because of the severe stress gradients that develop in the die, possibly leading to their premature failure.

Lubrication. Lubrication is important in hot extrusion, because of its effects on (a) material flow during extrusion, (b) surface finish and integrity, (c) product quality, and (d) extrusion forces. *Glass* (Section 8.4) is an excellent lubricant for steels,



(a) (b) Porthole die (c) Spider die (d) Bridge die

FIGURE 15.9 (a) An extruded 6063-T6 aluminum-ladder lock for aluminum extension ladders; this part is 8 mm thick and is sawed from the extrusion (see Fig. 15.2). (b) through (d) Components of various dies for extruding intricate hollow shapes.

stainless steels, and high-temperature metals and alloys. In a process developed in the 1940s and known as the **Séjournet process** (after J. Séjournet), a circular glass or fiberglass pad is placed in the chamber at the die entrance. The hot billet conducts heat to the glass pad, whereupon a thin layer of glass melts and acts as a lubricant. Before the hot billet is placed in the chamber, its surface is coated with a layer of powdered glass, to develop a thin glass lubricant layer at the billet–chamber interface.

For metals that have a tendency to stick or even weld to the container and the die, the billet can be enclosed in a *jacket*, a thin-walled container made of a softer and lower strength metal, such as copper or mild steel. This procedure is called **jacketing** or **canning**. In addition to acting as a low-friction interface, the jacket prevents contamination of the billet by the environment. For billet materials that are toxic or radioactive, the jacket also prevents it from contaminating the environment.

CASE STUDY 15.1 Manufacture of Aluminum Heat Sinks

Aluminum is used widely to transfer heat for both cooling and heating applications, because of its very high thermal conductivity. In fact, on a weight-to-cost basis, no other material conducts heat as efficiently as does aluminum.

Hot extrusion of aluminum is attractive for heat-sink applications, such as those in the electronics industry. Figure 15.10a shows an extruded heat sink, used for removing heat from a transformer on a printed circuit board. Heat sinks usually are designed with a large number of fins, that maximize the surface area and are evaluated from a thermodynamics standpoint, using computer simulations. The fins are very difficult and expensive to machine, forge, or roll form, but they can be made economically by hot extrusion, using dies made by electrical-discharge machining (Section 27.5).

Figure 15.10b shows a die and a hot-extruded cross-section, suitable to serve as a heat sink. The shapes shown also could be produced through a casting operation, but extrusion is preferred, because there is no internal porosity in the part and its thermal conductivity is thus higher.

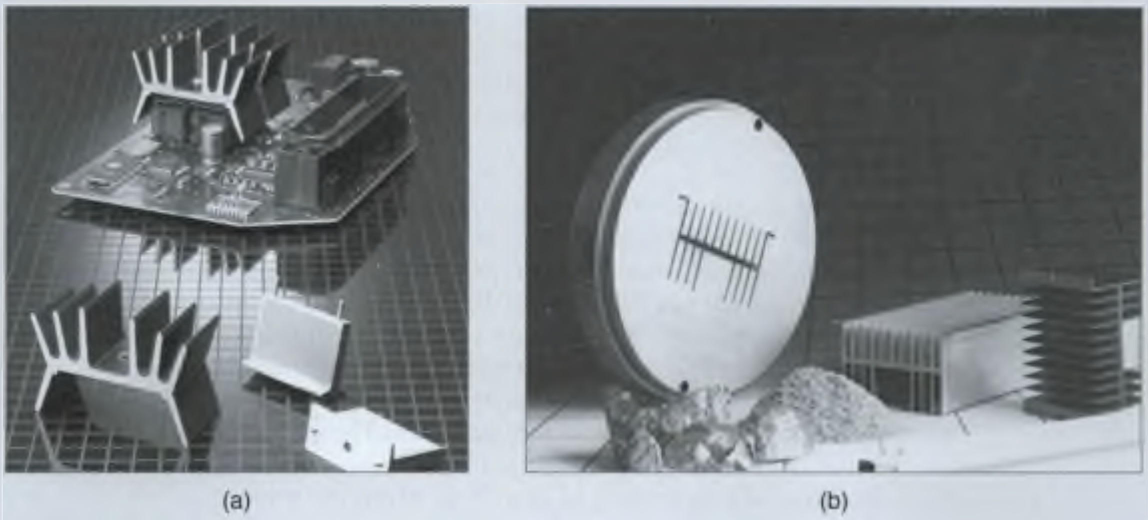

(a) (b)

FIGURE 15.10 (a) Aluminum extrusion used as a heat sink for a printed circuit board. (b) Extrusion die and extruded heat sinks. *Source:* Courtesy of Aluminum Extruders Council.

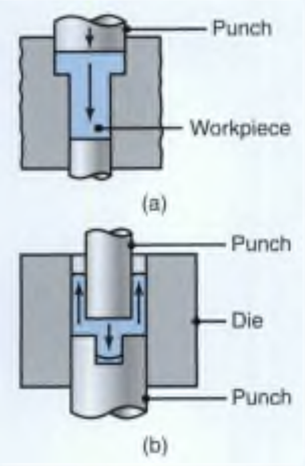


FIGURE 15.11 Two examples of cold extrusion; the arrows indicate the direction of metal flow during extrusion.

15.4 Cold Extrusion

Developed in the 1940s, *cold extrusion* is a general term often denoting a *combination* of operations, such as a combination of direct and indirect *extrusion and forging* (Fig. 15.11). Cold extrusion is used widely for components in automobiles, motorcycles, bicycles, appliances, and in transportation and farm equipment.

The cold-extrusion process uses slugs cut from cold-finished or hot-rolled bars, wire, or plates. Slugs that are less than about 40 mm in diameter are sheared (*cropped*), and, if necessary, their ends are squared off by processes such as upsetting, machining, or grinding. Larger diameter slugs are machined from bars into specific lengths. Cold-extruded parts weighing as much as 45 kg and having lengths of up to 2 m can be made, although most parts weigh much less. Powder metal slugs (*preforms*) also may be cold extruded (Section 17.3.3).

The *force*, F, in cold extrusion may be estimated from the formula

$$F = 1100\, A_o Y_{\text{avg}} \epsilon \tag{15.3}$$

where A_o is the cross-sectional area of the blank, Y_{avg} is the average flow stress of the metal, and ϵ is the true strain that the piece undergoes, based on its original and final cross-sectional area. For example, assume that a round slug 10 mm in diameter and made of a metal with $Y_{\text{avg}} = 350$ MPa is reduced to a final diameter of 7 mm by cold extrusion. The force would be

$$F = 1100(\pi)\left(10^2/4\right)(350)\left[\ln (10/7)^2\right] = 21.6 \text{ MN}$$

Cold extrusion has the following advantages over hot extrusion:

- Improved mechanical properties, resulting from work hardening, provided that the heat generated by plastic deformation and friction does not recrystallize the extruded metal.
- Good control of dimensional tolerances, thus reducing the need for subsequent machining or finishing operations.
- Improved surface finish, due partly to the absence of an oxide film and provided that lubrication is effective.
- Production rates and costs are competitive with those of other methods of producing the same part. Some machines are capable of producing more than 2000 parts per hour.

The magnitude of the stresses on the tooling in cold extrusion, on the other hand, is very high (especially with steel and specialty-alloy workpieces), being on the order of the hardness of the workpiece material. The punch hardness usually ranges between 60 and 65 HRC, and the die hardness between 58 and 62 HRC. Punches are a critical component, as they must possess not only sufficient strength but also high toughness and resistance to wear and fatigue failure. *Lubrication* is critical, especially with steels, because of the possibility of sticking (*seizure*) between the workpiece and the tooling, in case of lubricant breakdown. The most effective means of lubrication is the application of a *phosphate-conversion coating* on the workpiece, followed by a coating of soap or wax, as described in Section 34.10.

Tooling design and the selection of appropriate tool and die materials are essential to the success of cold extrusion. Also important are the selection and control of the workpiece material with regard to its quality and the repeat accuracy of the slug dimensions and its surface condition.

CASE STUDY 15.2 Cold-extruded Part

A typical cold-extruded part, similar to the metal component of an automotive spark plug, is shown in Fig. 15.12. First, a slug is sheared off the end of a round rod (Fig. 15.12, left). It then is cold extruded (Fig. 15.12, middle) in an operation similar to those shown in Fig. 15.11, but with a blind hole. Then the material at the bottom of the blind hole is punched out, producing the small slug shown. Note the respective diameters of the slug and the hole at the bottom of the sectioned part.

Investigating material flow during the deformation of the slug helps avoid defects and leads to improvements in punch and die design. The part usually is sectioned in the midplane, and then polished and etched to display the grain flow, as shown in Fig. 15.13 (see also Fig. 14.13).

FIGURE 15.12 Production steps for the metal portion of a cold-extruded spark plug. *Source:* Courtesy of National Machinery Company.

FIGURE 15.13 A cross-section of the metal part in Fig. 15.12, showing the grain-flow pattern (see also Fig 14.13b). *Source:* Courtesy of National Machinery Company.

15.4.1 Impact Extrusion

Impact extrusion is similar to indirect extrusion, and the process often is included in the cold-extrusion category. The punch descends rapidly on the blank (slug), which is extruded backward (Fig. 15.14). Because of volume constancy, the thickness of the tubular extruded region is a function of the clearance between the punch and the die cavity.

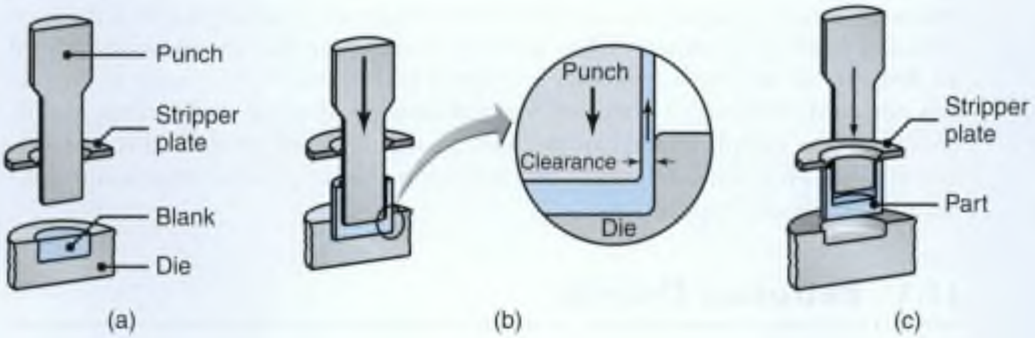


FIGURE 15.14 Schematic illustration of the impact-extrusion process; the extruded parts are stripped by using a stripper plate.

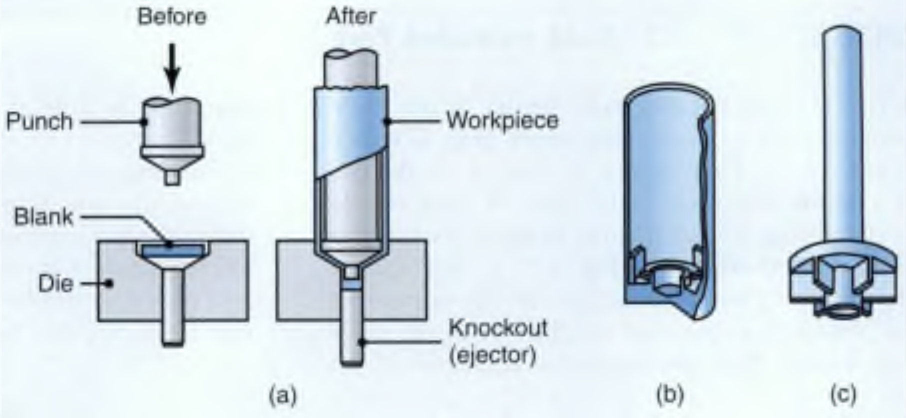


FIGURE 15.15 (a) Impact extrusion of a collapsible tube by the *Hooker process*. (b) and (c) Two examples of products made by impact extrusion. These parts also may be made by casting, forging, or machining; the choice depends on the materials part dimensions and wall thickness, and the properties desired. Economic considerations also are important in final process selection.

Typical products made by this process are shown in Fig. 15.15; other examples are collapsible tubes (similar to those used for toothpaste), light fixtures, automotive parts, and small pressure vessels. Most nonferrous metals can be impact extruded in vertical presses and at production rates as high as two parts per second.

The maximum diameter of the parts made is about 150 mm. The impact-extrusion process can produce thin-walled tubular sections, with thicknessto-diameter ratios as small as 0.005. Consequently, the symmetry of the part and the concentricity of the punch and the blank are important.

15.4.2 Hydrostatic Extrusion

In *hydrostatic extrusion*, the pressure required in the chamber is supplied via a piston and through an incompressible fluid medium surrounding the billet (Fig. 15.3b). Pressures are typically on the order of 1400 MPa. The high pressure in the chamber transmits some of the fluid to the die surfaces, where it significantly reduces friction. Hydrostatic extrusion is usually carried out at room temperature, typically using vegetable oils as the fluid.

Brittle materials can be extruded successfully by this method, because the hydrostatic pressure, along with low friction and the use of small die angles and high extrusion ratios, increases the ductility of the material. Long wires also have been extruded from an aluminum billet, at room temperature and an extrusion ratio of 14,000; this means that a 1-m billet becomes a 14-km-long wire. In spite of the success obtained, hydrostatic extrusion has had limited industrial applications, mainly because of the complex nature of the tooling, the design of specialized equipment, and the long cycle times required—all of which make the process uneconomical for most materials and applications.

15.5 Extrusion Defects

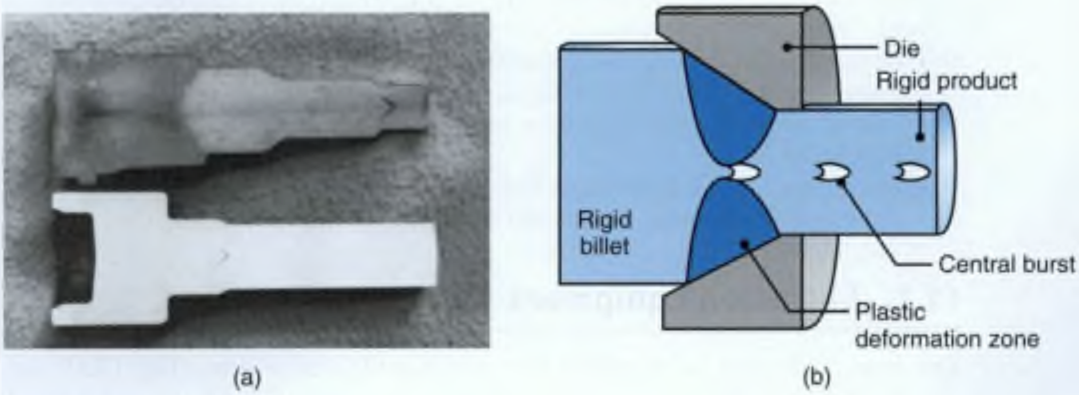
Depending on workpiece material condition and process variables, extruded products can develop several types of defects that can affect significantly their strength and product quality. Some defects are visible to the naked eye, while others can be detected only by the nondestructive techniques described in Section 36.10. There are three principal *extrusion defects*: surface cracking, pipe, and internal cracking.

Surface Cracking. If extrusion temperature, friction, or speed is too high, surface temperatures can become excessive, which may cause surface cracking and tearing (*fir-tree cracking* or *speed cracking*). These cracks are intergranular (along the grain boundaries; see Fig. 2.27), and usually are caused by **hot shortness** (Section 1.5.2). These defects occur especially in aluminum, magnesium, and zinc alloys, and can be avoided by lowering the billet temperature and the extrusion speed.

Surface cracking also may occur at lower temperatures, attributed to periodic sticking of the extruded part along the die land. Because of its similarity in appearance to the surface of a bamboo stem, it is known as a **bamboo defect**. The explanation is that, when the product being extruded temporarily sticks to the die land (see Fig. 15.7), the extrusion pressure increases rapidly; shortly thereafter, it moves forward again, and the pressure is released. The cycle is repeated continually, producing periodic circumferential cracks on the surface.

Pipe. The type of metal-flow pattern in extrusion shown in Fig. 15.6c tends to draw surface oxides and impurities toward the center of the billet, much like a funnel. This defect is known as *pipe defect*, *tailpipe*, or *fishtailing*; as much as one-third of the length of the extruded product may contain this type of defect, and has to be cut off as scrap. Piping can be minimized by modifying the flow pattern to be more uniform, such as by controlling friction and minimizing temperature gradients within the part. Another method is to machine the billet's surface prior to extrusion, so that scale and surface impurities are removed, or by chemical etching of the surface oxides prior to extrusion.

Internal Cracking. The center of the extruded product can develop cracks, called *center cracking*, *center-burst*, *arrowhead fracture*, or *chevron cracking* (Fig. 15.16a). They are attributed to a state of hydrostatic tensile stress that develops at the centerline in the deformation zone in the die (Fig. 15.16b), a condition similar to the



(a) (b)

FIGURE 15.16 (a) Chevron cracking (central burst) in extruded round steel bars; unless the products are inspected, such internal defects may remain undetected and later cause failure of the part in service; this defect can also develop in the drawing of rod, wire, and tubes. (b) Schematic illustration of rigid and plastic zones in extrusion; the tendency toward chevron cracking increases if the two plastic zones do not meet; note that the plastic zone can be made larger either by decreasing the die angle, by increasing the reduction in cross-section, or both. *Source:* After B. Avitzur.