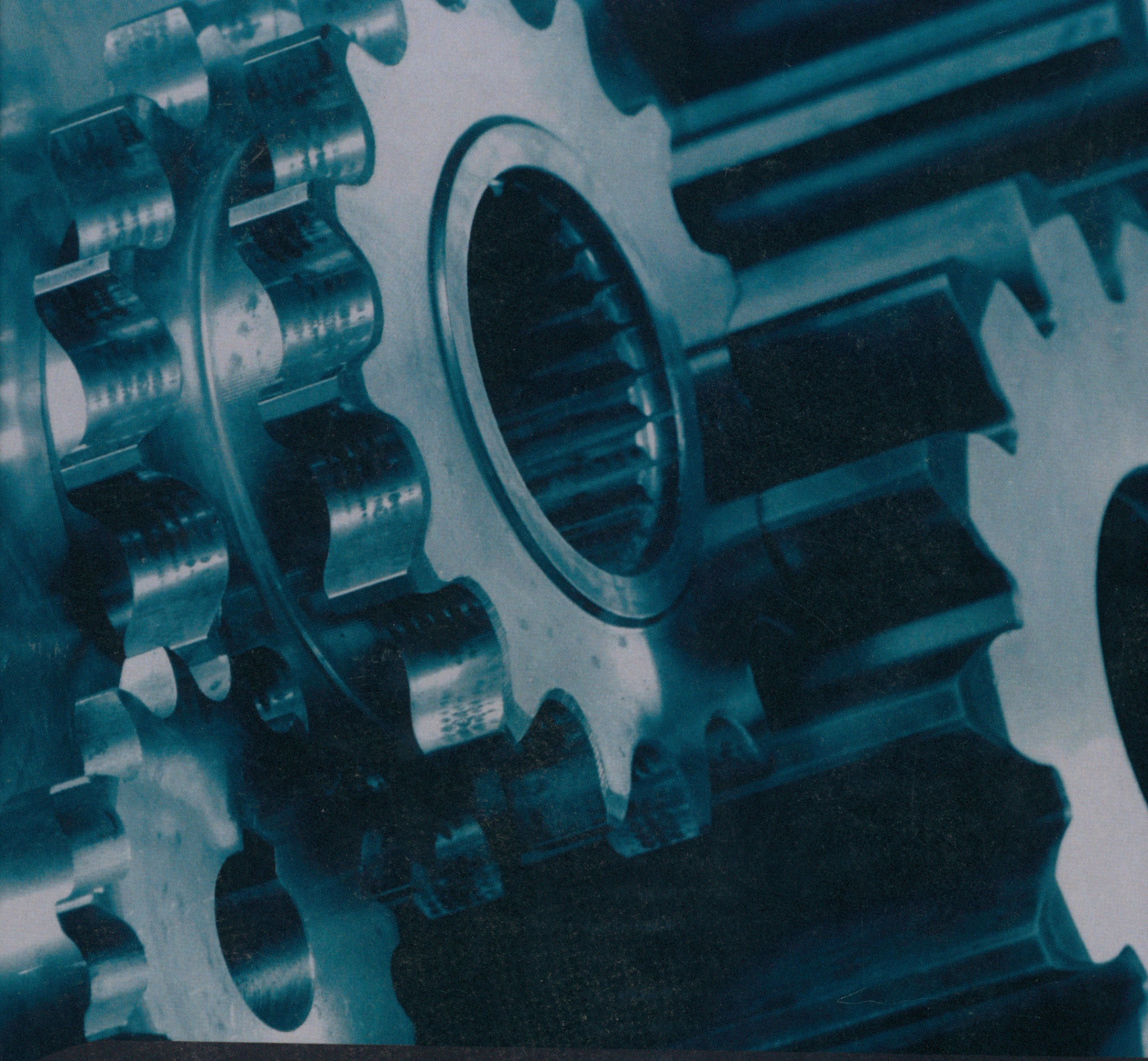


3GE COLLECTION ON ENGINEERING

Advanced Manufacturing

3G E-LEARNING

3GE COLLECTION ON ENGINEERING

ADVANCED MANUFACTURING



3G E-LEARNING

3GE COLLECTION ON ENGINEERING:
ADVANCED MANUFACTURING



3G E-LEARNING

© 2019 3G E-learning LLC
90 Church Street
FL 1 #3514
New York, NY 10008
United States of America
www.3ge-learning.com
email: info@3ge-learning.com

Authored and Edited by 3G E-learning LLC, USA

ISBN: 978-1-98462-354-6

All rights reserved. No part of this publication maybe reproduced, stored in a retrieval system or trans- mitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise without prior written permission of the publisher.

This book contains information obtained from highly regarded resources. A Wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the authors, editors, and the publisher cannot assume responsibility for the legality of all materials or the consequences of their use. The authors, editors, and the publisher have attempted to trace the copyright holders of all material in this publication and express regret to copyright holders if permission to publish has not been obtained. If any copyright material has not been acknowledged, let us know so we may rectify in any future reprint. Registered trademark of products or corporate names are used only for explanation and identification without intent to infringe.

Notice: Registered trademark of products or corporate names are used only for explanation and identification without intent of infringement. Case Studies and/or Images presented in the book are the proprietary information of the respective organizations, and have been used here specifically and only for educational purposes. Although care has been taken to check accuracy of formulas and procedures, the detailed methods should be tested further on a small scale before being adopted commercially.

For more information visit about 3G E-Learning LLC and its products, visit **www.3ge-learning.com**

EDITORIAL BOARD



Aleksandar Mratinković is born on May 5, 1988. in Arandjelovac, Serbia. He has graduated on Economic high school (2007), The College of Tourism in Belgrade (2013), and also has a master degree of Psychology (Faculty of Philosophy, University of Novi Sad). He has been engaged in different fields of psychology (Developmental Psychology, Clinical Psychology, Educational Psychology and Industrial Psychology) and has published several scientific works



Dan Piestun (PhD) is currently a startup entrepreneur in Israel working on the interface of Agriculture and Biomedical Sciences and was formerly president-CEO of the National Institute of Agricultural Research (INIA) in Uruguay. Dan is a widely published scientist who has received many honours during his career including being a two-time recipient of the Amit Golda Meir Prize from the Hebrew University of Jerusalem, his areas of expertise includes stem cell molecular biology, plant and animal genetics and bioinformatics. Dan's passion for applied science and technological solutions did not stop him from pursuing a deep connection to the farmer, his family and nature. Among some of his interest and practices counts enjoying working as a beekeeper and onboard fishing.



Felecia Killings is the Founder and CEO of LiyahAmore Publishing, a publishing company committed to providing technical and educational services and products to Christian Authors. She operates as the Senior Editor and Writer, the Senior Writing Coach, the Content Marketing Specialist, Editor-in-Chief to the company's quarterly magazine, the Executive and Host of an international virtual network, and the Executive Director of the company's online school for Authors. She is a former high-school English instructor and professional development professor. She possesses a Master of Arts degree in Education and a Bachelor's degree in English and African American studies.



Dr. Sandra El Hajj, Ph.D. in Health Sciences from Nova Southeastern University, Florida, USA is a health professional specialized in Preventive and Global Health. With her 12 years of education obtained from one of the most prominent universities in Beirut, in addition to two leading universities in the State of Florida (USA), Dr. Sandra made sure to incorporate interdisciplinary and multicultural approaches in her work. Her long years of studies helped her create her own miniature world of knowledge linking together the healthcare field with Medical Research, Statistics, Food Technology, Environmental & Occupational Health, Preventive Health and most noteworthy her precious last degree of Global Health. Till today, she is the first and only doctor specialized in Global Health in the Middle East area.



Hazem Shawky Fouda has a PhD. in Agriculture Sciences, obtained his PhD. From the Faculty of Agriculture, Alexandria University in 2008, He is working in Cotton Arbitration & Testing General Organization (CATGO).



Fozia Parveen has a Dphil in Sustainable Water Engineering from the University of Oxford. Prior to this she has received MS in Environmental Sciences from National University of Science and Technology (NUST), Islamabad Pakistan and BS in Environmental Sciences from Fatima Jinnah Women University (FJWU), Rawalpindi.



Igor Krunic 2003-2007 in the School of Economics. After graduating in 2007, he went on to study at The College of Tourism, at the University of Belgrade where he got his bachelor degree in 2010. He was active as a third-year student representative in the student parliament.Then he went on the Faculty of science, at the University of Novi Sad where he successfully defended his master's thesis in 2013. The crown of his study was the work titled Opportunities for development of cultural tourism in Cacak". Later on, he became part of a multinational company where he got promoted to a deputy director of logistic. Nowadays he is a consultant and writer of academic subjects in the field of tourism.



Dr. Jovan Pehcevski obtained his PhD in Computer Science from RMIT University in Melbourne, Australia in 2007. His research interests include big data, business intelligence and predictive analytics, data and information science, information retrieval, XML, web services and service-oriented architectures, and relational and NoSQL database systems. He has published over 30 journal and conference papers and he also serves as a journal and conference reviewer. He is currently working as a Dean and Associate Professor at European University in Skopje, Macedonia.



Dr. Tanjina Nur finished her PhD in Civil and Environmental Engineering in 2014 from University of Technology Sydney (UTS). Now she is working as Post-Doctoral Researcher in the Centre for Technology in Water and Wastewater (CTWW) and published about eight International journal papers with 80 citations. Her research interest is wastewater treatment technology using adsorption process.



Stephen obtained his PhD from the University of North Carolina at Charlotte in 2013 where his graduate research focused on cancer immunology and the tumor microenvironment. He received postdoctoral training in regenerative and translational medicine, specifically gastrointestinal tissue engineering, at the Wake Forest Institute of Regenerative Medicine. Currently, Stephen is an instructor for anatomy and physiology and biology at Forsyth Technical Community College.



Michelle holds a Masters of Business Administration from the University of Phoenix, with a concentration in Human Resources Management. She is a professional author and has had numerous articles published in the Henry County Times and has written and revised several employee handbooks for various YMCA organizations throughout the United States.

Table of Contents

Preface xi

Chapter 1 Advanced Manufacturing: An Introduction 1

Introduction 1
1.1 Principles of Manufacturing 3
1.1.1 Definition 3
1.1.2 Manufacturing System 4
1.1.3 The History of Manufacturing 5
1.1.4 Types of Manufacturing Systems 7
1.2 Manufacturing Processes 16
1.2.1 Meaning 17
1.2.2 Types of Manufacturing Processes 17
1.3 Cellular Manufacturing 21
1.3.1 Characteristics of Cellular Manufacturing 22
1.3.2 Cellular Manufacturing Objectives 23
1.3.3 Benefits of Cellular Manufacturing 23
1.3.4 Limitations 25
1.3.5 The Implementation Process 25
1.3.6 The Impact of Cellular Manufacturing on Workers 28
1.4 Advanced Manufacturing Technology 31
1.4.1 Definitions of AMT 32
1.4.2 History of AMT 34
1.4.3 Types of AMT 35
1.4.4 Benefits of Advanced Manufacturing Technology 39
1.4.5 Disadvantages of AMT 40
Summary 43
References 45

Chapter 2 Material Removal Processes 47

Introduction 47
2.1 Non-Conventional Machining 48
2.1.1 Classification of Non Traditional Machining Processes 48
2.1.2 Need for Non Traditional Machining 51
2.1.3 Abrasive Jet Machining 51

2.1.4 Equipment 52
2.1.5 Process Parameters and Machining Characteristics 53
2.1.6 Modelling of Material Removal 54
2.2 Turning 57
2.2.1 Process Cycle 58
2.3 Drilling 61
2.3.1 Drilling Time Estimation 62
2.4 Milling 63
2.4.1 Types of Milling Machine 64
2.4.2 Knee and Column Milling Machine 65
2.4.3 Bed-Type Milling Machine 66
2.5 Grinding 67
2.5.1 Grain Size 67
2.5.2 Bonded Abrasives 68
2.5.3 Centre-Less Grinding 68
2.6 Broaching 70
2.6.1 Construction of Broaching Tools 71
2.7 Electrochemical Machining (ECM) 72
2.7.1 ECM Fundamentals 73
2.7.2 Mechanism of Material Removal in ECM 75
Summary 78
References 79

Chapter 3 Cutting Tools and Accessories 81

Introduction 81
3.1 Superabrasive Technology 81
3.1.1 Manufactured Diamond 84
3.1.2 Work Materials 88
3.1.3 Cubic Boron Nitride (CBN) 88
3.1.4 Characteristics of Superabrasives 91
3.1.5 Machinability and Grindability 93
3.1.6 Material-Removal Rates 93
3.1.7 Grinding Wheels 94
3.1.8 Polycrystalline Tools 96
3.1.9 Machine Requirements 96
3.1.10 Grinding Wheels 97
3.1.11 Applications of Superabrasives 98
3.1.12 Polycrystalline Superabrasive Tools 99
3.1.13 Manufacture of Polycrystalline Tools 99
3.1.14 Types of PCD and PCBN Inserts 99
3.1.15 Advantages of Polycrystalline Tools 100
3.1.16 Types of Materials Machined With PCD (Compax®) Tools 101

3.1.17 Types of Materials Machined with PCBN (Borazon®) Tools... 102
3.1.18 Advantages of Superabrasives... 102
3.2 Carbide Tooling... 103
3.2.1 Cemented Carbides... 103
3.2.2 Carbide Tool Identification... 106
3.2.3 Carbide Tool Advantages... 108
Summary... 110
References... 112

Chapter 4 Special Machines 115

Introduction... 115
4.1 Linear Motors... 116
4.1.1 The advantages and disadvantages of linear motors... 117
4.1.2 Benefits of Linear Motors... 118
4.1.3 Designing with Linear Motor... 120
4.2 Types of Linear Motors... 124
4.2.1 Voice coil... 124
4.2.2 Stepper Motor... 129
4.2.3 Induction Motor... 133
4.2.4 Permanent-magnet motor... 136
4.3 Non-Cartesian Machines... 142
4.3.1 Different Types of Robots... 143
4.3.2 Articulated Robots... 144
4.3.3 Cartesian Robots... 146
4.3.4 SCARA Robots... 147
4.3.5 Parallel Robot... 149
4.3.6 Polar Robots... 150
4.3.7 Cylindrical Robots... 151
4.4 Manufacturing Applications of Automation And Robotics... 152
4.4.1 Automated production lines... 153
4.4.2 Numerical control... 155
4.4.3 Automated assembly... 156
4.4.4 Robots in manufacturing... 157
4.4.5 Flexible manufacturing systems... 159
4.4.6 Computer process control... 160
4.4.7 Computer-integrated manufacturing... 162
Summary... 165
References... 167

Chapter 5 Manufacturing System 169

Introduction... 169
5.1 Lean Manufacturing... 170

5.1.1 Purpose of Lean Manufacturing 171
5.1.2 The Business Impact of Lean Manufacturing 173
5.1.3 Key Factors in Lean Manufacturing 174
5.1.4 Improve Quality with Lean Manufacturing 175
5.1.5 Lean Manufacturing Pros & Cons 176
5.1.6 Key Issues for the Implementation of a Lean Manufacturing System 178
5.2 Flexible Manufacturing System 179
5.2.1 Organizational Structure for Flexible Manufacturing Systems . 180
5.2.2 Flexible Manufacturing Systems and Today Factories 181
5.2.3 Flexibility and Its Types 184
5.2.4 FMS and its Rule in CIM Environment 186
5.2.5 Advantages and disadvantages of FMSs implementation 188
5.3 Group Technology / Cellular Manufacturing 189
5.3.1 Historical Development 190
5.3.2 Production Flow Analysis (PFA) 194
5.4 Just-In-Time Manufacturing 199
5.4.1 JIT as a Philosophy 201
5.4.2 JIT as an Environment 206
5.4.3 JIT as a Control Technique 208
5.4.4 Differences between JIT & Lean Manufacturing 209
5.4.5 High Velocity Manufacturing 210
Summary 212
References 214

Chapter 6 CNC and CAD Manufacturing 215

Introduction 215
6.1 Concept of CNC 216
6.2 Computer Aided Manufacturing 219
6.2.1 History 220
6.2.2 Benefits of CAM 221
6.2.3 CAD to CAM Process 222
6.2.4 CNC Machines at a Glance 224
6.2.5 The Human Element of CAM 227
6.2.6 The Impact of CAM 229
6.3 Applications of Computer Aided Manufacturing 231
6.3.1 The Origins of CAD/CAM 232
6.3.2 The Case for CAS and CAS/CAM 234
6.4 CAD-CAM in the CNC Manufacturing Process 237
6.4.1 Increase Programming Potential 238
6.4.2 Makes You More Accessible by Clients 238
6.4.3 Improved Control over Job Programming 239

6.4.4 Machining Wizards Remove the Guesswork 239
6.4.5 Getting the Most Out of Your CNC Machine Tool 240
6.4.6 Eliminate Costly Mistakes & Waste 240
6.4.7 Powerful 3 Axis CNC Programming Operations 241
6.4.8 Multiaxis CAM Technology Makes Complex Machining Simple and Cost Effective 242
6.4.9 Turn Art into CNC Programs & Finished Parts Easily 242
6.4.10 Seamless Integration with Popular CAD Design Products 243
Summary 246
References 248

Chapter 7 Measurement, Inspection and Quality Control 249

Introduction 249
7.1 Basics Of Metrology and Quality In Manufacturing 250
7.1.1 Origins of Measurement 251
7.1.2 Calibration, True Value and Measurement Error 251
7.1.3 Uncertainty and Quality 253
7.1.4 Uncertainty and Error 254
7.1.5 Measurement and Quality Assurance 257
7.2 Quality Control In Manufacturing 259
7.2.1 Quality Control Inspection Tools 260
7.2.2 Types of Quality Control 262
7.2.3 Benefits of Using Quality Control in Manufacturing 263
7.2.4 Incorrect Implementation of Quality Control in Manufacturing 267
7.2.5 Using Quality Assurance with Quality Control in Manufacturing 267
7.2.6 Quality Control, Quality Assurance and Lean Manufacturing 268
7.2.7 How to Implement Quality Control in Manufacturing 269
7.3 Additive Manufacturing And Inspection Difficulties 270
7.3.1 Industrial CT for Use in Additive Manufacturing Inspection ... 276
7.3.2 Challenges Currently Facing the Additive Manufacturing Industry 277
7.3.3 Quality Control Inspection for Additive Manufactured Parts ... 279
7.3.4 Visual Inspection of Internal Features 279
7.3.5 Part-to-CAD and Internal Part Inspection 280
7.3.6 Digital Radiography and Industrial CT Industry Standards 281
Summary 283
References 285

Index 287

Preface

The market place of the twenty-first century is evolving into one of merging national markets, fragmented consumer markets, and rapidly changing product technologies. These changes are driving firms to compete, simultaneously, along several different dimensions: design, manufacturing, distribution, communication, sales and others. Although manufacturing has not been utilized as a competitive weapon historically, the market place of the twenty first century will demand that manufacturing assume a crucial role in the new competitive arena.

This book *"Advanced Manufacturing"* summarizes the trends we observe in technology research and development that relate to the current and future state of advanced manufacturing. The book explains how manufacturing has traditionally been defined and how the processes in a production plant have been viewed as a mainly step-wise linear transformation of inputs towards finished goods.

The goal of this book is to find how innovation in manufacturing processes and associated product design impacts the prospects for manufacturing in the early 21st century. Innovations in manufacturing are often reported one-at-a-time and it is not immediately clear how these innovations fit together and how they collectively impact the practice and economics of manufacturing. This book is intended to present advanced manufacturing technology innovations in a larger context.

Innovation involves important feed-forward and feedback mechanisms in the real economy. The invention of new products and processes, as well as the improvement of existing processes, leads to higher productivity and expansion of product portfolios and associated service offerings. Progress in human society has been accomplished by the creation of new technologies. The last few years have witnessed unparalleled changes throughout the world. Rapid changes in the markets demand drastically shortened product life cycles and high-quality products at competitive prices. Customers now prefer a large variety of products. This phenomenon has inspired manufacturing firms to look for progressive computerized automation in various processes. Thus mass production is being replaced by low-volume, high-variety production. Manufacturing firms have recognized the importance of flexibility in the manufacturing system to meet the challenges posed by the pluralistic market. The concept of flexibility in manufacturing systems has attained significant importance in meeting the challenges for a variety of products of shorter lead-times, together with higher productivity and quality.

This book provides an overview of the processes in discrete-event manufacturing systems, and emphasizes concepts relating to the interconnection of the wide range of activities involved. This book provides a broad vision of the future of manufacturing, analysed from a system-management viewpoint and with a special focus on ICT-related matters.

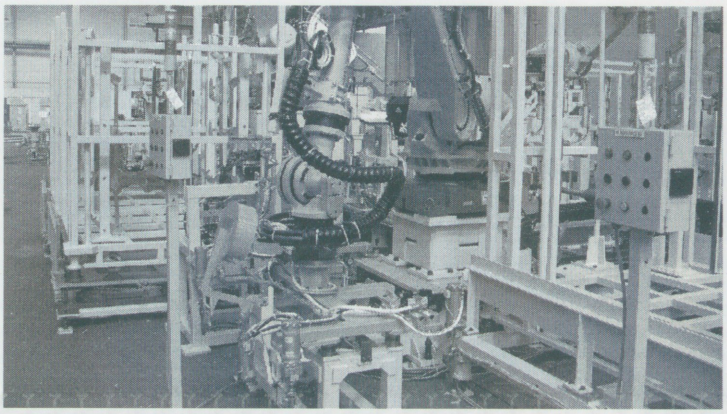
1

CHAPTER

ADVANCED MANUFACTURING: AN INTRODUCTION

INTRODUCTION

Manufacturing covers wide areas of inputs, processes and products. It reaches out to the demands in production for thousands of different varieties and types of goods. These demands range from large ships to hand drilling equipment, and from micro circuits to automobiles. The number and complexity of processes involved in the production of these goods varies drastically. The extent of alterations involved in these processes form the very basis for getting a bird's eye view of the manufacturing activity. Some are simple primary product and some are simply transformed products such as basic metallic shapes, paint and utensils. The next are moderately transformed products such as wires, rods, metal pipes and tubes, while others are elaborately transformed products such as prefabricated metal shapes, wire products, glassware and ceramic products. The mechanization and extent to which it is involved in the process of production gives another view of manufacturing. Manufacturing covers a very wide range of situations right from robot controlled highly mechanized lines of production to some simple day to day use equipments with mechanical activities.



Thus, manufacturing industries, today, encompasses a dimension scale of more than fifteen orders of magnitudes. The design and manufacture of huge machinery, ship and spacecrafts on one side while nano and pico technology on the other side of the dimension scale, highlights the challenges ahead for engineers and technologists. With the advancement of technology newer materials, energy sources, manufacturing technology, decision-making and management techniques are being developed. These unfold lot of opportunities for the scientific and academic fraternity. At the same time, newer challenges in the form of environmental and other issues put stringent requirements on the technology. Global competition, the thrust on quality and demand for higher productivity are some of the challenges before the present industrial and manufacturing units. To survive and to succeed further, the competitors have a unique option, which is understanding of the dynamic changes that are taking place in the business environment. In view of the above, a nation should develop and update its infrastructure, such that the new and advanced technology gets into hand in hand, with the ongoing time.

Manufacturing processes and systems used in design and production are undergoing dramatic changes in response to new customer needs and emerging technologies. Complexity, dynamism and uncertainty have become dominant characteristics of recent competition patterns which have resulted in a demand-diversified market with more multifaceted products. AMT appears to represent a perfect interaction between technological potential and the manufacturing challenges. The major benefits of Advanced Manufacturing Technologies (AMTs) include faster machine cycle, greater reliability, and reduced inventory, saving on labor, greater flexibility and improved quality. The use of AMTs permits the integration of the full spectrum of production functions and manufacturing processes with computer technologies. With the use of computer technology, AMTs make the data storing and manipulation possible. Data held electronically can be changed and distributed easily and cheaply between these technologies. Companies therefore adopt these technologies for a wide range of activities, ranging from scheduling to quality inspection.

1.1 PRINCIPLES OF MANUFACTURING

Manufacturing refers to a large-scale production of goods that converts raw materials, parts and components into finished merchandise using manual labor and/or machines. The finished goods can be sold directly to consumers, to other manufacturers for the production of more complex products, or to wholesalers who distribute the goods to retailers.



1.1.1 Definition

There are many ways and definitions available to explain the concept of manufacturing. Some of these definitions are listed below:

- The process of converting raw materials into finished products
- Manufacturing is defined as the making of goods or wares by manual labor and / or by the use of machinery, especially on a large scale
- Manufacturing is a very broad activity, encompassing many functions – everything from purchasing to quality control of the final product
- Chemical or Physical transformation of the materials, substances or components into some new products
- Manufacturing is a value addition activity to the raw materials, substances or components
- Manufacturing is a process through which products are made through various production activities
- Manufacturing may be considered as a system, wherein there is an integration of people, equipment, policies and procedures to accomplish the objectives of an organization i.e. production of the required product.
- Manufacturing is the use of machines, tools and labor to make things for use or sale

- Manufacturing is an application of different resources such as machinery and people used for converting the materials into finished goods

1.1.2 Manufacturing System

In order to consider manufacturing, as a system; we need to look beyond the conversion of raw materials and processes which lead to finished products. The understanding of the manufacturing system as a whole helps in identifying, which process parameters and functions of the organizations are important; this helps to make decisions about the economical ways of producing the end products. There are several factors which are usually considered in taking a final and relevant decision about the best way of producing the desired end product. Figure 1 gives the general definition for any manufacturing system.

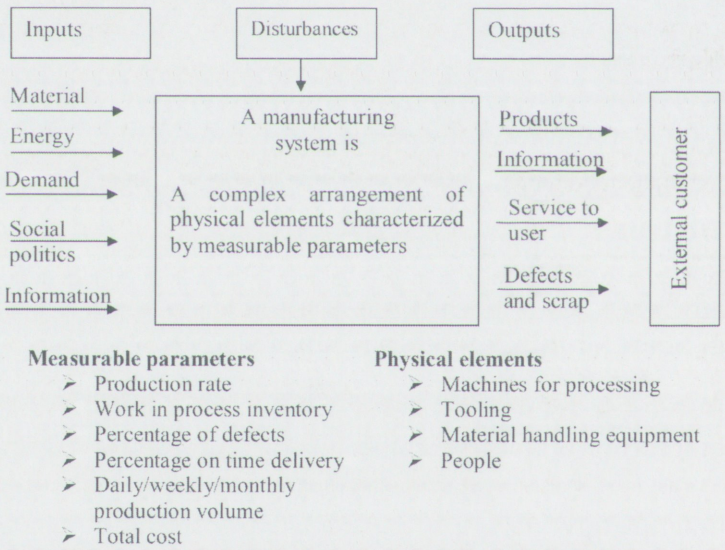


Figure 1: General definitions for any manufacturing system.

The input-output system does not provide the sufficient information about all the aspects of manufacturing. Manufacturing involves more than just processing of raw materials. The overall manufacturing system starts from the market or specifically from the customer requirements and ends when the product reaches the hands of customers. The present day trends also look beyond the delivery of the product to the customer i.e. after sale, services offered by the organization. The basic model at Fig. 2 is further expanded to incorporate most of the functions involved in an organization for the design, planning and manufacturing of a product. The manufacturing system incorporating all the above aspects (holistic approach) as shown in Fig. 2

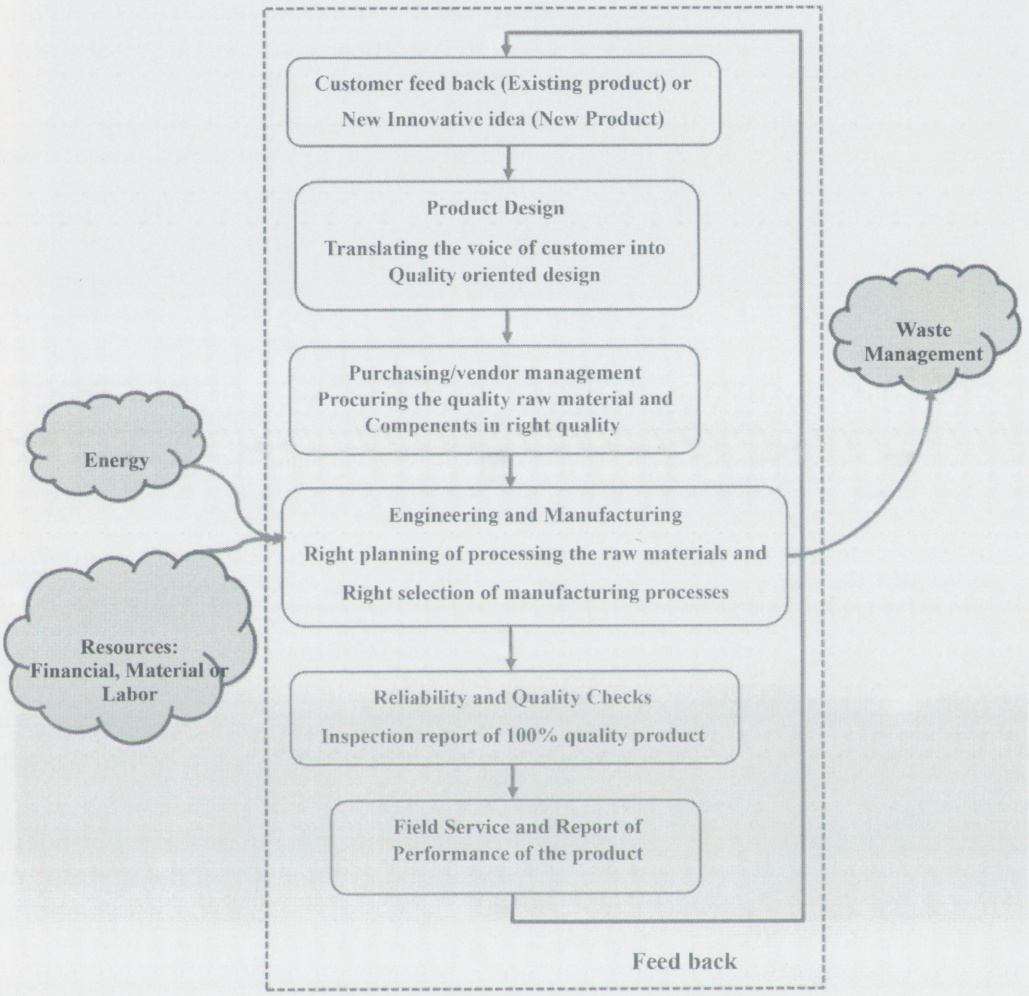
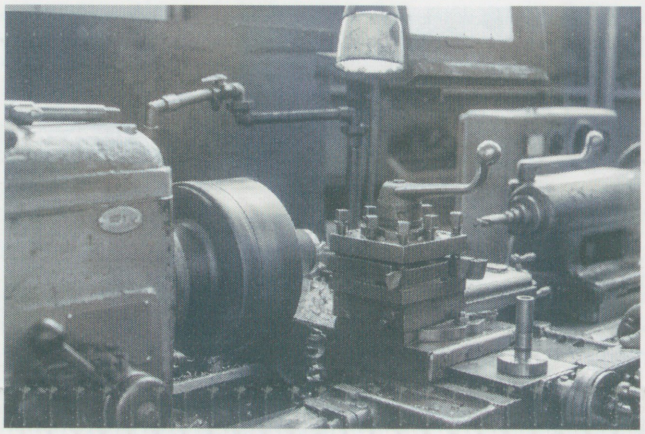


Figure 2: Manufacturing System Boundary.

1.1.3 The History of Manufacturing

Manufacturing has long been a cornerstone of the modern economy, with advances in technology changing the processes and output volume drastically for all sorts of industries from food production to home goods, chemicals and electronics. Where it will go in 2017 and beyond will depend heavily on economic changes, but a look at where it was and where it is now can give us a good idea as to what manufacturing will do in the future.



Manufacturing in the Beginning

Manufacturing industries are the chief wealth producing sectors of an economy.

Before heavy machinery and automation, manufacturing was done by hand. With no computers to handle each step of the design, production and QA, the responsibilities fell to skilled tradespeople.

- Only the most skilled workers could perform these tasks, slowing production time but keeping demand high.
- Apprenticing was a common way for knowledge to be passed down correctly while maintaining quality, keeping these skill sets fairly small amongst the general population.
- Most of these skilled trades were performed rurally.

Rural manufacturing could only support so many people before it plateaued, so putting-out systems were implemented to centralize a collective of manufacturers under one business hub. The central provider was able to subcontract specific orders to rural manufacturers, spreading the workload among tradespeople and giving those tradespeople a wider customer base. Versatility and the division of labor would be key if the American **manufacturing industry** were to take off, however.

- Interchangeable parts led to reduced downtime, efficient labor usage and mass production.

- Fixtures, jigs and gauges paved the way for identical parts to be manufactured quickly and correctly before being passed along to less-skilled assembly workers.

Manufacturing Today

With connectivity at our fingertips through the internet, customization of the labor flow and segmentation of the various components of manufacturing is easier than ever. The addition of robotic systems has cut down on labor costs, human error, and lag time between steps in the assembly process.

- Raw materials can be quickly processed at one location, shipped and then manufactured elsewhere.
- Just-in-time and lean manufacturing eliminate waste and reduce flow times.
- Prefabrication saves on time by shipping fully assembled or partially assembled units directly to the site where they will be used.
- Flexible manufacturing systems allow for systems to react in case of predicted or unpredicted changes to workflow.

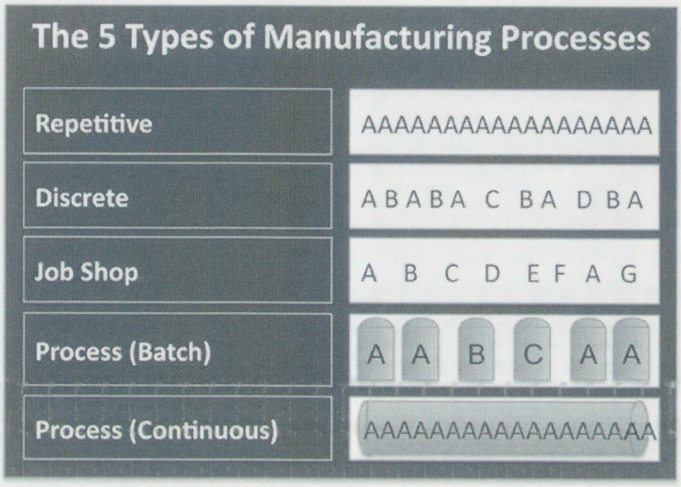
Manufacturing in the Future?

The continued automation of manufacturing tasks paired with emerging smart technologies such as the Internet of Things signals that streamlining in manufacturing will play an even bigger role in 2017 and beyond. Toll manufacturing could become less of a practice as more facilities process materials and manufacture finished products on site, which is sure to impact logistical networks from resource to refinery to manufacturer and so on.

The evolution of manufacturing has shaped the way we do business, as it is always factored into what types of services we offer and what sorts of efficiencies we keep in place.

1.1.4 Types of Manufacturing Systems

The manufacturing systems differ in structure or physical arrangement. According to the physical arrangement, there are four kinds of classical manufacturing systems and two modern manufacturing systems that is rapidly gaining acceptance in industries.



The classical systems are:

- Job shop
- Flow shop
- Project shop
- Continuous process

The modern manufacturing systems are

- Linked cell system (Cellular manufacturing system)
- Flexible manufacturing system (FMS)

Job shops

Process layout is a design for the floor plan of a plant which aims to improve efficiency by arranging equipment according to its function.

In a Job shop, varieties of products are manufactured in small lot sizes to a specific customer order. To perform a wide variety of manufacturing processes, general purpose production equipment is required. Workers must have relatively high skill levels to perform a range of different work arrangements.

The production machines are grouped according to the general type of manufacturing processes as shown in Figure 3. The lathes are in one department, drill presses in another and so on. Each different part requiring its own sequence of operations can be routed through the various departments in the proper order. For this 'ROUTE SHEETS' are used. The layout made for this purpose is called as functional or **process layout**.

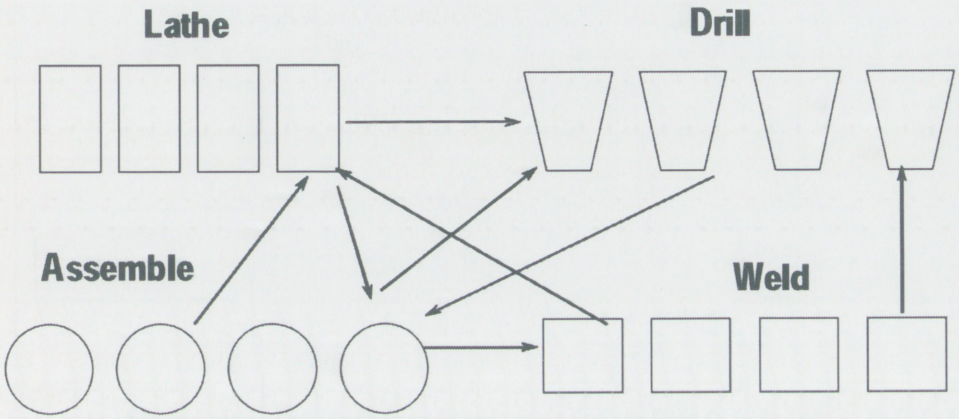


Figure 3: Functional or process layout.

Advantages of process layouts:

- Can handle a variety of processing requirements
- Not particularly vulnerable to equipment failures
- Equipment used is less costly
- Possible to use individual incentive plans

Disadvantages of process layouts:

- In-process inventory costs can be high
- Challenging routing and scheduling
- Equipment utilization rates are low
- Material handling is slow and inefficient
- Complexities often reduce span of supervision
- Special attention for each product or customer
- Accounting and purchasing are more involved

Examples: Machine shops, foundries, press working shops, plastic industries.

Flow Shops

The flow shops have a "product oriented layout" composed mainly of flow lines. This system can have high production rates. The plant may be designed to produce the particular product or family, using "Special purpose machines" rather than general purpose equipments. The skill level of the laborer tends to be lower than in production job shop. When the volume of production becomes large, it is called "mass production". The material flow is through a sequence of operations by material handling devices. The time the item spends in each station or location is fixed and equal. The workstations are arranged in line according to the processing sequence needed as shown in Figure 4.

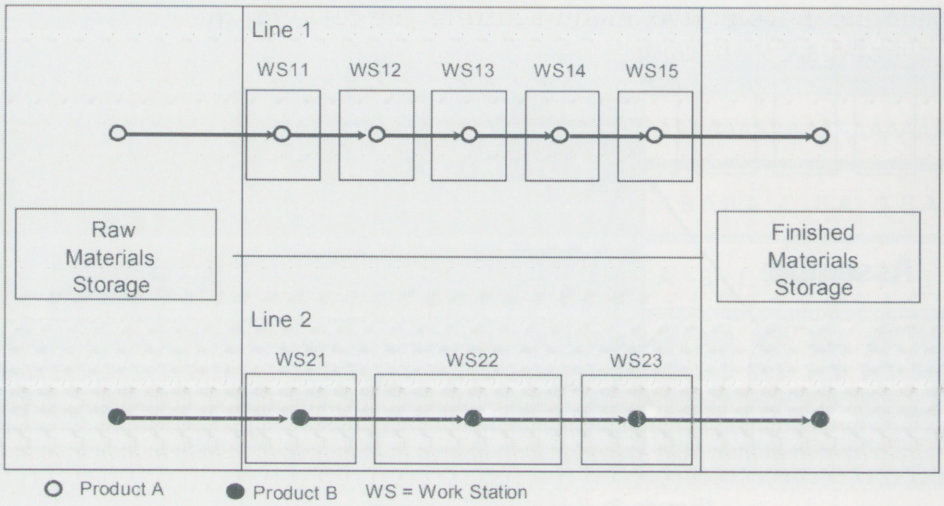


Figure 4: Product layout.

Advantages of product layout:

- High rate of output
- Low unit cost
- Labor specialization
- Low material handling cost
- High utilization of labor and equipment
- Established routing and scheduling
- Routing accounting and purchasing

Disadvantages of product layout:

- Creates dull, repetitive jobs
- Poorly skilled workers may not maintain equipment or quality of output
- Fairly inflexible to changes in volume
- Highly susceptible to shutdowns
- Needs preventive maintenance
- Individual incentive plans are impractical

Example: Automated assembly line and Television manufacturing factory.

Project Shop

In this type, a product must remain in a fixed position or location because of its size and weight. The materials, machines and people in fabrication are brought to site. The layout is also called as fixed position layout. Figure 5 shows the project shop layout.

Example: Locomotive manufacturing, large aircraft assembly and ship building.

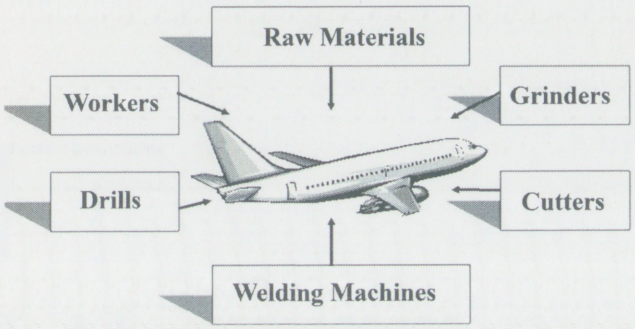


Figure 5: Project shop layout.

Advantages of project layout:

- Minimum capital investment
- Continuity of operation
- Less total production cost.
- Offers greater flexibility
- Allows the change in production design.
- Permits a plant to elevate the skill of its operators

Disadvantages of project layout:

- Machines, tools and workers take more time to reach the fixed position.
- Highly skilled workers are required.
- Complicated jigs and fixtures (work holding device) may be required.

Continuous Process

In this continuous process, the product seems to flow physically. This system is sometimes called as flow production when referring to the manufacture of either complex single parts, such as a canning operation, or assembled products such as TVs. However, this is not a continuous process, but high volume flow lines. In **continuous process**, the products really do flow because they are liquids, gases, or powers. Figure 6 shows the continuous process layout. It is the most efficient but least flexible kind of manufacturing system. It usually has the leanest and simplest production

Continuous process is a series of steps that is executed such that each step is run concurrently with every other step. In other words, all the steps in the process are potentially running at the same time.

system because this manufacturing system is the easiest to control because it has the least work- in-progress (WIP).

Examples: Oil refineries, chemical process plants and food processing industries

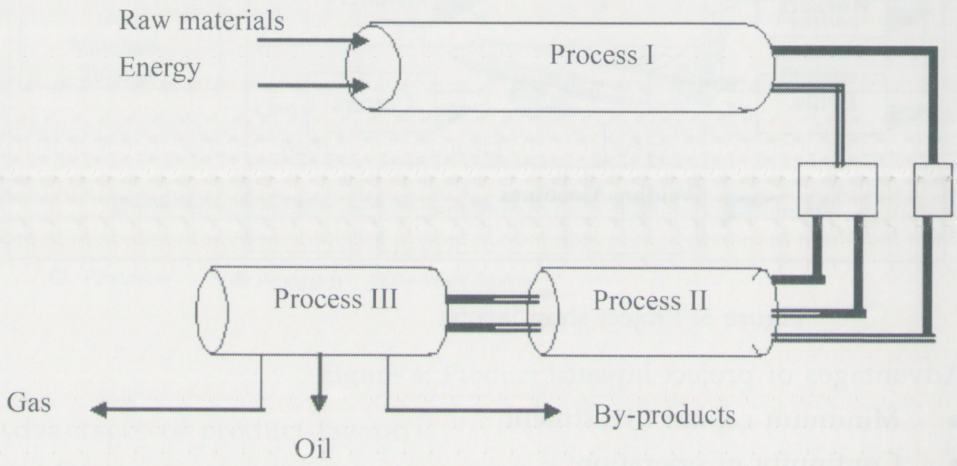


Figure 6: Continuous process layout.

Linked Cell Manufacturing System

Cellular manufacturing (CM) is a hybrid system for linking the advantages of both job shops (flexibility in producing a wide variety of products) and flow lines (efficient flow and high production rate). A cellular manufacturing system (CMS) is composed of "linked cells". Figure 7 shows the main structure of cellular manufacturing system. In cells, the workstations are arranged like a flow shop. The machines can be modified, retooled and regrouped for different product lines within the same "family" of parts. This system has some degree of automatic control for loading and unloading of raw materials and work pieces, changing of tools, transferring of work pieces and tools between workstations. Cells are classified as manned and unmanned cells. In manned cells multifunctional operators can move from machine to machine and the materials can be moved by the operator. In the unmanned cells, an industrial robot is located centrally in the cell for material handling. Automated inspection and testing equipment can also be a part of this cell.

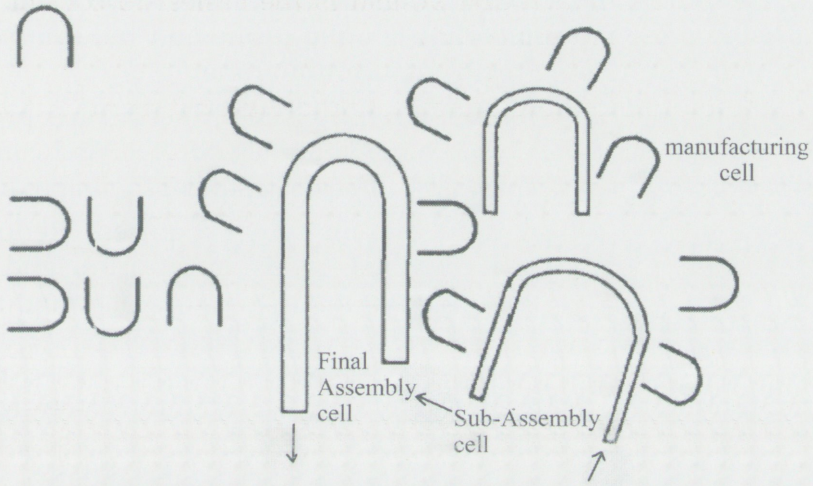


Figure 7: Main structure of cellular manufacturing System.

Advantages of CMS

The advantages derived from CMS in comparison with traditional manufacturing systems in terms of system performance have been discussed. These benefits have been established through simulation studies, analytical studies, surveys, and actual implementations.

They can be summarized as follows:

- Setup time is reduced: A manufacturing cell is designed to handle parts having similar shapes and relatively similar sizes. For this reason, many of the parts can employ the same or similar holding devices (fixtures). Generic fixtures for a part family can be developed so that time required for changing fixtures and tools is decreased.
- Lot sizes are reduced: Once setup times are greatly reduced in CM, small lots are possible and economical. Small lots also provide smooth production flow.
- Work-in-process (WIP) and finished goods inventories are reduced: With smaller lot sizes and reduced setup times, the amount of WIP can be reduced. The WIP can be reduced by 50% when the setup time is cut to half. In addition to the reduced setup times and WIP inventory, finished goods inventory is reduced. Instead of make-to-stock systems with parts either being run at long, fixed intervals or random intervals, the parts can be produced either JIT in small lots or at fixed, short intervals.
- Material handling costs and time are reduced: In CM, each part is processed completely within a single cell (wherever possible). Thus, part travel time and distance between cells is minimal.

- A reduction in flow time is obtained: Reduced materials handling time and reduced setup time greatly reduce flow time.
- Tool requirements are reduced: Parts produced in a cell are of similar shape, size, and composition. Thus, they often have similar tooling requirements.
- A reduction in space required: Reductions in WIP, finished goods inventories, and lot sizes lead to less space required. Throughput times are reduced: In a **job shop**, parts are transferred between machines in batches. However, in CM each part is transferred immediately to the next machine after it has been processed. Thus, the waiting time is reduced substantially.

Job shops are typically small manufacturing systems that handle job production, that is, custom/bespoke or semi-custom/bespoke manufacturing processes such as small to medium-size customer orders or batch jobs.

- Product quality is improved: Since parts travel from one station to another as single unit, they are completely processed in a small area. The feedback is immediate and the process can be stopped when things go wrong.
- Better overall control of operations: In a job shop, parts may have to travel through the entire shop. Scheduling and material control are complicated. In CM, the manufacturing facility is broken down into manufacturing cells and each part travels with a single cell, resulting in easier scheduling and control.

The basic differences between functional layout and cellular layout is depicted in Table 1

Table 1: Differences between functional layout and cellular layout

Dimension	Functional	Cellular
Number of moves between departments	many	few
Travel distances	longer	shorter
Travel paths	variable	fixed
Job waiting times	greater	shorter
Throughput time	higher	lower
Amount of work in process	higher	lower
Supervision difficulty	higher	lower
Scheduling complexity	higher	lower
Equipment utilization	lower	higher

Flexible Manufacturing System

A FMS integrates all major elements of manufacturing into a highly automated system. The flexibility of FMS is such that it can handle a variety of part configurations and produce them in any order. Figure 8 shows flexible manufacturing system. The basic elements of FMS are a) works station b) automated material handling and automated storage and retrieval systems c) control systems.

Because of major capital investment; efficient machine utilization is essential. Consequently proper scheduling and process planning are crucial, that are complex in nature. Because of the flexibility in FMS, no setup time is wasted in switching between manufacturing operations; the system is capable of different operations in different orders and on different machines.

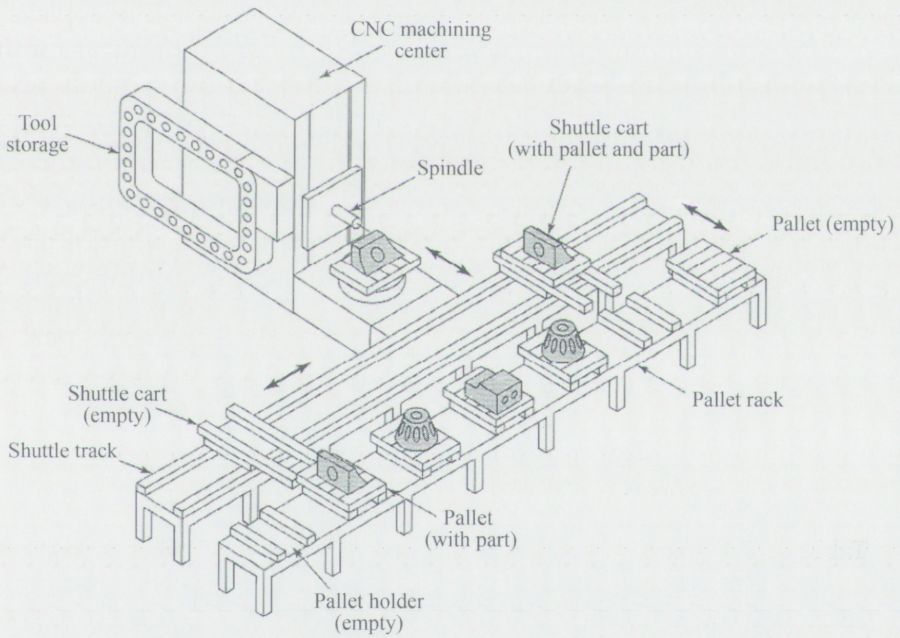


Figure 8: Flexible manufacturing system.

Advantages:

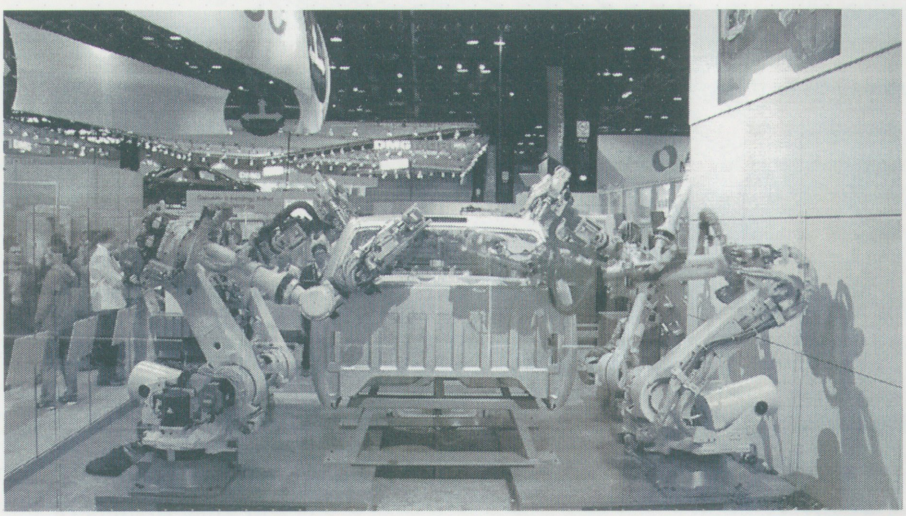
- Parts can be produced randomly in batch sizes, as small as one, and at lower cost.
- The lead times required for product changes are shorter
- Reduced WIP
- Labor and inventories are reduced
- Production is more reliable, because the system is self-correcting and so product quality is uniform.

- Increased machine utilization
- Fewer machines required
- Reduced factory floor space
- Greater responsiveness to change

1.2 MANUFACTURING PROCESSES

Manufacturing is generally a complex activity, involving people who have a broad range of disciplines and skills and a wide variety of machinery, equipment, and tooling with various levels of automation, including computers, robots, and material-handling equipment. Manufacturing activities must be responsive to several demands and trends:

- A product must fully meet design requirements and specifications.
- A product must be manufactured by the most economical methods in order to minimize costs.
- Quality must be built into the product at each stage, from design to assembly, rather than relying on quality testing after the product is made.
- In a highly competitive environment, production methods must be sufficiently flexible so as to respond to changing market demands, types of products, production rates, production quantities, and on-time delivery to the customer.



- New developments in materials, production methods, and computer integration of both technological and managerial activities in a manufacturing organization must constantly be evaluated with a view to their timely and economic implementation.

- Manufacturing activities must be viewed as a large system, each part of which is interrelated to others. Such systems can be modelled in order to study the effect of factors such as changes in market demands, product design, material and various other costs, and production methods on product quality and cost.
- The manufacturing organization must constantly strive for higher productivity, defined as the optimum use of all its resources: materials, machines, energy, capital, labor and technology. Output per employee per hour in all phases must be maximized.

1.2.1 Meaning

The complete knowledge of fundamental workshop technology and manufacturing processes is highly troublesome for anybody to claim competence over it. It deals with numerous aspects of workshops procedures also for providing the basic working awareness of the various engineering materials, tools, accessories, manufacturing processes, basic concepts of machine instruments, production criteria's, traits and uses of numerous testing instruments and calibrating or inspecting units for checking materials or products designed in various production shops in a commercial environment. It also explains and illustrates the use of several hand tools (calibrating, marking, forming and supporting gear etc.), tools, machinery and diverse methods of production that facilitate forming or shaping the existing raw materials into appropriate usable forms. Below are some of the manufacturing processes that are worth reading.

1.2.2 Types of Manufacturing Processes

Many processes are used to produce parts and shapes. There is usually more than one method of manufacturing a part from a given material. The broad categories of processing methods for materials are:

Metal Casting	Expendable mold and permanent mold.
Metal Forming & shaping	Rolling, forging, extrusion, drawing, sheet forming, powder metallurgy, and molding.
Plastics Molding & Forming	Blow Molding, CNC Machining, Centrifugal Casting, Continuous Strip Molding, Compression Molding, Profile Extrusion, Continuous Lamination, Injection Molding, Filament Winding, Thermoforming, Vacuum Forming, Pressure Bag Molding, Pressure Forming, Pulshaping, Twin Sheet Forming, Pultrusion, Liquid Resin Molding, Reaction Injection Molding (RIM), Rotational Molding, Resin transfer molding (RTM)

Rapid Prototyping	Stereolithography - SLA or SL, 3D Printing - 3DP, Selective Laser Sintering - SLS, Fused-Deposition Modeling - FDM, Solid-Ground Curing - SGC, Laminated Object Manufacturing - LOM, Multi-Jet Modeling - MJM, Direct Shell Production Casting - DSPC, Polyjet Technology, Laser Engineered Net Shaping - LENS
Joining	Welding, brazing, soldering, diffusion bonding, adhesive bonding, and mechanical joining.
Machining	Turning, boring, drilling, milling, planing, shaping, broaching, grinding, ultrasonic machining, chemical, electrical, and electrochemical machining and high-energy beam machining .
Finishing Operations	Honing, lapping, polishing, burnishing, deburring, surface treating, coating and plating processes.

Machining

Tools used for machining are immobile power-driven units used to form or shape solid materials, specifically metals. The forming is done by removing extra materials from a work-piece. Machine tools make up the foundation of advanced industry and are utilized either indirectly or directly in the manufacturing of tool parts.



They are categorized under three main categories:

- Traditional Chip-making tools.
- Presses.
- Modern machine tools.

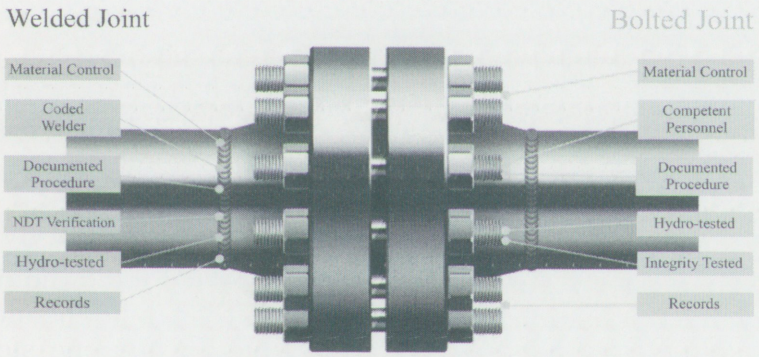
Traditional chip-making tools form the work-piece by trimming away the unwanted part accessible as chips. Presses implement a several shaping processes, which includes **shearing**, pressing, or elongating. Non-traditional machine tools

implement light, electric powered, chemical, and sonic power; superheated gas; and high-energy compound beams to form the exotic supplies and materials that have been created to meet the requirements of modern technology.

Shearing is a process which cuts stock without the formation of chips or the use of burning or melting.

Joining

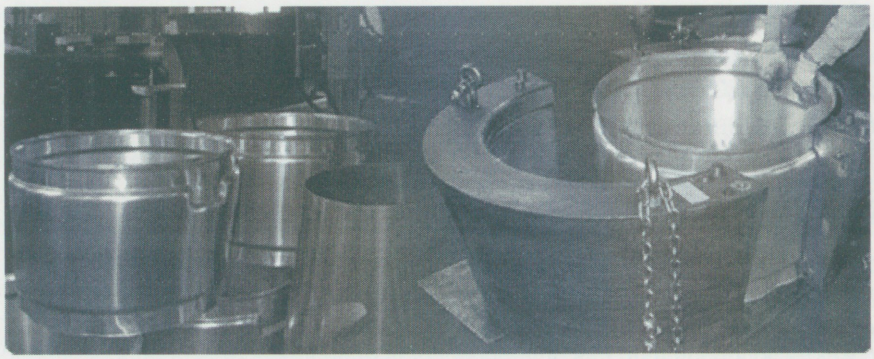
Every joining approach has particular design needs, while certain joint needs may propose a particular joining approach. Design for assembly, and fastener selection apply their own specifications. Bolting is a standard fastening method, for instance, but welding may cut down the weight of assemblies. Naturally, joints intended for the two approaches would differ tremendously.



However, all joint patterns must consider features such as load factors, assembly effectiveness, operating surroundings, overhaul and upkeep, and the materials chosen. Welding is generally a cost-effective approach to fabricate. It doesn't require overlapping materials, and so it removes excess weight brought on by other fastening methods. Fasteners don't have to be purchased and stored in stock. Welding also can minimize costs related to extra parts, for example angles mounted between parts.

Forming

Metal forming is the approach of creating the metallic components by deforming the metal but not by removing, cutting, shredding or breaking any part. Bending, spinning, drawing, and stretching are a few important metal forming process in manufacturing. The metal press such as die and punching tools are implemented for this manufacturing process.



Advantages

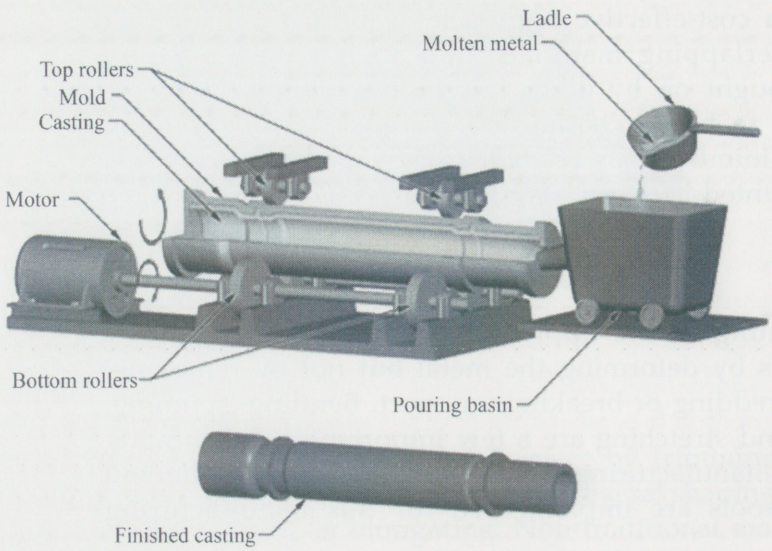
Same equipment can be utilized for manufacturing various components by simply changing the dies.

Disadvantages

High apparatus and tooling expenses. – Heat treatment must be applied afterwards.

Casting

Casting is a manufacturing process in which a solid is dissolved into a liquid, heated to appropriate temperature (sometimes processed to change its chemical formula), and is then added into a mold or cavity. Thus, in just one step, complex or simple shapes can be crafted from any kind of metal that has the capability to be melted. The end product can have practically any arrangement the designer wants.



Furthermore, the reluctance to working challenges can be improved, directional attributes can be managed, and a pleasing look can be developed.

1.3 CELLULAR MANUFACTURING

Cellular manufacturing is a manufacturing process that produces families of parts within a single line or cell of machines operated by machinists who work only within the line or cell. A cell is a small scale, clearly-defined production unit within a larger factory. This unit has complete responsibility for producing a family of like parts or a product. All necessary machines and manpower are contained within this cell, thus giving it a degree of operational autonomy. Each worker is expected to have mastered a full range of operating skills required by his or her cell. Therefore, systematic job rotation and training are necessary conditions for effective cell development. Complete worker training is needed to ensure that flexible worker assignments can be fulfilled.

Cellular manufacturing, which is actually an application of group technology, has been described as a stepping stone to achieving world class manufacturing status. The objective of cellular manufacturing is to design cells in such a way that some measure of performance is optimized. This measure of performance could be productivity, cycle time, or some other logistics measure. Measures seen in practice include pieces per man hour, unit cost, on-time delivery, lead time, defect rates, and percentage of parts made cell-complete.



This process involves placing a cluster of carefully selected sets of functionally dissimilar machines in close proximity to each other. The result is small, stand-alone manufacturing units dedicated to the production of a set or family of parts—or essentially, a miniature version of a plant layout.

While the machinery may be functionally dissimilar, the family of parts produced contains similar processing requirements or has geometric similarities. Thus, all parts basically follow the same routing with some minor variations (e.g., skipping an operation). The cells may have no conveyorized movement of parts between machines, or they may have a flow line connected by a conveyor that can provide automatic transfer.

Cellular manufacturing is a hybrid system that links the advantages of a job shop with the product layout of the continuous flow line. The cell design provides for quick and efficient flow, and the high productivity associated with assembly lines. However, it also provides the flexibility of the job shop, allowing both similar and diverse products to be added to the line without slowing the process. Figures 9 and 10 compares a cellular layout to that of the typical job shop (process layout).

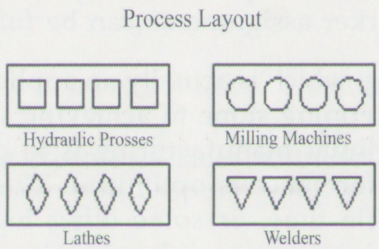


Figure 9: Process Layout.

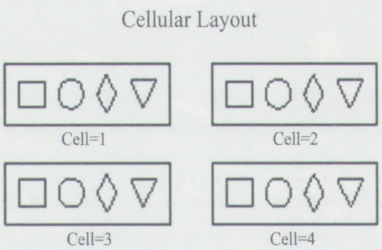


Figure 10: Cellular Layout.

1.3.1 Characteristics of Cellular Manufacturing

In cellular manufacturing, the cell can meet the entire production requirement. Furthermore, these cells are self-efficient and self-managed. Manufacturing cell has got the following characteristics:

- Each cell has a particular set of family of components or products.
- Each cell is provided with all the machines and other facilities, which it needs to, complete its own particular family.
- Production targets for each cell are given as a whole and not separately of different individuals in the cell, and these targets are set by management in consultation with cell foreman and operators.
- Within the cells, there is a pool of labor with a certain degree of flexibility and a team of workers control each cell solely. The **foreman** or cell leader is in direct change of each cell, working solely for that group.
- Each cell does its own inspection and work scheduling.

Foreman is a supervisor, often in a manual trade or industry.

1.3.2 Cellular Manufacturing Objectives

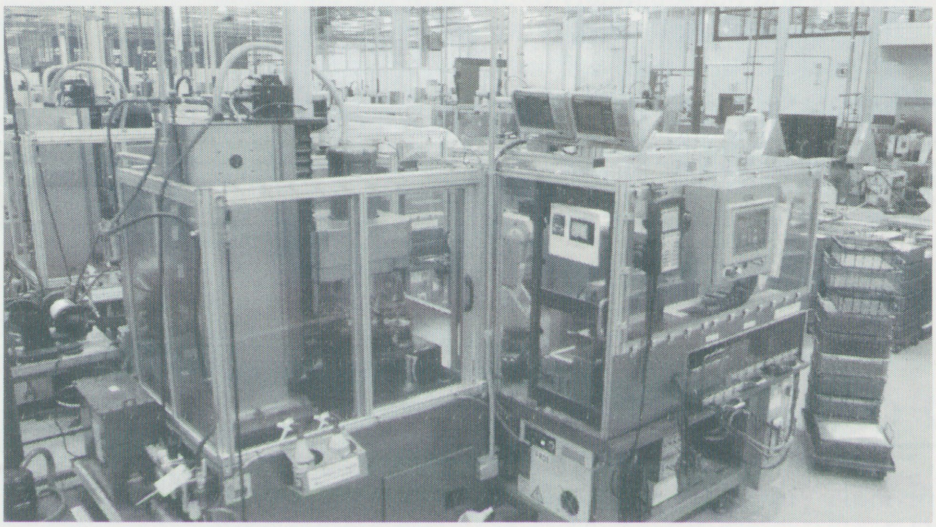
The primary objectives in implementing a cellular manufacturing are reduced. Therefore, some important objectives include:

- Reducing setup time by using part family tooling and sequencing.
- Reducing inventories.
- Reducing flow line (by reducing setup time and move times, wait time for movies and using smaller batch size).
- Increasing the labor and machine utilization.
- Maximization of output. In addition, the cell appears as an approach that in more tendencies to teamwork. Manufacturing cells are natural candidates for just in time implementation.

1.3.3 Benefits of Cellular Manufacturing

Many firms utilizing cellular manufacturing have reported near immediate improvements in performance, with only relatively minor adverse effects. Cited improvements which seem to have occurred fairly quickly include reductions in work-in-process, finished goods, lead time, late orders, scrap, direct labor, and workspace.

In particular, production and quality control is enhanced. By breaking the factory into small, homogeneous and cohesive productive units, production and quality control is made easier. Cells that are not performing according to volume and quality targets can be easily isolated, since the parts/products affected can be traced to a single cell. Also, because the productive units are small, the search for the root of problems is made easier.



Quality parameters and control procedures can be dovetailed to the particular requirements of the parts or workpieces specific to a certain cell. By focusing quality control activity on a particular production unit or part type, the cell can quickly master the necessary quality requirements. Control is always enhanced when productive units are kept at a minimum operating scale, which is what cellular manufacturing provides.

When production is structured using cellular manufacturing logic, flow systematization is possible. Grouping of parts or products into sets or families reveals which ones are more or less amenable to continuous, coupled flow. Parts that are standardized and common to many products will have very low changeover times, and thus, are quickly convertible to continuous, line-flow production. Products that are low-volume, high-variety and require longer set-up times can be managed so that they evolve toward a line flow.

Cells can be designed to exploit the characteristics peculiar to each part family so as to optimize the flow for each cell and for groups of cells as a whole. Flow systematization can be done one cell at a time so as to avoid large disruptions in operations. Then the cells that were easy to systemize can provide experience that can be exploited when the more difficult systematization projects occur later. Cells that have been changed to a line flow will invariably show superior performance in the areas of quality, throughput time, and cost, which can lead to eventual plant wide benefit.

Work flow that is adapted to the unique requirements of each product or part allows the plant to produce high-volume and high-variety products simultaneously. Since the cell structure integrates both worker and product versatility into a single unit, it has the potential to attain maximum system flexibility while maintaining factory focus. Cells can be designed around single products, product groups, unique parts, part families, or whatever unique market requirements are identified. For the same part, there may be one high-volume, standardized design and one low-volume customized design. Cells can be built specifically for any of these with a focus on the individual marketing or production requirement called for by the individual product or part.

Systematic job rotation and training in multiple skills also make possible quick, flexible work assignments that can be used to alleviate bottlenecks occurring within the cell. Since normal cell operation requires the workers to master all the skills internal to the cell, little or no additional training should be needed when workers have to be redeployed in response to volume or sales mix changes. When it is routine for workers to learn new skills, they can be easily transferred to another job within the cell or possibly even to an entirely different production unit. Without this worker flexibility and versatility, there can be no real production system flexibility.

1.3.4 Limitations

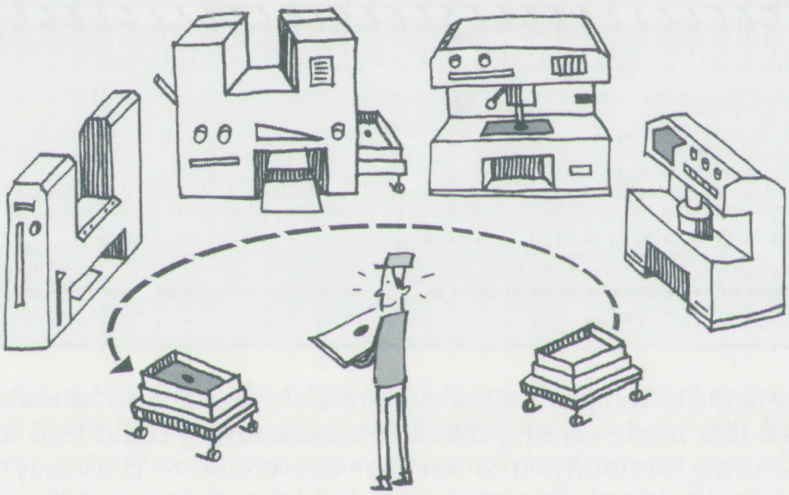
While its benefits have been well documented, it should also be noted that some have argued that implementing cellular manufacturing could lead to a decrease in manufacturing flexibility. It is felt that conversion to cells may cause some loss in routing flexibility, which could then impact the viability of cell use. Obtaining balance among cells is also more difficult than for flow or job shops. Flow shops have relatively fixed capacity, and job shops can draw from a pool of skilled labor so balance isn't that much of a problem. By contrast, with cells, if demand diminishes greatly, it may be necessary to break up that cell and redistribute the equipment or reform the families.

Also, some researchers have warned that the benefits of cellular manufacturing could deteriorate over time due to ongoing changes in the production environment. Finally, it must be noted that conversion to cellular manufacturing can involve the costly realignment of equipment. The burden lies with the manager to determine if the costs of switching from a process layout to a cellular one outweigh the costs of the inefficiencies and inflexibility of conventional plant layouts.

1.3.5 The Implementation Process

A wide variety of methods for the implementation of cellular manufacturing have been proposed. These range from complex computer and mathematical models to straightforward applications, such as production flow analysis. A pattern for implementation is now presented.

The first step in implementing cellular manufacturing is to break down the various items produced by the company into a number of part sets or families. The grouping process (group technology) involves identifying items with similarities in design characteristics or manufacturing characteristics, and grouping them into part families. Design characteristics include size, shape, and function; manufacturing characteristics or process characteristics are based on the type and sequence of operations required. In many cases, though not always, the two kinds of characteristics are correlated. Therefore design families may be distinctly different from processing families.



Once identified, similar items can be classified into families. Then a system is developed that facilitates retrieval from a design and manufacturing database. For example, the system can be used to determine if an identical or similar part exists before a completely new part is designed. If a similar part is found, it may be that a simple modification would produce satisfactory results without the expense of new part design. Similarly, planning the manufacturing of a new part after matching it with an existing part family can eliminate new and costly processing requirements.

This grouping of part or product families requires a systematic analysis that often proves to be a major undertaking. Usually, there is a considerable amount of data to analyze, and this in turn can be quite time-consuming and costly. Three primary methods exist for accomplishing the grouping process: visual inspection, examination of design and production data, and production flow analysis. **Visual inspection** is the least accurate of the three but nonetheless the simplest and the least costly. The most commonly used method of analysis is the examination of design and production data. This method is more accurate but is also more time-consuming. Production flow analysis examines operation sequences and

machine routing to uncover similarities (therefore, it has a manufacturing perspective rather than a design perspective). However, unless the operation sequencing and routings are verified, this method could be far from optimal.

The resulting number of families determines the number of cells required, as well as what machines are required within each cell. The cell usually includes all the processing operations needed to complete a part or subassembly. However, it is possible for a product to go from raw materials to packaging and be ready for shipment by the time it reaches the end of the cell.

Visual Inspection, used in maintenance of facilities, mean inspection of equipment and structures using either or all of raw human senses such as vision, hearing, touch and smell and/or any non-specialized inspection equipment.

The families will also help determine where within the cell each machine will be located for the most efficient flow, and how many employees are needed within each cell. After the product families are determined, the machines needed for the production process of a specific family are organized into cells according to processing requirements (e.g., the order of processing). Frequently, machines are grouped in an efficient U-shaped configuration. Since each machine operates on its own for much of the cycle, few workers may be needed, and even then only for a limited number of steps.

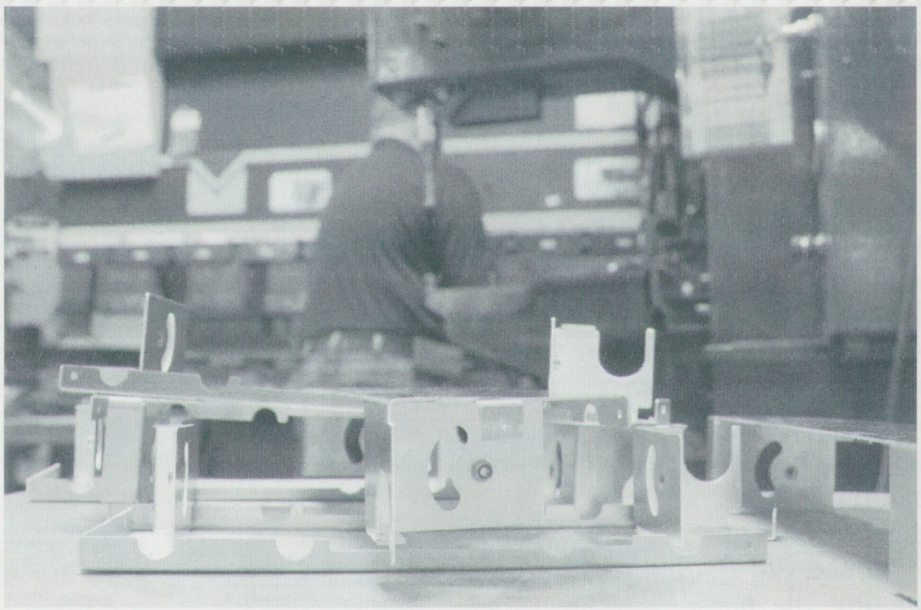
The optimal layout is one that minimizes the distance between cells, or the distance to the next production point. The resulting reduction in time and handling ultimately provides a reduction in processing costs. Some firms utilize "linked-cell manufacturing," which is the concept of arranging the manufacturing cells near the assembly cells. Again, this decreases travel distances while reducing materials handling. Hopefully, the floor layout will also provide for the easy flow of a product to shipping, if shipping is located close to the cells in a streamlined flow.

Some plants in advanced stages of cellular manufacturing utilize what is known as a "mini-plant." The cell not only does the manufacturing, but also has its own support services, including its own industrial engineer, quality manager, accountant, and marketing representative and/or salesperson. Only research and development and human resource management are not dedicated to the mini-plant.

An entire facility can be broken down into a number of mini-plants, each of which operates as an independent profit center.

1.3.6 The Impact of Cellular Manufacturing on Workers

While technology and processes represent the "hard side" of cells, people represent the "soft side." They state that the soft side factors are far more difficult to change than are the hard side factors. Most implementing firms spend most of their time struggling with soft issues. Cellular manufacturing calls for radical changes in the way industrial work is designed, structured, planned, controlled, and supervised. It makes worker self-management a reality, so management must be convinced that the workers can master all the required aspects of the work.



The decision to implement cellular manufacturing requires a deep commitment to excellence and a desire to permanently change the way factories are viewed and managed. Cellular manufacturing affects workers in a number of ways. Among the factors now discussed are issues of self-management, motivation, employee input, supervision, and group cohesiveness.

Self-Management

Cell workers are encouraged to think creatively about production problems and are expected to arrive at pragmatic solutions to them. While they are free to seek advice from plant management and staff, the identified problems and subsequent analysis, and usually the solutions, are entirely their own. Workers have the authority and are encouraged to implement and follow up on action plans to improve their work. Some managers ask cells to set improvement targets for themselves and measure their performance in comparison to these

targets. In addition, workers are given the freedom to plan, coordinate, and control their work within their cell as long as they meet company standards of quality, volume, time, and cost.

Motivation

Behavioral psychology proposes that challenging work assignments keep employees motivated, satisfied, and productive. Flexible work assignments within the cells ensure that employees are constantly learning new tasks and constantly being challenged. **Job rotation** within the cell introduces variety in work patterns, thereby breaking the monotony (which has been known to cause absenteeism and problems in quality and productivity). Industrial work is productively accomplished in a group work setting. Cellular manufacturing can energize the group, attacking the lethargy found in many industrial situations.

Job rotation is a technique used by some employers to rotate their employees' assigned jobs throughout their employment. Employers practice this technique for a number of reasons.

Employee Input

With the cell work group energized and motivated, the employees are more likely to actively and continually bring their mental capabilities to bear on job-related problems. Cell workers are the closest ones to the production process, so practical ideas are likely to instigate other ideas, which could then give rise to a continuous, almost self-sustaining chain reaction of improvement. As the workers see their own creative output being implemented, they begin to develop self-esteem and a stronger desire to succeed. They even begin to challenge each other to improve on their prior accomplishments.

The drive toward excellence is fueled by the human need to achieve until the desire to excel and continuously improve becomes part of the factory culture. Then as workers learn by doing more, they become more proficient at generating ideas which, perpetuates the cycle of improvement. Cellular manufacturing can be the structural catalyst that starts, contains, and sustains the improvement process.

Supervision

The intense use of manufacturing cells tends to flatten the factory management structure and reduce overhead costs. When work group autonomy, worker versatility, and small

group improvement activities converge, the need for supervision is drastically reduced, if not eliminated all together. Cell manufacturing perpetuates the idea that the work group should supervise itself. A workforce that is motivated, trained, and assigned specific clear responsibility for a product or part, coupled with simplified production planning and control, does not need to be minutely controlled or supervised in order to do a good job.

Group Cohesiveness

The creation of small-scale productions dedicated to production of a few similar parts increases work group cohesiveness. Since each cell has few employees, typically less than fourteen, extensive interpersonal contact is unavoidable. The workers are now part of a single, identifiable unit with operating autonomy and responsibility for a specific product, linked by the common purpose of continually improving the productive unit for which they are responsible. The cell structure keeps problems at a level where they are manageable and gives employees the opportunity to exercise their creative potential in a pragmatic way. When problems calling for technical expertise beyond that of the workers, managers and production staff can be called on to provide assistance. Cell manufacturing builds a cohesive subculture within the wider social environment of the plant.

The use of flexible work assignments contributes even more to the group's cohesiveness and loyalty. Employees who regularly perform the work also done by coworkers are more likely to demonstrate empathy and support when dealing with each other on the job. If each worker has experienced each job firsthand, they are more able to offer encouragement and advice on how the work can be improved and each worker is more receptive to the input of his or her coworkers. Each worker can view and understand completely the task, responsibilities, and mission that top management has dedicated to the cell. The cross-fertilization process that emerges can generate some truly creative ideas for process improvement. As the expression goes, "as iron sharpens iron, so shall one man sharpen another."

Finally, work group cohesiveness, reinforced by the cell structure, facilitates total people management. Due to its small scale and mission focus, the cell can be easily mobilized. Top management is too far removed, spatially and socially, from the workers to be able to interact with them extensively enough to significantly control the socialization process. Management can shape corporate values and create a nurturing social environment, but it cannot instill these values into the minds of the lower level employees. Hence, corporate values are better communicated and instilled into daily work habits by small group processes.

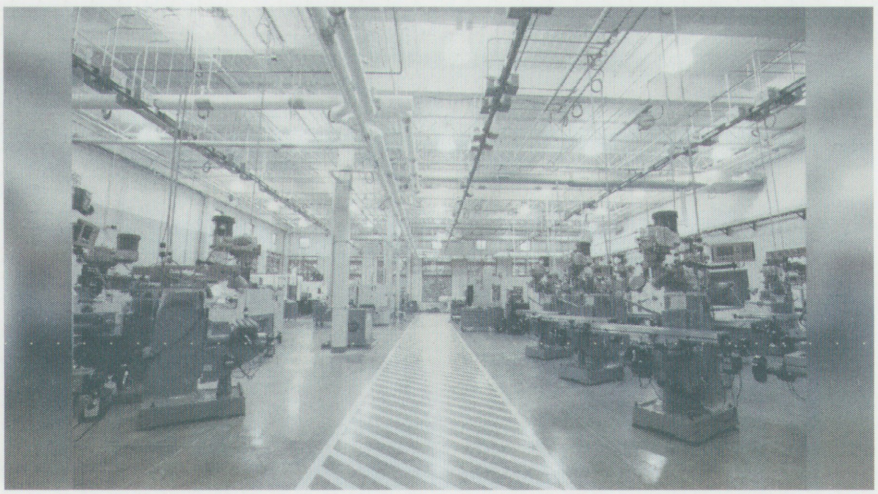
The cell is better able to exercise social control over deviant workers since it can directly and immediately manipulate social rewards and punishment. Any worker who fails to conform may find his deviant behavior quickly detected and reacted to by the withdrawal of the social support of the cell. Deviant behavior

that is hidden from management for long periods of time is very visible to the small group and can be dealt with quickly.

Conversely, high-performing group members are also quickly visible but are rewarded with esteem and respect from the other cell workers. Consequently, management can work through the cell to instill the corporation's values, attitudes, and philosophies. Once these are internalized by the group's key members, the group itself will take over the socialization process of indoctrinating these values into the mindset of each worker.

1.4 ADVANCED MANUFACTURING TECHNOLOGY

Advanced Manufacturing technology (AMT) is "a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies."



Advanced Manufacturing is not limited to emerging technologies; rather, it is composed of efficient, productive, highly integrated, tightly controlled processes across a spectrum of globally competitive U.S. manufacturers and suppliers. For advanced manufacturing to accelerate and thrive in the United States, it will require the active participation of communities, educators, workers, and businesses, as well as Federal, State, and local governments.

1.4.1 Definitions of AMT

AMT is as 'a group of integrated hardware-based and software-based technologies, which if properly implemented, monitored, and evaluated, will lead to improving the efficiency and effectiveness of the firm in manufacturing a product or providing a service.'

Advanced Manufacturing technology (AMT) represents a wide variety of mainly computer-based systems, which provide adopting firms with the potential to improve manufacturing operations greatly. It is generally expected that the resultant improvement in operational performance will enhance the firm's ability to reap the underlying marketing, strategic and business benefits for which the systems were adopted. Another definition is AMT refers to a family of technologies that include computer-aided design (CAD) and engineering systems, materials resource planning systems, automated materials handling systems, **robotics**, computer controlled machines, flexible manufacturing systems, electronic data interchange and computer-integrated manufacturing systems.

Robotics is an interdisciplinary branch of engineering and science that includes mechanical engineering, electronics engineering, information engineering, computer science, and others.

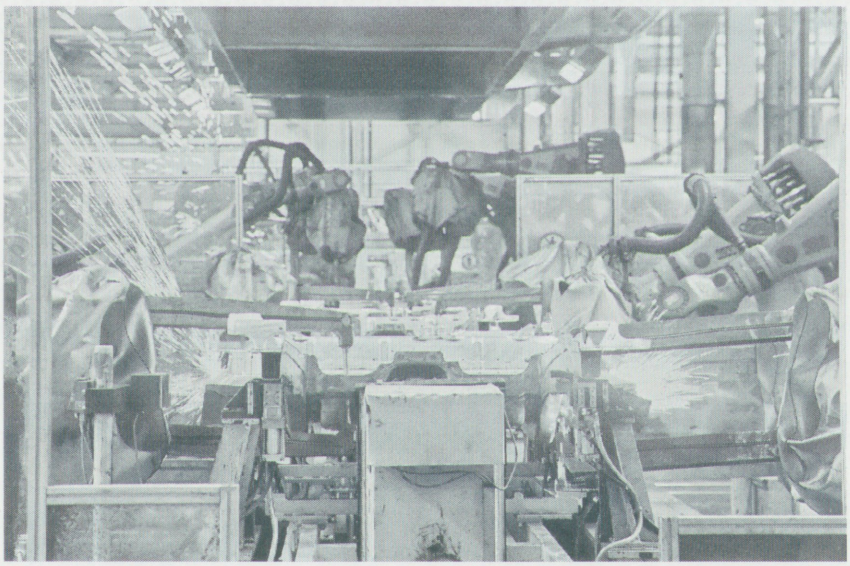
AMT represents a wide variety of modern computer-based systems devoted to the improvement of manufacturing operations and thereby enhancement of firm competitiveness.

AMT has been described as programmable machinery or a system of programmed machines that can produce a variety of products or parts with virtually no time lost for changes. The process of introducing AMT is generally evolutionary but in some settings the pace is quickening. As innovations spill over into practical application there is a simultaneous change in the mix and range of elements generally labeled as AMT. The machines, computer control and linkages, as well as the human operator involvement, appear to be on a windy route from islands of technology towards some far wider degree of computer integration, referred to as computer integrated manufacturing (CIM).

AMT represents a wide variety of modern computer-based or numerical control based systems devoted to the improvement of manufacturing operations. AMT is broadly defined as 'an automated production system of people, machines and tools for the planning and control of the production process, including the procurement of raw materials, parts and components and the shipment and service of finished products. The properties of AMT

overcome the limitations of conventional technology in enabling small firms to develop economies of scope based on low volume and low cost production. Specifically, AMT facilitates customization and reduces lead times through the productions of variety, frequent design changeovers, and rapid processing of design, assembly, materials handling and market information.

In general, AMT typically involves (a) a computer-aided design system (CAD) that develops designs, displays them and stores them for future reference: (b) a computer-aided manufacturing system (CAM) that translates CAD information for production and further controls machine tools, material flow, and testing; (c) an automotive storage and retrieval system for delivery or pack up of parts between machines and storage: and (d) a supervisory computer that integrates all of the above (CIM).



AMTs refer to a family of technologies that include computer-aided design (CAD) and engineering systems, materials resource planning systems, automated materials handling systems, robotics, computer-controlled machines, flexible manufacturing systems, electronic data interchange and computer-integrated manufacturing systems.

Advanced manufacturing encompasses all aspects of the value chain from concept to end-of-life considerations, and relies on information communication technology (ICT) to integrate the manufacturing and business activities into a seamless efficient operation.

The technologies involved in advanced manufacturing can be divided into three main groupings: efficient production, intelligent production and effective organization.

- Efficient production involves design, simulation, physical and computer modelling, advanced production technologies, and control techniques. The emphasis is on simultaneous rather than sequential engineering.

Relevant production technologies include rapid prototyping, near net shape manufacture, and precision casting, machining and joining techniques.

- Intelligent production involves the use of ICT in manufacturing and related logistics systems. As well as production orientated intelligent machines, cells and production lines, the philosophy involves implementing systems for the extended life and optimal use of production facilities through efficient monitoring, maintenance and repair strategies.
- Effective organization involves the efficient co-ordination and exploitation of manufacturing resources. This encompasses both physical resources and knowledge. Relevant topics include virtual tendering and enterprises, shared facilities and resources, novel organizations, incubation units, knowledge management and trading, and electronic commerce. Emphasis in this area is on the use of technology to enhance the involvement and capability of SMEs as well as large organizations.

1.4.2 History of AMT

Historically, manufacturing organizations made improvements in their productions processes primarily through investments in physical capital. Advices in mechanization, for example, enabled manufacturing firms to enhance efficiency in production while actually lowering the required skills and capabilities of employees. As a result, many firms actually took the tactic of deskilling their workforces to reduce labor expenses, thereby diminishing the necessary level of investments in human capital with the hope of increasing profits.

In contrast to this perspective, advocates of the cotemporary manufacturing paradigm argue for a dramatically different orientation toward employees. These post-industrial theorists propose that compared to the deskilling tactics of traditional manufacturing, more advanced systems require a set of complementary practices for upskilling the workforce. Indeed, some studies have suggested that modern manufacturing systems demand more enhanced technical, conceptual, analytic and problem solving skills than typically were required in traditional manufacturing environments.

In the manufacturing sector, the new technological advances have revolved around machine tools and equipment. Advances in automation of machine tools began about 30 years ago with the first generation of programmable machine tools-the numerical controlled machine tools (NC). The NC did not become widely used until the 1970s. The second generation, computerized numerical control machine (CNC), was introduced in the late 1970s. These new machine tools have the capacity to produce the high volume standardized parts and products necessary for competitive success in undifferentiated markets.

The first AMT technologies were introduced in the 1950s, but it was not until the 1970s that the adoption of AMTs took off and the 1980s that their use became

widespread. Today, nearly all currently produced manufacturing equipment incorporates some electronics element and thus fits the definitions for AMTs.

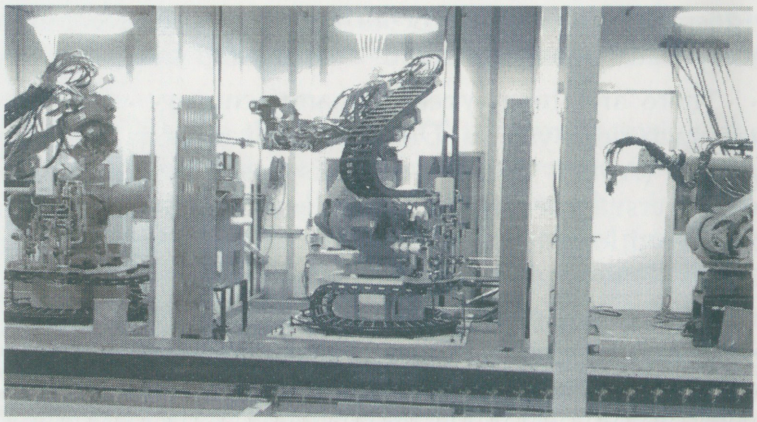
There are three types of manufacturing systems: crafts shops; dedicated manufacturing systems (DMS); and advanced manufacturing technology –based systems (AMT). Their research is based on Teece conceptualization of long linked versus intensive technologies. Using their classification scheme, DMS are considered long-linked industrial systems employing hard automation whereas AMT are post-industrial enterprises employing flexible resources.

There are many distinctions between craft shops and DMS. While craft shops employ skilled artisans who use various hand tools, DMS deploy special-purpose machinery operated by unskilled manual laborers. In a craft shop, workers are organized into task-oriented work groups. Work is functionally specialized and used usually a single task is assigned to a worker in a DMS. In a craft shop, performance measures are based on customs and other craftsmen evaluate the work. DMS are controlled through a hierarchical structure. In addition to the above characteristics, DMS are product-oriented, concerned with efficiency and productivity. An information system controls task execution and co-ordinates sequential activities within a DMS.

1.4.3 Types of AMT

Advanced manufacturing Technologies involve the application of computers to various facets of the production process. The manufacturing technologies are grouped into six functional categories, each capturing a different aspect of the process-fabrication and assembly, automated materials handling systems, design and engineering, inspection and communications, manufacturing information systems, or integration and control.

Advanced manufacturing technologies (AMTs) involve new manufacturing techniques and machines combined with the application of information technology, microelectronics and new organizational practices within the manufacturing process. These hardware technologies have found wide acceptance in discrete manufacturing and in resource and processing sectors. Computer numeric controls have been applied to systems for machining, forming, cutting and molding. The accuracy, speed and control of robots have improved significantly and, as a result, they are used extensively in welding, painting, material handling and an enormous number of unique assembly applications. Vision systems provide, in real time, monitoring for precision machining and high-speed printing and remote handling of mining equipment used thousands of Metrecs underground. Computer-aided design (CAD) and rapid prototyping have substantially shortened the development time for new products. Computer integrated manufacturing (CIM) is applied in machine shops for tool building, the production of engines and body assemblies for passenger cars, the manufacture of airplane landing gear and the production of hypodermic needles for the medical devices sector.



Complementary to the hardware technologies of AMTs is a wide range of 'soft' manufacturing process technologies. Just-in-time (JIT) manufacturing, **total quality management** (TQM) and supply chain management are but a few of the many 'soft' AMTs adopted by manufacturers and processors globally.

Total quality management consists of organization-wide efforts to "install and make permanent a climate where employees continuously improve their ability to provide on demand products and services that customers will find of particular value."

The nature of competition in manufacturing has changed. High-quality and highly customized goods are demanded. There is a premium for being the first to market with a product. This has created a demand for 'hard' and 'soft' technologies that help shorten design and production cycles.

Manufacturing practices and processes have come under increased pressure from global competition. Demands for improved customer service, breadth of product line, improved quality, quick response and a much shortened time-to-market for new product introduction cannot be ignored by firms.

Manufacturing has been influenced by trade liberalization, global competition, market fragmentation, technological innovation and the demands of more sophisticated consumers. In response to these pressures, manufacturers are incorporating more flexibility and technology in their production practices. These features have become a trademark of world-class corporations. AMTs are a key enabler for firms attempting to meet world-class performance targets.

Table 2: Type of Advanced Manufacturing Technologies

Functional Group	Technology
Processing, Fabrication and Assembly	Flexible manufacturing cells or systems (FMC/FMS)
	Programmable logic control machines or processes (CNC and NC)
	Lasers used in materials processing
	Robots with sensing capabilities
	Robots without sensing capabilities
	Rapid Prototyping systems
	High speed machining
	Near net shape technologies
Automated Material Handling	Part identification for manufacturing automation (bar coding)
	Automated storage and Retrieval system (AS/RS)
	Automated Guided Vehicle Systems (AGVS)
Design and Engineering	Computer-aided design and engineering (CAD/CAE)
	Computer-Aided Design/Manufacturing CAD/CAM
	Modeling or simulation Technologies
	Electronic exchange of CAD files
	Digital representation of CAD output
Inspection and Communications	Automated Vision-based systems used for inspection/ testing of inputs/or final products
	Other automated sensor-based systems used for inspection/testing of inputs
Manufacturing Information Systems	Manufacturing Resource Planning (MRP)
	Manufacturing Resource Planning (MRP11)
Integration and Control	Supervisory Control & Data Acquisition (SCADA)
	Artificial Intelligence/Expert Systems (AI)
	Computer Integrated Manufacturing (CIM)

The functional groups and their constituent technologies, along with a brief description of each, are provided in Table 2. AMT is a generic term for a group of manufacturing technologies, which combine both scope and scale

capabilities in a manufacturing environment. Manufacturing strategy has become more sophisticated. As a result, AMT can play a crucial role in making it possible for firms to compete on 'traditionally' contradictory competitive priorities simultaneously.

Two subgroups of technologies within AMT are the traditional hardware technology consisting of systems, devices and stations (SDS): and a second group of technologies, often in software form, which perform integrative and managerial functions-integrative and managerial systems (IMS).

Typical examples of systems, devices, and stations (SDS) include automated identification station, automated inspection stations, automated material handling devices, computer aided design workstations, computerized numerical control machine tools, numerical control machine tools, programmable production controllers, robots, shop-floor control systems.

Examples of integrated and managerial systems (IMS) include computer aided manufacturing, computer-aided engineering, statistical process control, production planning/inventory management software, engineering data management, computer aided process planning, local area networks, group technology.

Both SDS and IMS technologies can be used individually or in combination with other technologies to achieve desired economies of scale and scope. When taken together SDC and IMS constitute AMT.

AMT represents a wide variety of mainly computer-based systems that provide adopting firms with the potential to improve manufacturing operations greatly. It is generally expected that the resultant improvement in operational performance will enhance the firm's ability to reap the underlying marketing, strategic and business benefits for which the systems were adopted. Some of the benefits attributed to these technologies are improving market share, gaining earlier entrance to market share, responding more quickly to changing customer needs and the quality to offer products with improved quality and reliability.

Computer-aided design is the use of computer systems to aid in the creation, modification, analysis, or optimization of a design.

These technologies have been classified as stand-alone systems, intermediate systems and integrated systems. Technologies such as **computer aided design** (CAD) and computer numerical control machines (CNC) are typically categorized as standalone systems. Automated material

handling systems (AMHS) and automated inspection and testing systems (AITS) are classified as intermediated systems. Integrated technologies can be categorized as either integrated process technologies (e.g. computer manufacturing systems (CIM) and flexible manufacturing systems (FMS) or integrated information/logistic technologies (e.g. just-in-time production (JIT) and manufacturing resources planning (MRPII). The general trend in the AMT research has been to examine technology adoption and any resultant change in firm performance on the basis of the implementation of individual technologies or in terms of implementation of specific technology classifications such as those presented above.

AMTs refer to a family of technologies that include computer-aided design (CAD) and engineering systems, materials resource planning systems, automated materials handling systems, robotics, computer controlled machines, flexible manufacturing systems, electronic data interchange and computer-integrated manufacturing systems. Numerous studies have emphasized the potential strategic benefits of flexibility, responsiveness, improved quality and improved productivity through purposeful investment in AMTs. Such benefits are increasingly important in the current global manufacturing environment, which has been described as hyper competitive, high-velocity and characterized by fragmenting markets, shorter product life cycles, and increasing consumer demand for customization. Thus, AMTs have, and will continue to have, a key strategic role in improving competitiveness by utilizing the manufacturing function more effectively in overall business strategy.

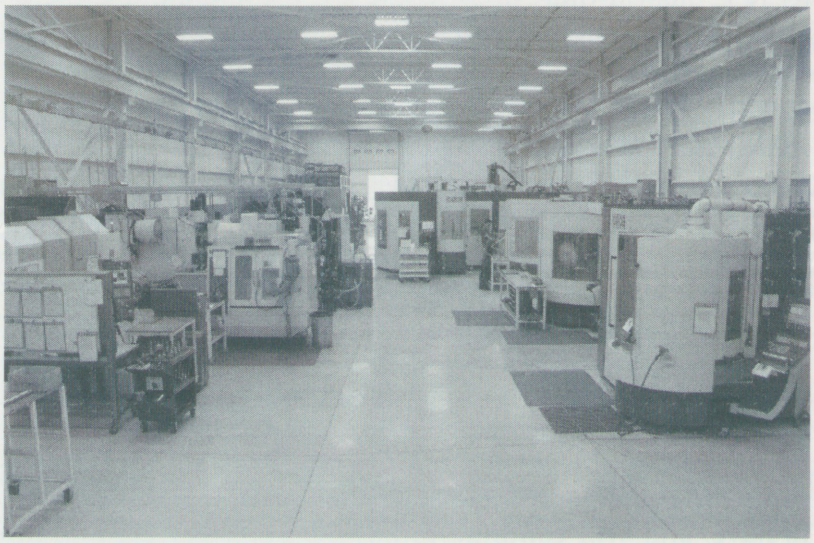
AMT includes a group of integrated hardware-based and software-based technologies which, when properly implemented, monitored and evaluated, can improve the operating efficiency and effectiveness of the adopting firms. They encompass a broad range of computer-based technological innovations, which include numerical control (NC) machine tools, cellular manufacturing, machining (CAD/CAM) systems, and automated storage and retrieval systems (AS/RS). These islands of automation are integrated manufacturing (CIM). AMT has the potential to improve operating performance dramatically and create vital business opportunities for companies, which are capable of successfully implementing and managing them.

AMT can also provide distinctive competitive advantages in cost and process leadership. Events of the last decade, such as the US productivity problems, Japanese manufacturing success stories and the competitive global economy, have moved manufacturing strategy and process technology issues from the bottom to the top of the firm's priority list.

1.4.4 Benefits of Advanced Manufacturing Technology

The section identifies a variety of technical and strategic factors that include AMT adoption: reduced product development time, labor costs savings, material costs savings, a need to remain competitive, tax incentives, financing availability, a need for product change flexibility, environmental, safety or health concerns,

increased profitability or plant performance and customer requirements. These factors have a broad, strategic impact on the firm and affect virtually every major element of a firm's operating environment.



AMT represents a wide variety of modern computer-based systems devoted to the improvement of manufacturing operations and thereby enhancement of the firm competitiveness. AMT, in its varying forms, has been credited with the potential to bestow, among other things, earlier entrance to market, faster responses to changing customer needs, and higher quality products with improved consistency and reliability, however, results of several empirical studies indicate that, while most firms achieve some benefits, many of them are not fully exploiting their AMTs touted capabilities.

Since the technical capabilities of AMT are well proven, failure to achieve the potential benefits has been attributed to infrastructure problems such as inadequate organizational planning and preparation for the adoption of the AMT or defines a life-cycle implementation process which consists of the following three phases: pre-installation (planning and justification), installation and commissioning (monitoring and evaluation). Implementation is typically viewed as a combination of the actions in the installation and commissioning and post-commissioning phases.

1.4.5 Disadvantages of AMT

Companies have identified some of the issues and problems arising from implementing an AMT project and discuss the following issues, namely scope of AMT projects, simulation modeling, cell design, cell operational logistics, and labor issues in AMT.

Traditionally there has been little awareness of the need to link technology issues with human resource management issues. Technologies have been deployed to improve firm performance independent of programs and practices that involve workers in decision-making. Firms implement new technologies to improve their competitiveness. Reductions in labor costs are made possible by new automated machines and equipment which take over decisions about production and perform at accelerated rates operations formerly performed by humans. Faster performing technologies permit increased production using the same fewer, or less skilled employees.

The impediments that were investigated by Baldwin can be divided into five groups. The first includes a set of general cost-related problems associated with AMT adoption, including the cost of capital, the cost of technology acquisition, the cost of related equipment acquisition, the cost of related software development, and increased maintenance expenses.

Four other areas were also identified-impediments that arise from government policy (Institutional-related problems), from labor market imperfections, from internal organization problems and from imperfections in the market for information. Each of these also increases the costs of adopting AMT-but the causes are somewhat more narrowly focused than the general cost-related items that are included in the first category.

Labor-related problems include difficulties that arise because new technologies and innovation generally need higher skill levels. In the face of these needs, a firm may encounter impediments to adoption if there is a shortage of skills available on the market, or if it faces training difficulties in overcoming deficiencies, or if its labor contracts act to constrain its ability to substitute labor across tasks.

Organizational problems are those associated with difficulties in implementing the types of internal change in a firm that are required for the adoption of AMTs. The first of these is the difficulty in introducing important changes to the organization. For example, the introduction of computer-aided design may require new structure that link engineering development with the production department so that the advantages of concurrent engineering practices can be fully exploited. Other organizational problems stem from a poor attitude of senior management towards new technologies, or worker resistance.

Institution-related problems are those associated with tax regimes (both the R&D tax credit and capital cost allowances) and with government regulations and standards. Information-related problems arise if markets for knowledge are imperfect.

They include lack of scientific and technical information, technological services, and technical supports from vendors. Table 3 reports the percentage of plant managers who reported that these problems impeded the adoption of AMT.

Table 3: Problems Impeded the Adoption of AMT

Types of Impediment	Percentage
Cost-related	79.1
Institution-related	15.5
Labor-related	37.2
Organization-related	34.1
Information-related	24.9

SUMMARY

- Manufacturing covers wide areas of inputs, processes and products. It reaches out to the demands in production for thousands of different varieties and types of goods.
- Manufacturing processes and systems used in design and production are undergoing dramatic changes in response to new customer needs and emerging technologies.
- Manufacturing refers to a large-scale production of goods that converts raw materials, parts and components into finished merchandise using manual labor and/or machines.
- The understanding of the manufacturing system as a whole helps in identifying, which process parameters and functions of the organizations are important; this helps to make decisions about the economical ways of producing the end products.
- The manufacturing systems differ in structure or physical arrangement.
- Manufacturing is generally a complex activity, involving people who have a broad range of disciplines and skills and a wide variety of machinery, equipment, and tooling with various levels of automation, including computers, robots, and material-handling equipment.
- Many processes are used to produce parts and shapes. There is usually more than one method of manufacturing a part from a given material.
- Cellular manufacturing is a manufacturing process that produces families of parts within a single line or cell of machines operated by machinists who work only within the line or cell.
- In cellular manufacturing, the cell can meet the entire production requirement. Furthermore, these cells are self-efficient and self-managed.
- Many firms utilizing cellular manufacturing have reported near immediate improvements in performance, with only relatively minor adverse effects. Cited improvements which seem to have occurred fairly quickly include reductions in work-in-process, finished goods, lead time, late orders, scrap, direct labor, and workspace.
- Advanced Manufacturing technology (AMT) is "a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies."
- Advanced manufacturing Technologies involve the application of computers to various facets of the production process. The manufacturing technologies are grouped into six functional categories, each capturing

a different aspect of the process-fabrication and assembly, automated materials handling systems, design and engineering, inspection and communications, manufacturing information systems, or integration and control.

REFERENCES

1. Al-Mubarak, Fahad and Basheer M. Khumawala. "Focused Cellular Manufacturing: An Alternative to Cellular Manufacturing." *International Journal of Operations and Production Management* 23, no. 3 (2003): 277–299.
2. Clinton, William J., and Albert Gore, Jr. 1993. *Technology for America's Economic Growth, a New Direction to Build Economic Strength*, February 22.
3. Computer Science and Telecommunications Board (CSTB) and Manufacturing Studies Board (MSB), National Research Council. 1993. *Information Technology and Manufacturing: A Preliminary Report on Research Needs*. National Academy Press, Washington, D.C.
4. Computer Science and Telecommunications Board (CSTB), National Research Council. 1992. *Computing the Future: A Broader Agenda for Computer Science and Engineering*. National Academy Press, Washington, D.C.
5. Computer Science and Telecommunications Board (CSTB), National Research Council. 1993. *National Collaboratories: Applying Information Technology for Scientific Research*. National Academy Press, Washington, D.C.
6. Computer Science and Telecommunications Board (CSTB), National Research Council. 1994a. *Information Technology in the Service Society: A Twenty-first Century Lever*. National Academy Press, Washington, D.C.
7. Computer Science and Telecommunications Board (CSTB), National Research Council. 1994b. *Academic Careers for Experimental Computer Scientists and Engineers*. National Academy Press, Washington, D.C.
8. G Dieter, Engineering Design - a materials and processing approach, McGraw Hill, NY, 2000.
9. http://shodhganga.inflibnet.ac.in/bitstream/10603/26942/6/06_chapter1.pdf
10. http://www.engineeringarticles.org/manufacturing-process-meaning-and-types/
11. https://blog.gesrepair.com/a-brief-history-of-manufacturing/
12. https://ijret.org/volumes/2015v04/i10/IJRET20150410059.pdf
13. https://searcherp.techtarget.com/definition/lean-production
14. Hyer, Nancy and Urban Wemmerlov. "Cell Manufacturing: The Hard Part Is to Get People in Step with the Program." *Mechanical Engineering* 126, no. 3 (1 March 2004): E14–16.
15. John A. Schey, Introduction to Manufacturing Process.
16. M F Ashby, Material Selection in Mechanical Design, Butterworth-Heinemann, 1999.

17. Meredith, Jack R., and Scott M. Shafer. *Operations Management for MBAs.* Hoboken, NJ: John Wiley & Sons, Inc., 2004.

18. Robert W. Messler, Principles of Welding: Processes, Physics, Chemistry, and Metallurgy, John Wiley &Sons, 1999

2 CHAPTER

MATERIAL REMOVAL PROCESSES

INTRODUCTION

The material removal processes are a family of shaping operations in which excess material is removed from a starting work part so that what remains is the desired final geometry. The "family tree" is shown in Figure 1. Machining is a manufacturing process in which a sharp cutting tool is used to cut away material to leave the desired part shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed, a new surface is exposed. Machining is most frequently applied to shape metals.

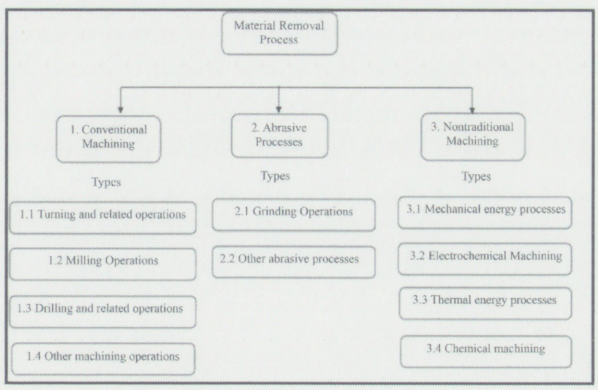


Figure 1: Material removal processes.

2.1 NON-CONVENTIONAL MACHINING

Manufacturing processes can be broadly divided into two groups and they are primary manufacturing processes and secondary manufacturing processes. The former ones provide basic shape and size to the material as per designer's requirement. Casting, forming, powder metallurgy are such processes to name a few. Secondary manufacturing processes provide the final shape and size with tighter control on dimension, surface characteristics etc. Material removal processes are mainly the secondary manufacturing processes.

Ultrasonic machining is an abrasive process which can create any material into hard and brittle form with the help of its vibrating tool and the indirect passage of abrasive particles towards the work piece. It is a low material removal rate machining process.

Material removal processes once again can be divided into mainly two groups and they are "Conventional Machining Processes" and "Non-Traditional Manufacturing Processes". Examples of conventional machining processes are turning, boring, milling, shaping, broaching, slotting, grinding etc. Similarly, Abrasive Jet Machining (AJM), **Ultrasonic Machining (USM)**, Water Jet and Abrasive Water Jet Machining (WJM and AWJM), Electrodischarge Machining (EDM) are some of the Non Traditional Machining (NTM) Processes.

2.1.1 Classification of Non Traditional Machining Processes

To classify Non Traditional Machining Processes (NTM), one needs to understand and analyses the differences and similar characteristics between conventional machining processes and NTM processes.

Conventional Machining Processes mostly remove material in the form of chips by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition. Such forces induce plastic deformation within the work piece leading to shear deformation along the shear plane and chip formation. Figure 2 depicts such chip formation by shear deformation in conventional machining.

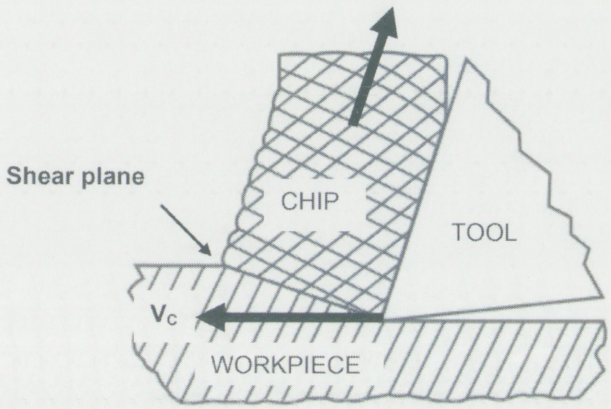


Figure 2: Shear deformation in conventional machining leading to chip formation.

Thus the major characteristics of conventional machining are:

- Generally macroscopic chip formation by shear deformation
- Material removal takes place due to application of cutting forces – energy domain can be classified as mechanical
- Cutting tool is harder than work piece at room temperature as well as under machining conditions

Non Traditional Machining (NTM) Processes on the other hand are characterized as follows:

- Material removal may occur with chip formation or even no chip formation may take place. For example in AJM, chips are of microscopic size and in case of Electrochemical machining material removal occurs due to electrochemical dissolution at atomic level
- In NTM, there may not be a physical tool present. For example in laser jet machining, machining is carried out by laser beam. However in Electrochemical Machining there is a physical tool that is very much required for machining
- In NTM, the tool need not be harder than the work piece material. For example, in EDM, copper is used as the tool material to machine hardened steels.
- Mostly NTM processes do not necessarily use mechanical energy to provide material removal. They use different energy domains to provide machining. For example, in USM, AJM, WJM mechanical energy is used to machine material, whereas in ECM electrochemical dissolution constitutes material removal.

Thus classification of NTM processes is carried out depending on the nature of energy used for material removal. The broad classification is given as follows:

- Mechanical Processes

- Abrasive Jet Machining (AJM)
- Ultrasonic Machining (USM)
- Water Jet Machining (WJM)
- Abrasive Water Jet Machining (AWJM)

■ Electrochemical Processes
- Electrochemical Machining (ECM)
- Electro Chemical Grinding (ECG)
- Electro Jet Drilling (EJD)

■ Electro-Thermal Processes
- Electro-discharge machining (EDM)
- Laser Jet Machining (LJM)
- Electron Beam Machining (EBM)

■ Chemical Processes
- Chemical Milling (CHM)
- Photochemical Milling (PCM) etc.

Figure 3 schematically depicts some of the NTM processes:

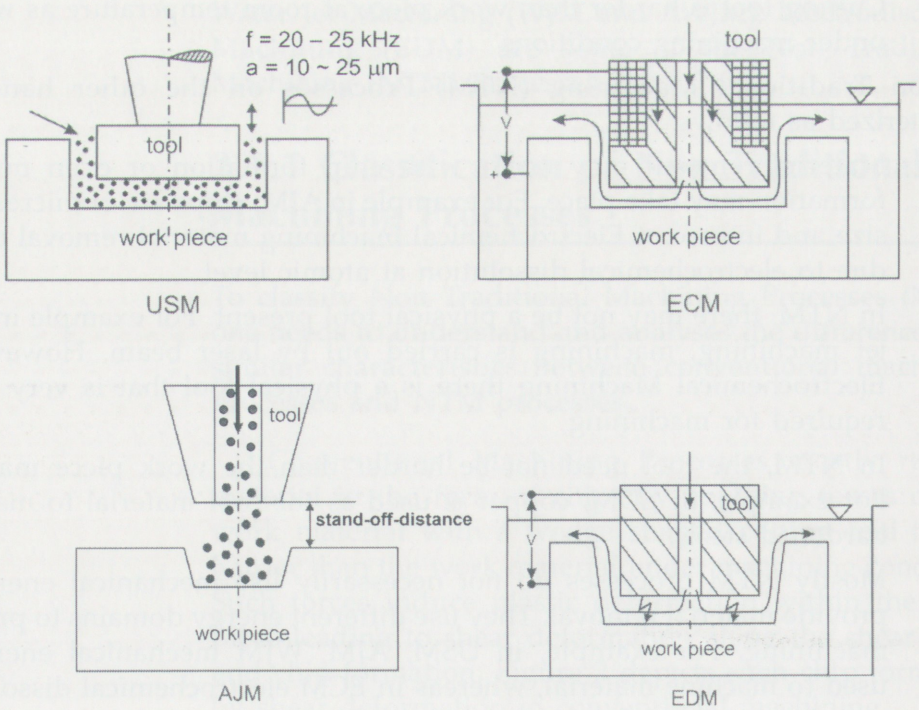


Figure 3: Schematic representation of various metal cutting operations.

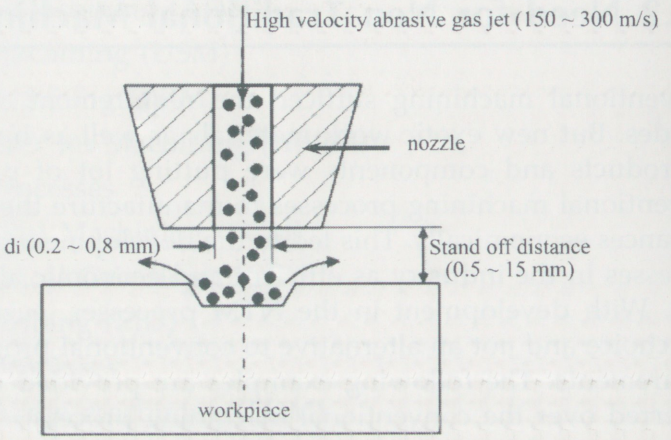
2.1.2 Need for Non Traditional Machining

Conventional machining sufficed the requirement of the industries over the decades. But new exotic work materials as well as innovative geometric design of products and components were putting lot of pressure on capabilities of conventional machining processes to manufacture the components with desired tolerances economically. This led to the development and establishment of NTM processes in the industry as efficient and economic alternatives to conventional ones. With development in the NTM processes, currently there are often the first choice and not an alternative to conventional processes for certain technical requirements. The following examples are provided where NTM processes are preferred over the conventional machining process:

- Intricate shaped blind hole – e.g. square hole of 15 mmx15 mm with a depth of 30 mm
- Difficult to machine material – e.g. same example as above in Inconel, Ti-alloys or carbides.
- Low Stress Grinding – Electrochemical Grinding is preferred as compared to conventional grinding
- Deep hole with small hole diameter – e.g. ϕ 1.5 mm hole with l/d = 20
- Machining of composites.

2.1.3 Abrasive Jet Machining

In Abrasive Jet Machining (AJM), abrasive particles are made to impinge on the work material at a high velocity. The jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasive is generated by converting the pressure energy of the carrier gas or air to its kinetic energy and hence high velocity jet. The nozzle directs the abrasive jet in a controlled manner onto the work material, so that the distance between the nozzle and the work piece and the impingement angle can be set desirably. The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material. Figure 4 schematically shows the material removal process.



AJM

Figure 4: Schematic representation of AJM.

is different from standard shot or sand blasting, as in AJM, finer abrasive grits are used and the parameters can be controlled more effectively providing better control over product quality. In AJM, generally, the abrasive particles of around 50 μm grit size would impinge on the work material at velocity of 200 m/s from a nozzle of I.D. of 0.5 mm with a stand off distance of around 2 mm. The kinetic energy of the abrasive particles would be sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives.

2.1.4 Equipment

In AJM, air is compressed in an air compressor and compressed air at a pressure of around 5 bar is used as the carrier gas as shown in Figure 5. Figure 5 also shows the other major parts of the AJM system. Gases like CO_2, N_2 can also be used as carrier gas which may directly be issued from a gas cylinder. Generally oxygen is not used as a carrier gas. The carrier gas is first passed through a pressure regulator to obtain the desired working pressure. The gas is then passed through an air dryer to remove any residual **water vapor**. To remove any oil vapor or particulate contaminant the same is passed through a series of filters. Then the carrier gas enters a closed chamber known as the mixing chamber. The abrasive particles enter the chamber from a hopper through a metallic sieve. The sieve is constantly vibrated by an electromagnetic shaker. The mass flow rate of abrasive (15 gm/min) entering the

Water vapor, water vapor or aqueous vapor is the gaseous phase of water. It is one state of water within the hydrosphere.

chamber depends on the amplitude of vibration of the sieve and its frequency. The abrasive particles are then carried by the carrier gas to the machining chamber via an electromagnetic on-off valve. The machining enclosure is essential to contain the abrasive and machined particles in a safe and eco-friendly manner. The machining is carried out as high velocity (200 m/s) abrasive particles are issued from the nozzle onto a work piece traversing under the jet.\

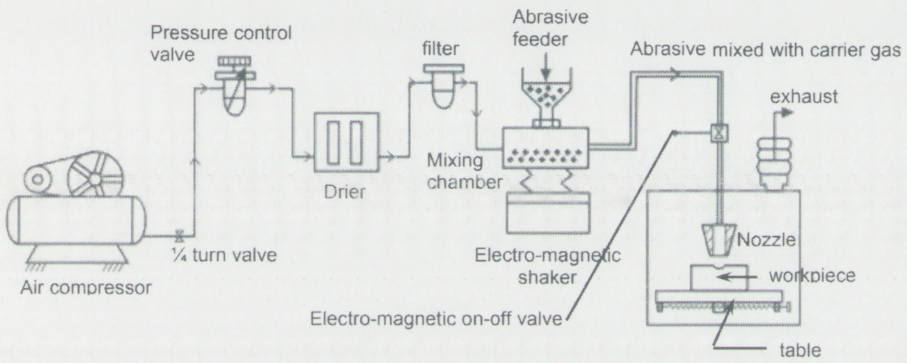


Figure 5: AJM set-up.

2.1.5 Process Parameters and Machining Characteristics

The process parameters are listed below:

- Abrasive
  - Material – Al_2O_3 / SiC / glass beads
  - Shape – irregular / spherical
  - Size – 10 ~ 50 μm
  - Mass flow rate – 2 ~ 20 gm/min
- Carrier gas
  - Composition – Air, CO_2, N_2
  - Density – Air ~ 1.3 kg/m^3
  - Velocity – 500 ~ 700 m/s
  - Pressure – 2 ~ 10 bar
  - Flow rate – 5 ~ 30 lpm
- Abrasive Jet
  - Velocity – 100 ~ 300 m/s
  - Mixing ratio – mass flow ratio of abrasive to gas – $\left(\frac{M_{abr}}{M_{gas}}\right)$
  - Stand-off distance – 0.5 ~ 5 mm

- Impingement Angle – 60^0 ~ 90^0

- Nozzle
  - Material – WC / sapphire
  - Diameter – (Internal) 0.2 ~ 0.8 mm
  - Life – 10 ~ 300 hours
- The important machining characteristics in AJM are
  - The material removal rate (MRR) mm^3/min or gm/min
  - The machining accuracy
  - The life of the nozzle

Figure 6 depicts the effect of some process parameters on MRR

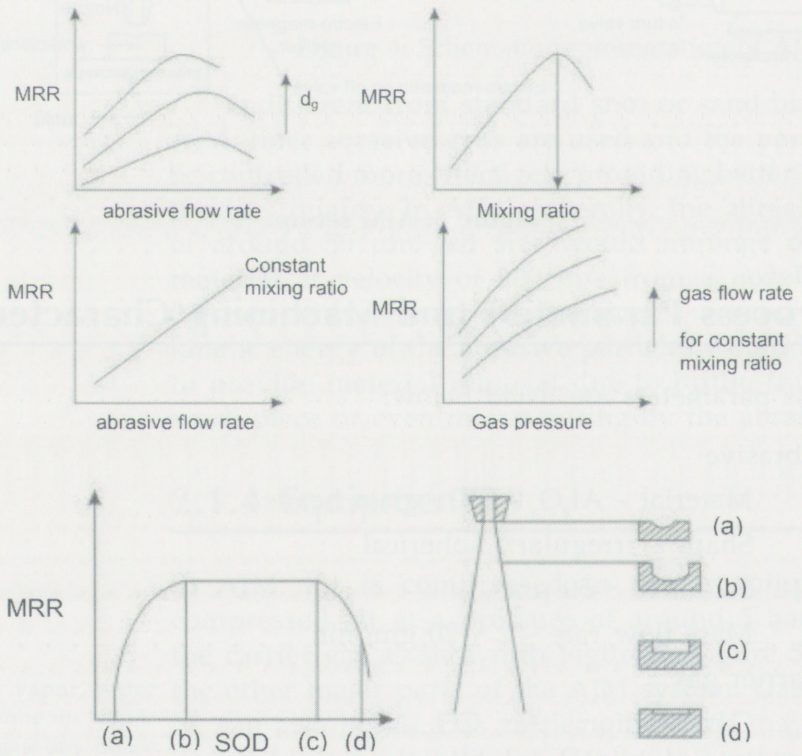


Figure 6: Effect of process parameters MRR.

2.1.6 Modelling of Material Removal

As mentioned earlier, material removal in AJM takes place due to brittle fracture of the work material due to impact of high velocity abrasive particles. Modelling has been done with the following assumptions:

- Abrasives are spherical in shape and rigid. The particles are characterized by the mean grit diameter
- The kinetic energy of the abrasives are fully utilized in removing material
- Brittle materials are considered to fail due to brittle fracture and the fracture volume is considered to be hemispherical with diameter equal to chordal length of the indentation
- For ductile material, removal volume is assumed to be equal to the indentation volume due to particulate impact.

Figure 7 schematically shows the interaction of the abrasive particle and the work material in AJM.

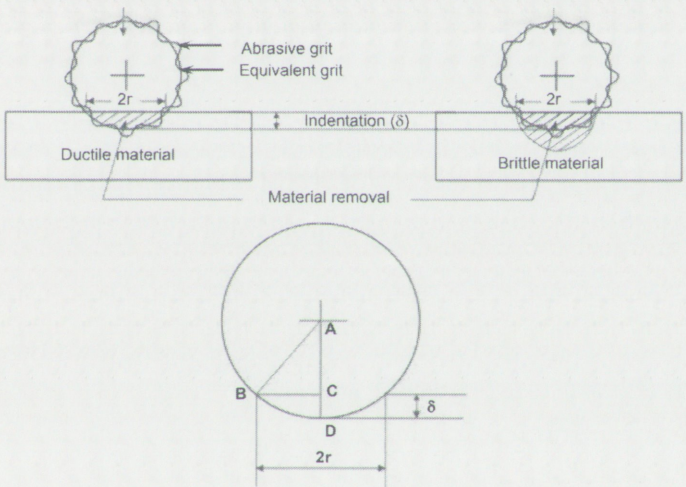


Figure 7: Interaction of abrasive particles with workpiece.

From the geometry of the indentation

$$AB^2 = AC^2 + BC^2$$

$$BC^2 = r^2 = AB^2 - AC^2$$

$$r^2 = \left(\frac{d_g}{2}\right)^2 - \left\{\frac{d_g}{2} - \delta\right\}^2$$

$$r^2 = -\delta^2 + d_g\delta \cong d_g\delta$$

$$r = \sqrt{d_g\delta}$$

∴ Volume of material removal in brittle material is the volume of the hemispherical impact crater and is given by:

$$\Gamma_B = \frac{2}{3}\pi r^3 = \frac{2\pi}{3}(d_g\delta)^{3/2}$$

For ductile material, volume of material removal in single impact is equal to the volume of the indentation and is expressed as:

$$\Gamma_D = \pi\delta^2\left[\frac{d_g}{2} - \frac{\delta}{3}\right] = \frac{\pi\delta^2 d_g}{2}$$

Kinetic energy of a single abrasive particle is given by

$$K.E._g = \frac{1}{2}m_g v^2 = \frac{1}{2}\left\{\frac{\pi}{6}d_g{}^3\rho_g\right\}v^2 = \frac{\pi}{12}d_g{}^3\rho_g v^2$$

where, v = velocity of the abrasive particle

m_g = mass of a single abrasive grit

d_g = diameter of the grit

ϱ_g = density of the grit

On impact, the work material would be subjected to a maximum force F which would lead to an indentation of 'δ'. Thus the work done during such indentation is given by

$$W = \frac{1}{2}F\delta$$

Now considering H as the hardness or the flow strength of the work material, the impact force (F) can be expressed as:

F = indentation area x hardness

$$F = \pi r^2 H$$

where, r = the indentation radius

$$\therefore W = \frac{1}{2}F\delta = \frac{1}{2}\pi r^2 H\delta$$

Now, as it is assumed that the K.E. of the abrasive is fully used for material removal, then the work done is equated to the energy

W = K.E.

$$\frac{1}{2}\pi r^2\delta H = \frac{\pi}{12}d_g{}^3\rho_g v^2$$

$$\delta = \frac{d_g{}^3\rho_g v^2}{6r^2 H} \qquad \text{now } r = \sqrt{d_g\delta} \quad \Rightarrow r^2 = d_g\delta$$

$$\delta^2 = \frac{d_g{}^2\rho_g v^2}{6H}$$

$$\delta = d_g v\left(\frac{\rho_g}{6H}\right)^{1/2}$$

Now MRR in AJM of brittle materials can be expressed as:

$MRR_B = \Gamma_B x$ Number of impacts by abrasive grits per second $= \Gamma_B N$

$$MRR_B = \Gamma_B \frac{m_a}{\text{mass of a grit}} = \frac{\dot{m}_a}{\frac{\pi}{6} d_g^{\,3} \rho_g} = \frac{6\Gamma_B \dot{m}_a}{\pi d_g^{\,3} \rho_g} \quad as\ \Gamma_B = \frac{2\pi}{3}(d_g \delta)^{3/2}$$

$$= \frac{6x \frac{2\pi}{3}(d_g\delta)^{3/2} \dot{m}_a}{\pi d_g^{\,3} \rho_g} = \frac{4\dot{m}_a}{\rho_g}\left(\frac{\delta}{d_g}\right)^{3/2}$$

$$MRR_B = \left(\frac{4\dot{m}_a}{\rho_g}\right)\left(\frac{\delta}{d_g}\right)^{3/2}$$

$$as \quad \delta = d_g v \left(\frac{\rho_g}{6H}\right)^{1/2}$$

$$MRR_B = \frac{4\dot{m}_a}{\rho_g} \cdot \left(\frac{d_g v}{d_g}\right)^{3/2} \left(\frac{\rho_g}{6H}\right)^{3/4}$$

$$MRR_B = \frac{4\dot{m}_a v^{3/2}}{6^{3/4} \rho_g^{\,1/4} H^{3/4}} \approx \frac{\dot{m}_a v^{3/2}}{\rho_g^{\,1/4} H^{3/4}}$$

as $\Gamma_D = \frac{\pi\delta^2 d_g}{2}$ for ductile material can be simplified as:

$$MRR_D = \Gamma_D N = \Gamma_D \frac{6\dot{m}_a}{\pi d_g^{\,3} \rho_g} = \frac{\pi\delta^2 d_g 6\dot{m}_a}{2\pi d_g^{\,3} \rho_g}$$

$$MRR_D = \frac{6\pi\delta^2 \dot{m}_a}{2\pi d_g^{\,2} \rho_g}$$

$$as \quad \delta = d_g v \left(\frac{\rho_g}{6H}\right)^{1/2}$$

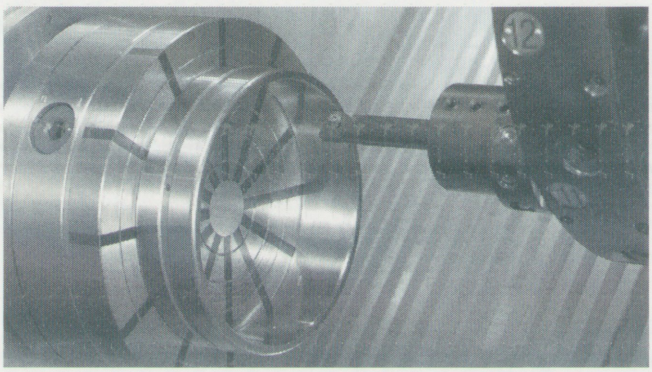
$$MRR_D = \frac{6\dot{m}_a d_g^{\,2} v^2}{2 d_g^{\,2} \rho_g}\left(\frac{\rho_g}{6H}\right)$$

$$MRR_D = \frac{1}{2}\frac{\dot{m}_a v^2}{H}$$

2.2 TURNING

Turning is a form of machining, a material removal process, which is used to create rotational parts by cutting away unwanted material. The turning process requires a turning machine or lathe, workpiece, fixture, and cutting tool. The

workpiece is a piece of pre-shaped material that is secured to the fixture, which itself is attached to the turning machine, and allowed to rotate at high speeds. The cutter is typically a single-point cutting tool that is also secured in the machine, although some operations make use of multi-point tools. The cutting tool feeds into the rotating workpiece and cuts away material in the form of small chips to create the desired shape.



Turning is used to produce rotational, typically axi-symmetric, parts that have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces. Parts that are fabricated completely through turning often include components that are used in limited quantities, perhaps for prototypes, such as custom designed shafts and fasteners. Turning is also commonly used as a secondary process to add or refine features on parts that were manufactured using a different process. Due to the high tolerances and surface finishes that turning can offer, it is ideal for adding precision rotational features to a part whose basic shape has already been formed.

2.2.1 Process Cycle

The time required to produce a given quantity of parts includes the initial setup time and the cycle time for each part. The setup time is composed of the time to setup the turning machine, plan the tool movements (whether performed manually or by machine), and install the fixture device into the turning machine. The cycle time can be divided into the following four times:

- *Load/Unload time* - The time required to load the workpiece into the turning machine and secure it to the fixture, as well as the time to unload the finished part. The load time can depend on the size, weight, and complexity of the workpiece, as well as the type of fixture.
- *Cut time* - The time required for the cutting tool to make all the necessary cuts in the workpiece for each operation. The cut time for any given operation is calculated by dividing the total cut length for that operation by the feed rate, which is the speed of the tool relative to the workpiece.

- *Idle time* - Also referred to as non-productive time, this is the time required for any tasks that occur during the process cycle that do not engage the workpiece and therefore remove material. This idle time includes the tool approaching and retracting from the workpiece, tool movements between features, adjusting machine settings, and changing tools.
- *Tool replacement time* - The time required to replace a tool that has exceeded its lifetime and therefore become to worn to cut effectively. This time is typically not performed in every cycle, but rather only after the lifetime of the tool has been reached. In determining the cycle time, the tool replacement time is adjusted for the production of a single part by multiplying by the frequency of a tool replacement, which is the cut time divided by the tool lifetime.

Following the turning process cycle, there is no post processing that is required. However, secondary processes may be used to improve the surface finish of the part if it is required. The scrap material, in the form of small material chips cut from the workpiece, is propelled away from the workpiece by the motion of the cutting tool and the spraying of lubricant. Therefore, no process cycle step is required to remove the scrap material, which can be collected and discarded after the production.

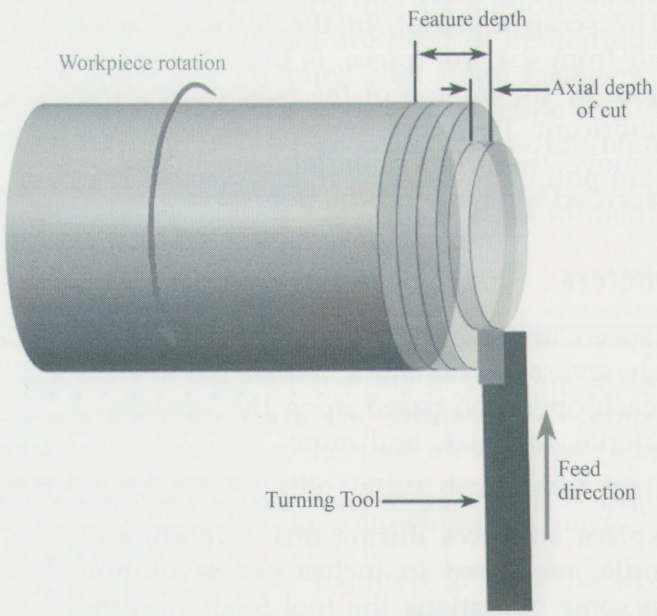
Cutting Parameters

In turning, the speed and motion of the cutting tool is specified through several parameters. These parameters are selected for each operation based upon the workpiece material, tool material, tool size, and more.

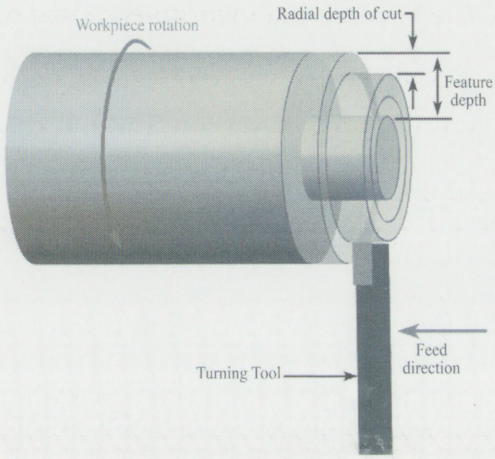
Revolutions per minute (abbreviated rpm, RPM, rev/min, r/min) is the number of turns in one minute. It is a unit of rotational speed or the frequency of rotation around a fixed axis.

- *Cutting feed* - The distance that the cutting tool or workpiece advances during one revolution of the spindle, measured in inches per revolution (IPR). In some operations the tool feeds into the workpiece and in others the workpiece feeds into the tool. For a multi-point tool, the cutting feed is also equal to the feed per tooth, measured in inches per tooth (IPT), multiplied by the number of teeth on the cutting tool.

- *Cutting speed* - The speed of the workpiece surface relative to the edge of the cutting tool during a cut, measured in surface feet per minute (SFM).
- *Spindle speed* - The rotational speed of the spindle and the workpiece in **revolutions per minute (RPM)**. The spindle speed is equal to the cutting speed divided by the circumference of the workpiece where the cut is being made. In order to maintain a constant cutting speed, the spindle speed must vary based on the diameter of the cut. If the spindle speed is held constant, then the cutting speed will vary.
- *Feed rate* - The speed of the cutting tool›s movement relative to the workpiece as the tool makes a cut. The feed rate is measured in inches per minute (IPM) and is the product of the cutting feed (IPR) and the spindle speed (RPM).
- *Axial depth of cut* - The depth of the tool along the axis of the workpiece as it makes a cut, as in a facing operation. A large axial depth of cut will require a low feed rate, or else it will result in a high load on the tool and reduce the tool life. Therefore, a feature is typically machined in several passes as the tool moves to the specified axial depth of cut for each pass.

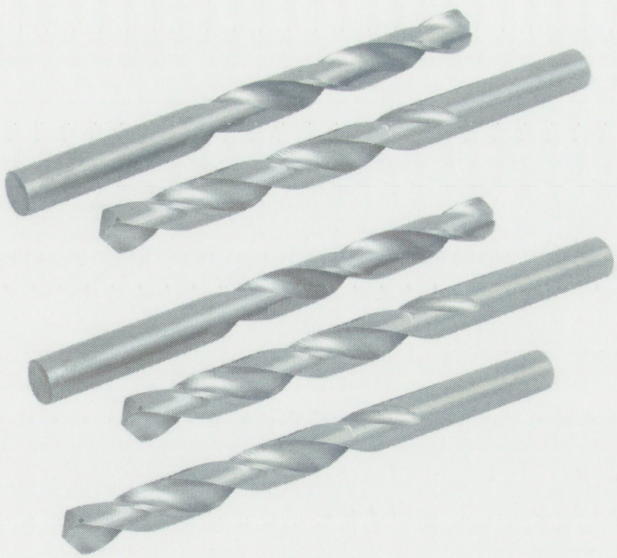


- *Radial depth of cut* - The depth of the tool along the radius of the workpiece as it makes a cut, as in a turning or boring operation. A large radial depth of cut will require a low feed rate, or else it will result in a high load on the tool and reduce the tool life. Therefore, a feature is often machined in several steps as the tool moves over at the radial depth of cut.



2.3 DRILLING

Drilling is a hole making process for which drill is used as a cutting tool for producing round holes of different sizes and depths. Drilling machines are subjected for drilling holes, tapping, counter boring, reaming, and general boring operations. Drills may be classified into a large variety of types. Twist drills are the most common tools used in drilling and are made in many sizes and lengths. Lengths range Straight-shank twist drills from 1/60 in diameter to 11/4 in by1/64; 2in by 1/16 in increment. Taper-shank drills range from 1/8 in diam to 13/4 in by 1/64 increments.



The cutting tool used for making holes is called as twist drill. Drill consists two parts. The body consists of cutting edge and the shank used for holding. Two cutting edge and two opposite spiral are cut into its surface the flute provides clearance to the chips produced at the cutting edge. The surface on the drill that extends behind the cutting tip to the following flute is termed as flank. The face is the portion of the flute surface adjacent to the cutting tip on which the chip moves. The land or the margin is the cylindrically ground body surface on the leading edge or flank face. The axial rake angle is the angle between face and the line parallel to the drill axis. Tolerances have been set on the various features of all drills so that the products of different manufacturers will be interchangeable in the user's plants. Twist drills are decreased in diameter from point to shank (back taper) to prevent binding. If the web is increased gradually in thickness from point to shank to increase the strength, it is customary to reduce the helix angle as it approaches the shank. The shape of the groove is important, the one that gives a straight cutting edge and allows a full curl to the chip being the best. The helix angles of the flutes vary from 10^0 to 45^0. The standard point angle is 118^0. There are a number of drill grinders on the market designed to give the proper angles. The point may be ground either in the standard or the crankshaft geometry.

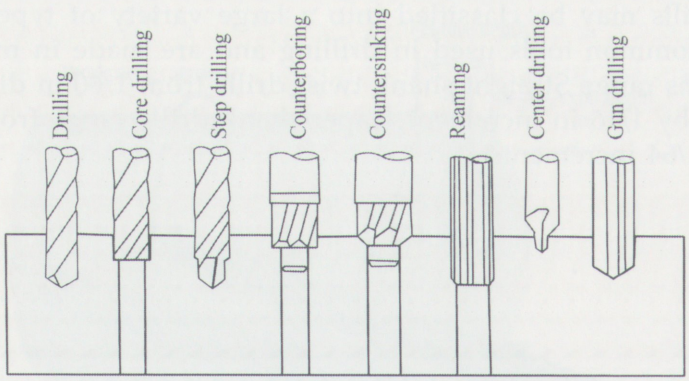


Figure 8: Various types of drills and drilling and reaming operations.

2.3.1 Drilling Time Estimation

The cutting speed in drilling is the surface speed of twist drill.

$$V = \frac{\Pi DN}{1000}$$

V=cutting speed (surface), m/min

D=diameter of twist drill, mm

N=rotational speed of drill, rev/min

The drill will have to approach the start of hole from a distance and traverse beyond the actual hole by a distance termed as the total approach allowance A. The initial approach is a small value for positioning the drill above the hole. The distance AI can generally be taken as 2 to 3mm.The traverse distance beyond the hole is termed as the breakthrough distance.

Breakthrough distance $A = \frac{D}{2\tan\alpha}$

For common case, $\alpha=59^0$

$$A = \frac{D}{3.3286}$$

Total length of tool travel L=l+A+2mm

Where l=length of the hole

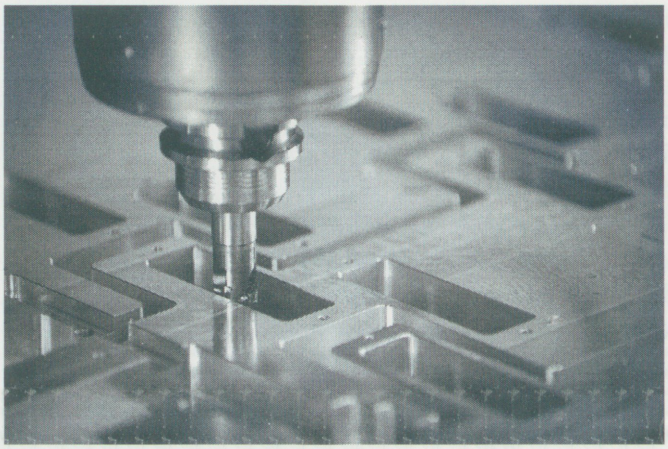
$$\text{Time for drilling the hole} = \frac{L}{fN} \text{ minutes}$$

F= feed rate,mm/rev

2.4 MILLING

A **cutting tool** or cutter is any tool that is used to remove material from the work piece by means of shear deformation.

Through milling process flat and complex shapes are formed by using multipoint **cutting tool**. The axis of rotation of cutting tool is perpendicular to the direction of feed. During each revolution of cutting operation the teeth of milling cutter enter and exit the work piece. Therefore on every rotation the teeth are subjected to impact force and thermal shock. The tool material and geometry must be designed to resist the conditions.



2.4.1 Types of Milling Machine

To satisfy the variety of requirement, milling machine comes in a number of ways, sizes and varieties.

a) Knee and column type
b) Horizontal
c) Vertical
d) Universal
e) Turret type

These are the general purpose milling machine, which have a high degree of flexibility and employed for all types of works, including batch manufacturing.

f) Production (bed) type
g) Simplex
h) Duplex

Triplex these machines are generally meant for regular production involving large batch sizes. The flexibility is relatively less in these machines than suitable for productivity enhancement.

i) Plano millers- these machines are used only for very large work-piece involving table travels in metres.

j) Special type

- Rotary table
- Drum type
- Copy milling (die sinking machine)
- Keyway milling machines
- Spline milling machine

These machines are of a special facilities to suit specific applications that catered by the other classes of milling machines.

2.4.2 Knee and Column Milling Machine

The knee and column type milling machine is the most commonly used machine in view of its flexibility and easier setup. The knee houses the feed mechanism and mounts the saddle and table. The table basically has the t-slots running along the x-axis for the purpose of work holding. The table moves along the x-axis on the saddle while the saddle moves along the y-axis on the guide ways provided on the knee. The feed is provided either manually by hand wheel or connected for automatic by the lead screw, which in turn is coupled to the main **spindle drive**. The knee can move up and down in a dovetail provided on the column.

Spindle drives convert the power generated by the motor into feed velocity and feed force. The integrated axial bearing can take extremely high axial loads.

Milling machines are generally specified based on the following features.

- Size of the table, which specifies the actual working area on the table and relates to the maximum size of the work-piece that can be accommodated.
- Amount of table travel which gives the maximum axis movement that is possible.
- Horse power of the spindle, which actually specifies the power of the spindle motor used. Smaller machines may come with 1 to 3 hp while the production machines may go from 10 to 50 hp.

Another type of knee and column milling machine possible is the vertical-axis type. Most of the construction is very is very similar to the horizontal-axis type except the spindle type and location. The spindle is located in the vertical direction and is suitable for using the shankmounted milling cutter such as end mills. In view of the location of the tool, the setting up of the work-piece and observing the machining operation is more convenient. The universal machine is suitable for milling spur and helical gears, as well as worm gears and cam as it can be swivelled in a horizontal plane about 45 degree to either left or right.

2.4.3 Bed-Type Milling Machine

These are made more rugged and consequently are capable of removing more material without any chatter. Here the table is directly mounted on the bed and is provided with only the longitudinal motion. The spindle will be moving along with the column to provide the cutting action. Simplex machines are the ones with only one spindle head while duplex machines have two spindles.

Milling operations are of two types

- Down milling

  Here the cutter direction is same direction as the motion of the work piece being fed.

- Up milling

  Here work piece is moving towards the cutter, opposing the cutter direction of rotation. Surface finish is better in case of down milling, but the stress load on the teeth is abrupt that may damage the cutter.

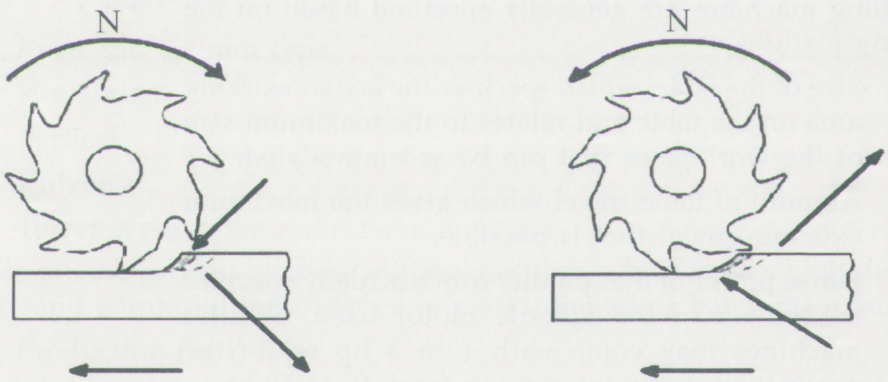


Figure 9: Schematic depiction of down milling (a) and up milling (b) operations.

Advantages

- Suited to machine-thin and hard to hold parts
- Work need not be clamped tightly
- Consistent parallelism and size may be maintained particularly on the thin parts
- Used where break out of the edge of the work piece could not be tolerated.
- Requires up to 20% less power to cut.
- Used when cutting off stock or when milling deep, thin slots.

Disadvantages

- Cannot be used unless the machine has a backlash eliminator and the table jibs have been tightened
- Cannot be used for machining castings or hot rolled steel, since hard outer scale will damage the cutter.

2.5 GRINDING

Grinding is the most common form of abrasive machining. It is a material cutting process that engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance. The grits are held together by a suitable bonding material to give shape of an abrasive tool. Grinding machine is employed to obtain high accuracy along with very high class of surface finish on the work piece. However, advent of new generation of grinding wheels and grinding machines, characterized by their rigidity, power and speed enables one to go for high efficiency deep grinding (often called as abrasive milling) of not only hardened material but also ductile materials.



2.5.1 Grain Size

Compared to the normal cutting tool, the abrasive used in grinding wheels are relatively small. The size of an abrasive grain or more generally called grit is identified by a number which is based on the sieve size used. This would vary from a very coarse size of 6 to 8 to a super fine size of 500 or 600. Sieve number

is specified in terms of the number of opening per square inch. The surface finish generated would depend upon grain size used. The fine grain will take a very small depth of cut and hence a better surface finish is produced. Fine grains generate less heat are good for faster material removal. Fine grains are used for making the form grinding wheels. Coarse grains are good for higher material removal rates. These have better friability and as a result are not good for intermittent where they are likely to chip easily.

2.5.2 Bonded Abrasives

- A composite of the abrasive powder and a matrix
- Bonding material can be glass, resin, rubber.
- Can be solid discs (grinding wheel) or bonded to paper/cloth which is then stuck to a backing disc.

The most commonly used bond materials are

- Vitrified
- Silicate
- Synthetic resin
- Rubber
- Shellac
- Metal

2.5.3 Centre-Less Grinding

It is used to grind cylindrical work-piece without actually fixing the work-piece using centers or a chuck, due to which the work rotation is not provided separately. Its process consists of wheel, one large grinding wheel and another smaller regulating wheel. The work-piece is supported by the rest blade and held against the regulating wheel by the grinding force which is mounted at an angle to the plane of grinding wheel. The regulating wheel is generally a rubber or resinoid bonded wheel with wide face. The axial feed of the work-piece is controlled by the angle of tilt of the regulating wheel. Typical work speeds are about 10 to 50 m/mm.

There are three types of center-less grinding operations possible. They are:

- Through feed center-less grinding.
- In feed center-less, the grinding is done by plunge feeding so that any form surface can be produced. This is useful if the work-piece has an obstruction which will not allow it to be traversed past the grinding wheel. The obstruction could be a shoulder, head, round form, etc.

- End feed center-less grinding, where tapered work-piece can be machined.

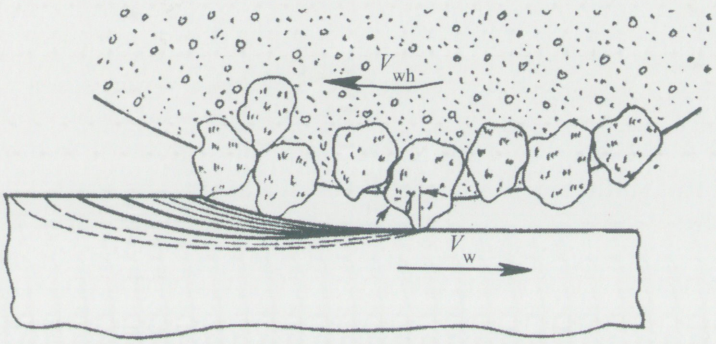


Figure 10: Cutting action of abrasive grain.

Conventional grinding machines can be broadly classified as:

- Surface grinding machine
- Cylindrical grinding machine
- Internal grinding machine
- Tool and cutter grinding machine

Advantages

A grinding wheel requires two types of specification

- dimensional accuracy
- good surface finish
- good form and locational accuracy
- applicable to both hardened and unhardened material

Applications

- surface finishing
- slitting and parting
- descaling, deburring
- stock removal (abrasive milling) finishing of flat as well as cylindrical surface
- grinding of tools and cutters and re sharpening of the same.

Conventionally grinding is characterized as low material removal process capable of providing both high accuracy and high finish. However, advent of advanced grinding machines and grinding wheels has elevated the status of

grinding to abrasive machining where high accuracy and surface finishas well as high material removal rate can be achieved even on an unhardened material.

2.6 BROACHING

Broaching is a machining process for removal of a layer of material of desired width and depth usually in one stroke by a slender rod or bar type cutter having a series of cutting edges with gradually increased protrusion as indicated in Figure 11. The difference in broaching and shaping, is that broaching enables remove the whole material in one stroke only by the gradually rising teeth of the cutter called broach where as shaping requires a number of strokes to remove the material in thin layers step by step by gradually in feeding the single point tool. Machining by broaching is preferably used for making straight through holes of various forms and sizes of section, internal and external through straight or helical slots or grooves, external surfaces of different shapes, teeth of external and internal splines and small spur gears etc.

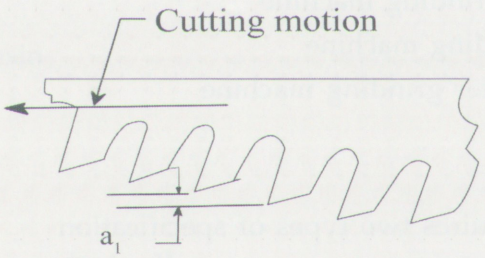


Figure 11: Principle of Broaching.

Figure shows how a through hole is enlarged and finished by broaching.

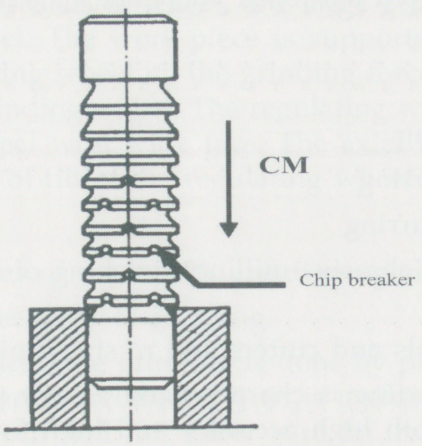


Figure 12: Vertical push type.

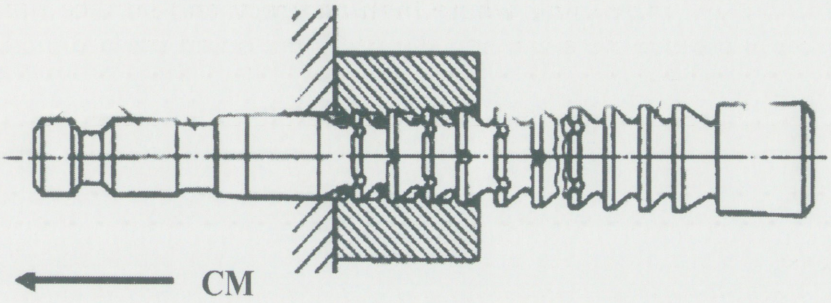


Figure 13: Horizontal pull type.

2.6.1 Construction of Broaching Tools

Construction of any cutting tool is characterized mainly by

- Configuration
- Material
- Cutting edge geometry

Both pull and push type broaches are made in the form of slender rods or bars of varying section having along its length one or more rows of cutting teeth with increasing height (and width occasionally). Push type broaches are subjected to compressive load and hence are made shorter in length to avoid buckling.

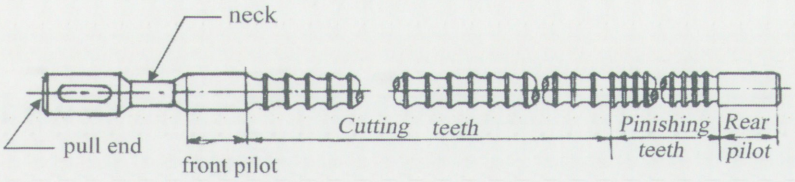


Figure 14: Pull type broach tool.

The essential elements of the broach are:

- Pull end for engaging the broach in the machine
- Neck of shorter diameter and length, where the broach is allowed to fail, if at all, under overloading
- Front pilot for initial locating the broach in the hole
- Roughing and finishing teeth for metal removal
- Finishing and burnishing teeth
- Rear pilot and follower rest or retriever

Advantages of broaching:

1. It is the fastest way of finishing an operation with a single stroke.
2. Very little skill is required from the operator.
3. It is simple since only a single reciprocating motion is required for cutting.
4. Final cost of the machining is one of the lowest for mass production.
5. Any type of surface, internal or external can be generated with broaching.
6. Good surface finish and fine dimensional tolerance can be achieved.

Limitations of Broaching:

- Custom made broaches are very expensive and hence generally used for very large volume production.
- The lead time for manufacturing is more for custom designed broaches.
- A broach can be designed and used for a specific application.
- As it is a very heavy metal removal operation, it requires that work-piece is rigid and capable of withstanding the large forces.

2.7 ELECTROCHEMICAL MACHINING (ECM)

Electrical discharge machining (EDM), also known as spark machining, spark eroding, burning, die sinking, wire burning or wire erosion, is a manufacturing process whereby a desired shape is obtained by using electrical discharges (sparks).

Electrochemical machining is a method of removing metal by an electrochemical process. It is a non-traditional machining process belonging to the electrochemical category. It is used for machining extremely hard materials or materials that are difficult to machine using conventional methods. Its use is limited to electrically conductive materials. The process has the capabilities of machining or cutting the intricate contours or cavities in hard steel such as titanium, Hastelloy, Kovar, Inconel, and Carbide. External as well as internal geometries can be machined with an electrochemical machine.

ECM is characterized as the opposite of electrochemical or galvanic coating or deposition process. It is sometimes referred to as reverse electroplating since it removes material instead of depositing it. In the year 1833, Faraday established the laws of electrolysis (electroplating). The mechanism in ECM process is similar to **electrical discharge machining (EDM)** concept-wise, wherein a high current is passed between the tool (cathode) and the workpiece (anode), through a conductive fluid (electrolyte). However, in ECM there is no tool wear.

In ECM, the metal removal takes place by electrochemical dissolution of an anodically polarized workpiece. By using the ECM process, very hard metals can be easily shaped electrolytically and being a chemical process, the rate of machining does not depend on the hardness of workpiece. Soft materials can be readily used as tool materials on harder work-pieces in ECM process since the tool doesn't wear unlike in the case of conventional machining methods.

2.7.1 ECM Fundamentals

The electrolysis process being the most fundamental activity in ECM, its characteristics are to be well understood before proceeding further into its other process details.

Electrolysis, as the name suggests is a chemical phenomenon that occurs between two conductors dipped in a suitable solution when electric current is passed between them. Example two copper wires, dipped in a copper sulphate solution are connected to a source of direct current as shown in Figure 15. This solution of copper sulphate is termed as the electrolyte and it has electrical conducting property. The entire system of electrolyte and electrodes is called as the electrolytic cell. As per the polarity, the chemical reactions occurring at the anode and cathode are called as anodic or cathodic reactions respectively.

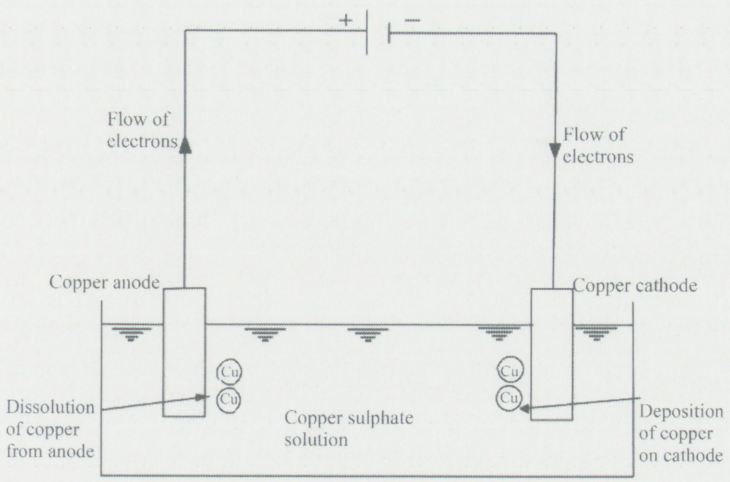


Figure 15: Electrolysis of a Copper Sulphate Solution.

Electrolytes are different from the metallic conductors that conduct electricity. In electrolytes, the current is carried by atoms or group of atoms and not by the electrons. The atoms have either lost or gained electrons, thereby acquiring either positive or negative charges and such atoms are called ions. The ions that carry positive charges are attracted by the cathode and they move through the electrolyte in the direction of the positive current and are referred to as the 'cat-ions'. The negatively charged ions get attracted to the positive electrode i.e. anode and they are referred to as the 'anions'. Due to the potential difference applied, the movement of ions is accompanied by the flow of electrons, in the opposite sense to the positive current in the electrolyte, outside the cell, as shown schematically in Figure 16.

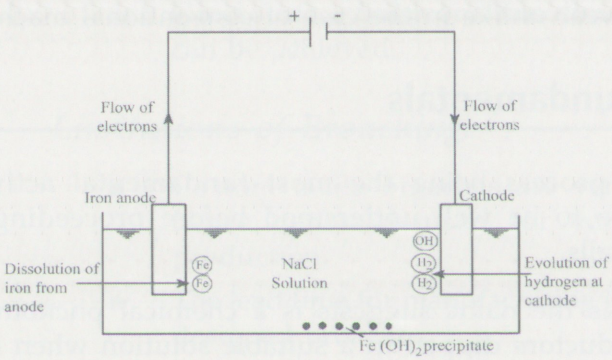


Figure 16: Electrolysis of a Copper Sulphate Solution.

In the electroplating process, which is a very popular application of electrolysis, the metal coatings are deposited on the surface of a cathodically polarized metal. An example of the anodic dissolution operation is electro-polishing. In this polishing process, the workpiece which has irregularities is made as the anode in the electrolytic cell. The work-piece gets polished and irregularities on its surface are dissolved preferentially so that after the process, the item gets shining effect and becomes flat.

The ECM and electro-polishing process are similar, such that both are anodic dissolution processes. The rate of metal removal obtained in the electro-polishing process is considerably less than that required in the metal removal processes. Some observations relevant to ECM are:

- At the anode, the metal dissolves electrochemically and its rate of dissolution depends upon number of factors such as the ionic charge, atomic weight, the current and the time of current passage.
- The rate of dissolution is not influenced by the hardness of the workpiece material or any other metal characteristics.
- At the cathode, only the hydrogen gas is evolved. The electrode shape remains unaltered during the electrolysis process. This is the most

relevant feature of ECM being used as a metal shaping process.

2.7.2 Mechanism of Material Removal in ECM

The working principle of ECM is schematically shown in Figure 17 (a and b), the workpiece and tool are the anode and cathode respectively. In the electrolytic cell a constant potential difference, usually of about 10 V is applied across them. A suitable electrolyte, for example an aqueous sodium chloride (table salt) solution is commonly chosen. In-order to remove the products of machining, the electrolyte is pumped through the gap between the two electrodes. The rate at which metal is then removed from the anode is approximately in inverse proportion to the distance between the electrodes. As the machining proceeds there is a simultaneous movement of the cathode towards the anode. The width of the gap along the **electrode** length will gradually tend towards a steady-state value. Under such conditions, a shape which is roughly complementary to that of the cathode will be reproduced on the anode. The schematic of "electrochemical machine" is shown in Figure 18.

An **electrode** is an electrical conductor used to make contact with a nonmetallic part of a circuit (e.g. a semiconductor, an electrolyte, a vacuum or air).

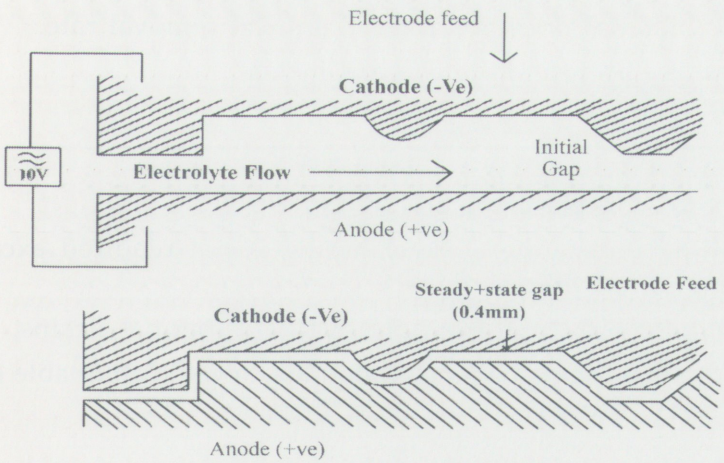


Figure 17: a and b working principle of ECM.

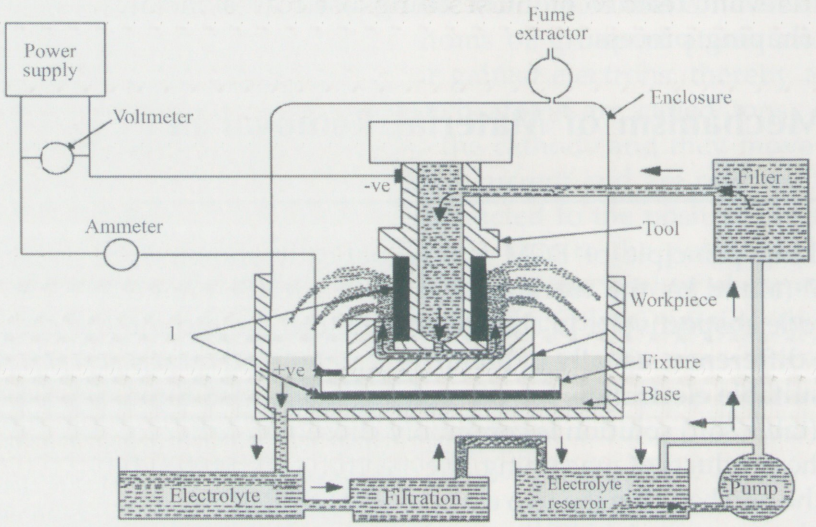


Figure 18: Schematic of "Electrochemical Machine".

Advantages of ECM

The major advantages of the ECM process are:

- No heat affected zone is formed.
- Harder metals than the tool can be machined.
- The hardness of material does not affect the metal removal rate.
- Complex shapes can be machined on hard metals,
- No tool wear occurs.
- Burr-free products are obtained in this process.
- There is no tool to workpiece contact.
- There is no cutting forces, therefore clamping is not required except for controlled motion of the work piece.
- The products obtained are free from physical and thermal strains.
- Depending on the materials, high surface quality level is attainable (Ra < 0.02 Âμm)
- High dimensional accuracies are attainable

Limitations of ECM

- The cost of tooling is high.
- Energy consumption is high: Power consumption is more as the ECM processes operates at high current and relatively low voltages (5-15V).

- The saline electrolyte poses a risk of corrosion to the tool, workpiece and the equipment.
- Since special electrodes need to be developed for each product, higher production numbers are required for economic viability. Depending on the complexity of the material, the optimum product numbers are decided.
- The electrode design is complex and has high initial cost but however it has a long life.
- Sharp corners or flat bottoms are not suitable through the ECM process, as there is a tendency of the electrolyte to erode away the sharp profiles.

SUMMARY

- The material removal processes are a family of shaping operations in which excess material is removed from a starting work part so that what remains is the desired final geometry.
- Material removal processes once again can be divided into mainly two groups and they are "Conventional Machining Processes" and "Non-Traditional Manufacturing Processes".
- Conventional Machining Processes mostly remove material in the form of chips by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition.
- In Abrasive Jet Machining (AJM), abrasive particles are made to impinge on the work material at a high velocity. The jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasive is generated by converting the pressure energy of the carrier gas or air to its kinetic energy and hence high velocity jet.
- Turning is a form of machining, a material removal process, which is used to create rotational parts by cutting away unwanted material. The turning process requires a turning machine or lathe, workpiece, fixture, and cutting tool.
- Drilling is a hole making process for which drill is used as a cutting tool for producing round holes of different sizes and depths. Drilling machines are subjected for drilling holes, tapping, counter boring, reaming, and general boring operations.
- Grinding is the most common form of abrasive machining. It is a material cutting process that engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance.

REFERENCES

1. http://www.uotechnology.edu.iq/dep-production/branch3_files/2luma.pdf
2. https://www.egr.msu.edu/~pkwon/me478/machining
3. http://home.iitk.ac.in/~nsinha/Machining%20I.pdf
4. http://ocw.snu.ac.kr/sites/default/files/NOTE/8029.pdf
5. https://nptel.ac.in/courses/112107077/module3/lecture14/lecture14.pdf
6. http://www.uotechnology.edu.iq/dep-production/branch3_files/2luma.pdf
7. http://www.mechscience.com/material-removal-processes-introduction/
8. https://nptel.ac.in/courses/112105127/pdf/LM-35.pdf
9. http://home.iitk.ac.in/~nsinha/Non-traditional-machining.pdf
10. DeGarmo, E.P.; Black J.T.; Kohser, R.A.; and Klamecki, B.E. "Materials and Processes in Manufacturing, Ninth Edition." Hoboken, N.J.: John Wiley & Sons, 2003.
11. http://www.minaprem.com/machining/cutter/introduction/single-point-cutting-tool-examples-advantages-and-disadvantages/
12. https://advancedmanufacturing.org/milling-vs-grinding-rapid-stock-removal/
13. https://www.dumoretools.com/tool-post-grinders/metal-removal-rate
14. http://home.iitk.ac.in/~nsinha/Abrasive_machining_processes.pdf
15. https://advancedmanufacturing.org/what-is-abrasive-machining/
16. https://www.custompartnet.com/wu/hole-making

3

CHAPTER

CUTTING TOOLS AND ACCESSORIES

INTRODUCTION

Over the past three to four decades industry in the United States has been affected by intense global competition from industries using the latest technologies in their manufacturing methods. Superabrasive tooling, designed to increase productivity, produce better quality products, and reduce manufacturing costs, can cut and grind the hardest materials known.

The fundamental cutting processes in machining - those of bringing the work into contact with the cutting tool - should remain mainstays of the industry. One of the most important components in the machining process is the cutting tool and its performance determines the efficiency of the operation. Modern tooling systems that can accommodate increased spindle speeds, higher feed rates, increased radial loads, modular adaptability, and profitable short part runs are required by manufacturers to stay competitive.

3.1 SUPERABRASIVE TECHNOLOGY

Over the past three to four decades, industry in the United States has been greatly affected by intense global competition from offshore industries that are using the latest technologies in their manufacturing methods. Even though the United States

continues to lead in the development of new technologies, other countries research, test, and implement them far sooner. Improved productivity and quality result in a larger share of the world market. Products that were previously produced in the United States are now being produced offshore; this has reduced employment opportunities in this country. U.S. industry must take advantage of the benefits of new technology as quickly as possible in order to maintain its leadership in **manufacturing**.

Manufacturing is the production of merchandise for use or sale using labor and machines, tools, chemical and biological processing, or formulation.

The superabrasives, Diamond and Cubic Boron Nitride, possess properties unmatched by conventional grinding wheels and cutting tools for grinders, lathes, and machining centers. The hardness, abrasion resistance, compressive strength, and thermal conductivity of superabrasives makes them the logical choice for many difficult grinding, sawing, lapping, machining, drilling, wheel dressing, and wire drawing applications. Superabrasives can cut and grind the hardest materials known, making difficult material-removal applications routine operations. Superabrasive cutting tools are designed to meet the challenge of today by increasing productivity, producing better quality products, and reducing manufacturing costs.

In 1954, The General Electric Company (GE), after years of research, produced **Man-Made® Diamond** in the laboratory. Carbon and a catalyst, such as iron, chromium, cobalt, and nickel, were subjected to tremendous heat and pressure to form diamond crystals, Fig. 1. Because the temperature, pressure, and catalyst solvent can be varied, it is possible to produce diamond abrasive of various sizes, shapes, and crystal structure to suit a range of grinding applications on nonferrous and nonmetallic materials.

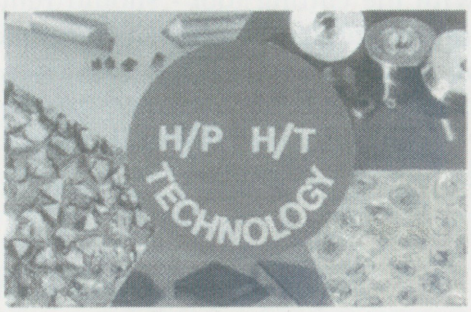


Figure 1. A combination of high pressure and high temperature plus carbon and a catalyst are necessary for diamond growth.

In 1969, GE introduced an entirely new material. **BORAZON® cubic boron nitride** (CBN). Cubic boron nitride is synthesized in crystal form from hexagonal boron nitride and a catalyst using the same high pressure, high temperature technology perfected to produce diamond, Fig. 2. CBN, second only to diamond in hardness, is used for the grinding of hard alloy steels and other difficult to grind ferrous materials.



Figure 2. The process for manufacturing CBN and the crystals produced.

Superabrasives are tools used in precision grinding. Superabrasive materials attach to a wheel to make Superabrasive grinding wheels. The reason some abrasives are Superabrasives is due to their extraordinary hardness, unparalleled performance, and longevity.

Abrasives that belong to the Superabrasive family includes, Industrial diamonds: an industrial diamond is a non-gem quality small diamond that is for abrasives, cutting, and drilling tools.

- ***Cubic boron nitride (CBN)***: Usually called CBN it is the second hardest cutting tool material after a diamond.

- ***Polycrystalline***: Is an abrasive material that has a multiple collection of crystal grain structures with individual orientations
- ***CVD Diamond***: These are synthetic diamonds made by a process known as chemical vapor deposition. CVD diamonds grow from a hydrocarbon gas mixture. They are extremely hard, have a high thermal conductivity that is five times that of copper. They also have broadband optical transparency, are chemically inert, and only reach graphitization at very high temperatures.
- ***Nanodiamonds***: These tiny diamonds are the product of a controlled explosion. Sometimes called a detonation nanodiamond (DND) or an ultradispersed diamond, as this is how they form.

Nanodiamonds are diamonds with a size below 1 micrometre.

A great number of industries use Superabrasive grinding wheels and the coated abrasives subsection of the abrasives industry continues to grow. Industries that are prime buyers of Superabrasive grinding wheels are:

- Aerospace
- Automotive
- Medical
- Electronics
- Composites
- Oil Industry

3.1.1 Manufactured Diamond

Diamond is used for truing and dressing grinding wheels and for the manufacture of diamonds' heels. The need for a reliable source of diamond during World War II was realized when natural diamond was not readily available.

To produce diamond by a manufacturing process, the conditions of pressure and temperature found far below the earth's surface had to be duplicated. This required a high-pressure, high-temperature belt apparatus capable of reproducing the conditions necessary for diamond growth. Graphite (a form of carbon) and a catalyst (such

as iron, chromium, cobalt, and nickel) were subjected to high temperatures (2550° to 4260°F. or 1400° to 2350°C) and high pressures (800,000 to 1,900,000 lbs./sq. in. of 55.000 to 130.000 atmospheres) to form diamond crystals. Fig. 3. Under these conditions, the graphite is transformed into diamond and remains that way when it is cooled and the pressure is removed.



Figure 3. The high-pressure, high temperature belt apparatus used for manufacturing diamonds.

Types of Manufactured Diamond

There are many different types of manufactured diamond to suit various grinding applications. Manufactured diamond is available for grinding cemented carbides, carbide/steel combinations, nonferrous and nonmetallic materials, and many products such as natural stone, concrete, and masonry. The four main manufactured diamonds arc:

- *TYPE RVG DIAMOND* is an elongated, friable crystal with rough edges. Fig. 4A, and consists of thousands of tightly bonded small crystals that make up each abrasive grain. Type RVG (resin and vitrified) wheels are used to grind ultra-hard materials, such as **tungsten carbide**, and tough, abrasive nonmetallic and nonferrous materials.

Tungsten carbide is a chemical compound (specifically, a carbide) containing equal parts of tungsten and carbon atoms.

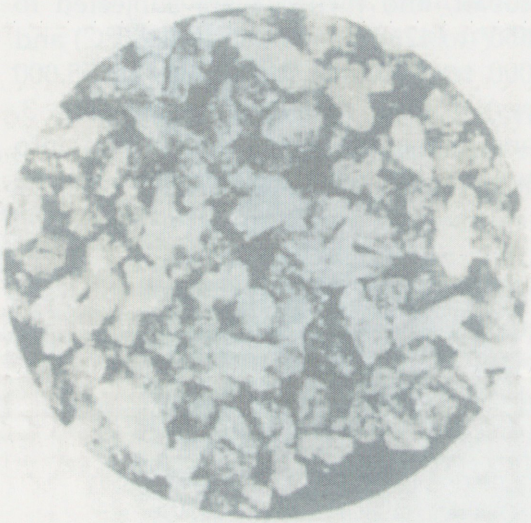


Figure 4A. Type RVG diamond is used to grind hard, abrasive nonferrous materials.

- ***TYPE CSG 11 DIAMOND***, Fig. 4B, is designed to grind cemented carbide brazed tools where it may be necessary to grind both the carbide and some of the steel shank supporting the carbide insert.

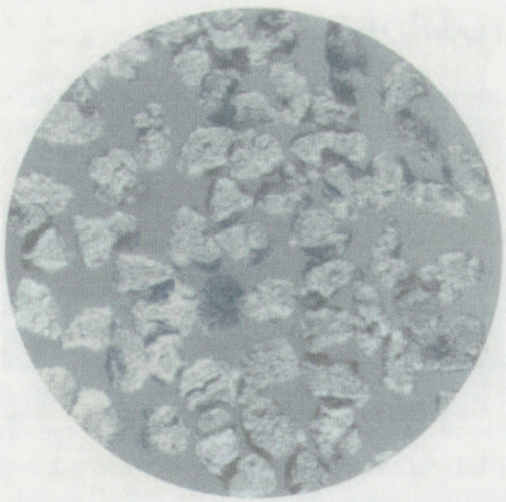


Figure 4B. Type CSG-11 diamond is used to grind carbide and steel combinations.

- ***TYPE MBG-11 DIAMOND***, Fig. 4C, is used for grinding glass, ceramics, and carbides. The wheels with N1BG (metal-bond grinding) abrasive have a metal bond to hold the tough diamond crystals in the wheel.



Figure 4C. Type MBG-11 diamond is used to grind carbides, glass, and ceramics.

- ***TYPE MBS DIAMOND*** - The Type MBS (metal-bond sawing) diamond. Fig. 4D, is used in metal-bond saws to cut granite, concrete, marble, and a variety of masonry and refractory materials.

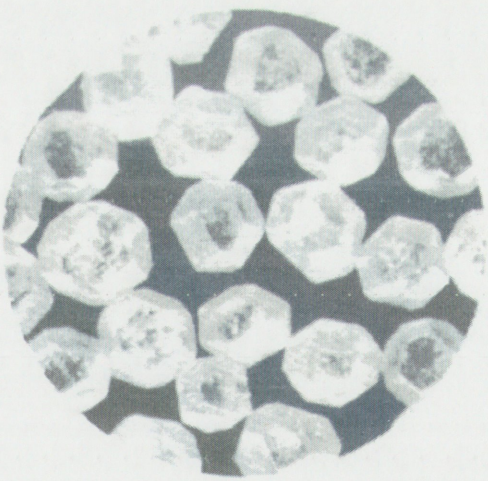


Figure 4D. Type MBS diamond is used primarily for grinding stone, marble, concrete, and masonry products.

Metal Coatings

The RVG diamond abrasive can be coated to prevent the diamond crystals from being pulled out from the resin bond. Coatings, such as nickel and copper provide better retention (holding power) for the RVG crystal in the wheel bond.

- *TYPE RVG-W* (Resin, Vitrified. Grinding—Wet) is an RVG diamond with a special nickel coating that covers all surfaces of the crystal, providing a better holding or bonding surface for the resin bond and results in much longer grinding wheel life.
- *TYPE RVG-D* (Resin, Vitrified. Grinding—Dry) is an RVG diamond with a special copper coating that improves the bonding strength of the diamond in the wheel and controls its fracturing (tiny particles breaking away) under the stresses of grinding.

3.1.2 Work Materials

Diamond is used to machine and grind hard, abrasive nonferrous, nonmetallic, and composite materials. It is not recommended for grinding and machining ferrous materials because of the chemical characteristic known as carbon solubility potential, where steels will react with any source of carbon to absorb carbon into their surface. The reaction occurs under the temperature and pressure created during the grinding or machining process, thus causing excessive wear of the diamond-cutting tool, Fig. 5.

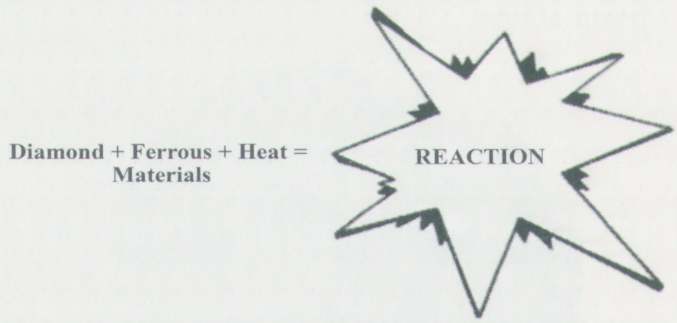


Figure 5. Diamond tools react chemically, under the proper temperature and pressure conditions, when cutting ferrous metals.

3.1.3 Cubic Boron Nitride (CBN)

A major breakthrough in the precision high-production grinding of hard, difficult-to-grind ferrous metals, was the discovery and manufacture of cubic boron nitride. CBN is twice as hard as aluminum oxide, and its performance on hardened steels is far superior. CBN is cool cutting, chemically resistant to inorganic salts and organic compounds, and can withstand grinding temperatures up to 1832°F (1000°C) before breaking down. Because of the cool-cutting action of CBN wheels, there is little or no thermal (heat) damage to the surface of the part being ground. The main benefits of grinding wheels made of CBN abrasive are shown in Fig. 6.

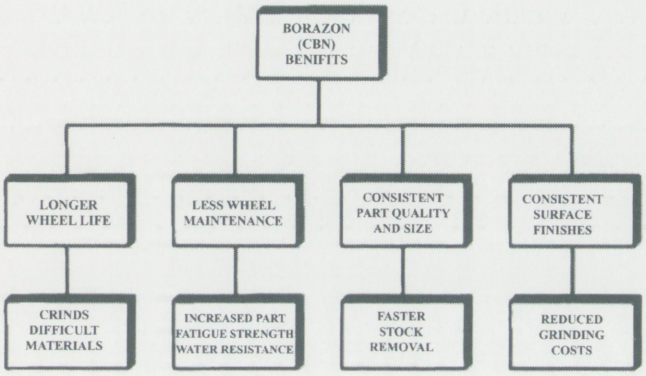


Figure 6. The main benefits of CBN grinding wheels.

Manufacture

CBN is manufactured in crystal form from hexagonal boron nitride, sometimes referred to as white graphite. Hexagonal boron nitride, which is composed of boron and nitrogen atoms along with a solvent catalyst, is convened into cubic boron nitride through the application of heat (3000°F or 1650°C) and pressure (up to 1.000.000 lbs./sq. in., or 68.500 atmospheres). The combination of high temperature and high pressure causes each nitrogen atom to donate an electron to a boron atom, which uses it to form another chemical bond to the nitrogen atom. This produces a strong, hard, blocky, crystalline structure similar to **diamond**.

Diamond is a solid form of carbon with a diamond cubic crystal structure.

CBN Types

There are various types of CBN available to suit a variety of steel grinding applications; CBN does not perform well on nonferrous or nonmetallic materials. Two main classes of CBN abrasive are monocrystailline and microcrystalline.

- *MONOCRYSTALLINE CBN* - Monocrystalline CBN abrasive contains a large number of cleavage (break) planes along which a fracture can occur. This macrofracture (large break) is necessary for the abrasive grains to resharpen themselves when they become dull, Fig. 7.

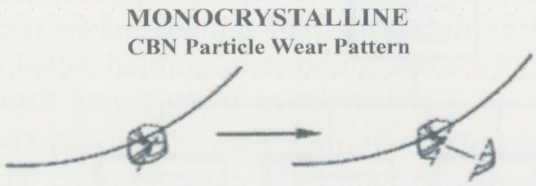


Figure 7. - Monocrystalline CBN crystals macrofracture (large break) under high grinding forces and expose new sharp cutting edges.

- *MICROCRYSTALLINE CBN* - Microcrystalline CBN abrasive consists of thousands of micron-size crystalline regions tightly bonded to each other to form a 100% dense particle. When the grains dull and the grinding pressure increases, they resharpen themselves by microfracturing (creating very small breaks), Fig. 8.

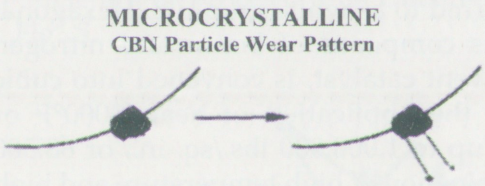


Figure 8. Microcrystalline CBN crystals microfracture (very small breaks) to resharpen a wheel and promote long wheel life.

Table 1 lists the various types of abrasives and the work-piece materials for which each is best suited.

Table 1. Abrasive-Workpiece profiles.

ABRASIVE - WORKPIECE PROFILE

RECOMMENDED ABRASIVES	WORKPIECE MATERIALS
DIAMOND ALUMINUM OXIDE SILICON CARBIDE	TUNGSTEN CARBIDE GLASS CERAMICS STONE
BORAZON*CBN ALUMINUM OXIDE SILICON CARBIDE	TOOL & DIE STEELS HARDENED ALLOY STEELS SUPERALLOYS

3.1.4 Characteristics of Superabrasives

The main physical properties of superabrasives that make them superior to conventional abrasives are shown in Fig. 9.

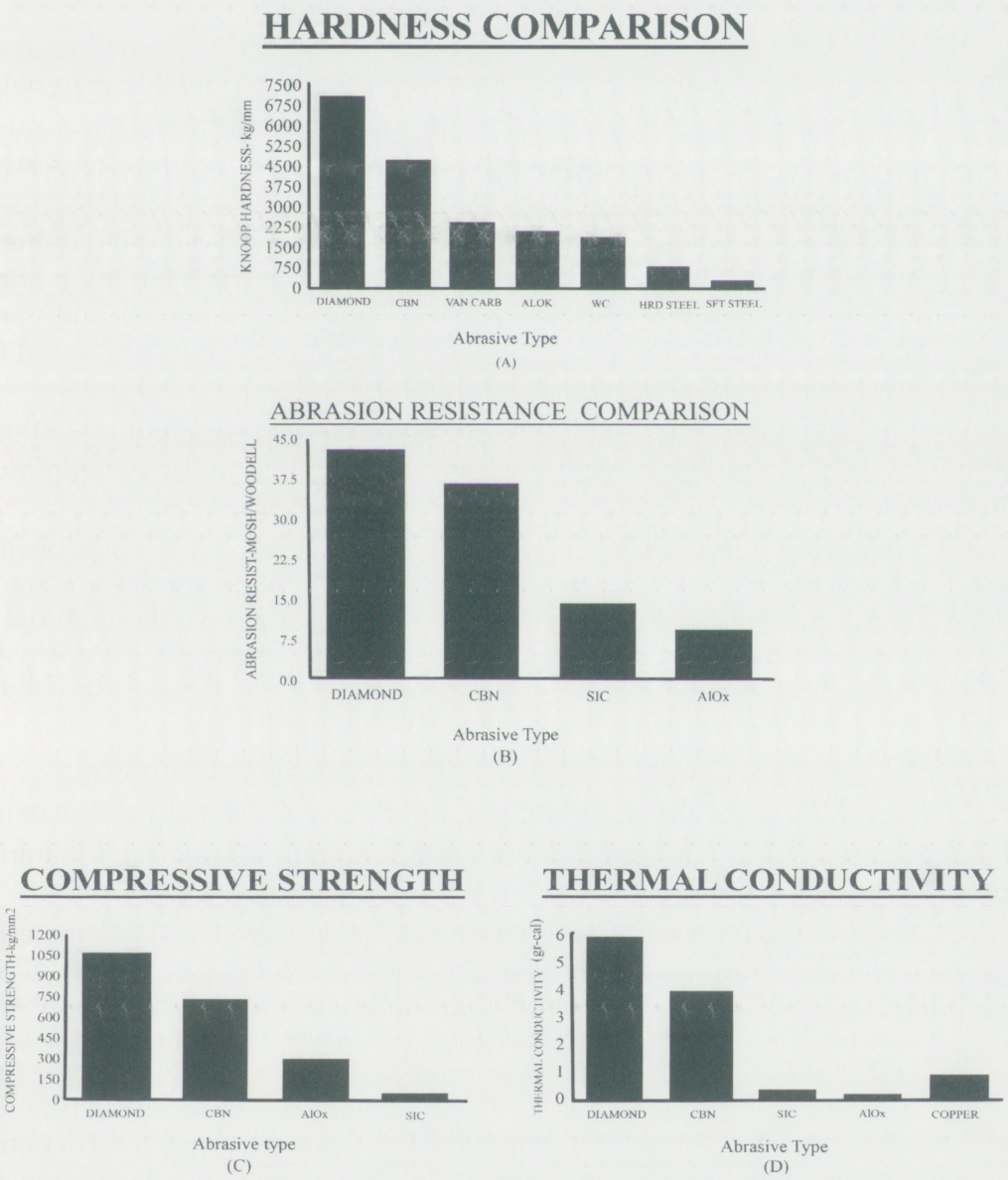


Figure 9. The properties that make superabrasives super-hard, super wear-resistant cutting tools.

- ***Hardness*** – The harder the abrasive with respect to the workpiece, the more easily it can cut and remove material. The basic principle in material removal is that the cut-ting tool must be harder than the material being removed. Hardness of the cutting tool with respect to the material allows higher cutting speeds and greater feeds to decrease the amount of time required to complete the work cycle. Due to the higher hardness, superabrasive tools last longer.
  - Diamond is four times harder than silicon carbide and is used for machining and grinding nonferrous and non-metallic materials.
  - Cubic boron nitride (CBN) is two and one half times harder than aluminum oxide and is used for machining and grinding ferrous materials.
- ***Abrasion Resistance*** - Resistance to abrasive wear is a desirable property in a cutting tool, it increases the productivity by maintaining a sharp cutting edge longer. It also allows increased cutting speeds and feeds, decreasing the time required to complete the work cycle and lessen the time required to maintain the cutting tool.
  - Diamond has three times the abrasive resistance of silicon carbide.
  - CBN has about four times the abrasive resistance of aluminum oxide.
- ***Compressive Strength*** - The physics of metal removal consists of high pressures created in the shear zone as a result of the materials resistance to rupture. Resistance to compressive pressure allows the material to fracture, thus producing a chip of material removed. Compressive strength of a material is a linear relationship to its density; the higher the density, the higher the compressive strength.
  - Diamond is eighteen times greater than silicon carbide.
  - CBN is about two and one half times greater than aluminum oxide.

Superabrasives can withstand forces of interrupted cuts and high material-removal rates.

- ***Thermal Conductivity*** - The majority of the heat produced in a material-removal process takes place in the shear zone because of the plastic deformation of the material being cut. As the shear angle decreases, due to heat, the length of the shear plane increases, producing more heat. The remainder of the heat produced is a result of friction as the chip slides over the tool. High thermal conductivity of the cutting tool allows the heat to be dissipated quicker. This decreases the friction at the chip/tool interface increasing the shear angle and decreasing the length of the shear plane.
  - Diamond has 27 times the thermal conductivity of silicon carbide.
  - CBN has 55 times the thermal conductivity of aluminum oxide.

The superior qualities of diamond and CBN allow cutting tools to stay sharp longer and allow free cutting at high temperatures and cutting speeds. Diamond and CBN tools increase productivity while producing dimensionally accurate parts.

3.1.5 Machinability and Grindability

The type of material and its physical, mechanical, and chemical properties have a major effect on its machinability. The mechanical properties of hardness, strength, toughness, and abrasion resistance are the main properties that determine the machinability and grindability of any given material. Naturally softer materials will have a higher machinability than would hard abrasive materials, making harder materials more expensive to machine.

Abrasive is a material, often a mineral, that is used to shape or finish a workpiece through rubbing which leads to part of the workpiece being worn away by friction.

- ***Hardness*** - The depth and distribution of hardness in a work material is generally the result of a heat treating operation, the alloy content, or a combination or both
- ***Strength*** - Refers to the tensile strength; the higher the tensile strength, the more difficult the material is to cut
- ***Toughness*** - Refers to the property of a material to absorb considerable energy before fracture and involves both ductility and strength
- ***Abrasion resistance*** - Refers to the material content of alloys or particles, which can cause rapid tool, wear

Low Machinability and Grindabillty Materials

The machining and grinding characteristics have an effect on tool life, the frequency of tool changes, and the cost of tools. The types of metals generally having a low machinability rating are tool steels, hardened alloy steels, high-temperature alloys, shape memory alloys, and highly **abrasive** materials.

3.1.6 Material-Removal Rates

In grinding operations, the material-removal rates are expressed as a grinding ratio (G ratio). It is calculated by

dividing the volume of work material removed by the volume of wheel material used. The higher the grinding ratio number, the more efficient the grinding operation.

$$G\ ratio = \frac{Volume\ of\ work\ material\ removed}{Volume\ of\ wheel\ material\ consumed}$$

The following examples in Fig. 10 show the differences in G ratio for various grinding wheels and work materials:

- The grinding ratio for a CBN wheel is 229 times greater than aluminum oxide when grinding M-2 tool steel.
- The grinding ratio for a CBN wheel is 150 times greater than aluminum oxide when grinding 1-15 tool steel.
- The grinding ratio for a CBN wheel is 217 times greater than aluminum oxide when grinding D-2 tool steel.

It is wise to try to match the cutting tool to the work material to get the best balance between productivity and tool life. Low material-removal rates extend the cutting tool life at the expense of productivity, while high material-removal rates increase productivity at the expense of tool life.

GRINDING RATIO EXAMPLES

WORKPIECE	HARDNESS	AlOx*	CBN**
M-2	60 Rc	4.5	1030
M-4	60 Rc	2.0	180
M-50	60 Rc	-	250
T - 15	65 Rc	0.8	120
O-1	62 Rc	50	750
A-2	62 Rc	20	390
D-2	62 Rc	3.0	650
GRAY IRON	32 RA	-	2700
NODULAR IRON	57 RA	-	870

*10 IN DIA
**5 IN DIA

Figure 10. The grinding ratio examples between aluminum oxide and CBN grinding wheels.

3.1.7 Grinding Wheels

The first application of superabrasives was in grinding wheels for sharpening milling cutters. Fig. 11. Although the applications for diamond and CBN grinding wheels are very different, these two superabrasives contain the four main properties that cutting tools must have to cut extremely hard or abrasive materials at high-material removal rates.



Figure 11. One of the first applications for superabrasive grinding wheels was in resharpening milling cutters.

Diamond grinding wheels are used to grind a variety of nonferrous and nonmetallic materials. In the metalworking industries, diamond wheels are widely used to regrind tungsten carbide tools. Diamond wheels are also important in the production of electronic components from materials such as silicon, germanium, and ferrites. Automotive, optical, and decorative glass finishing operations, and many non-metal space age materials such as silicon nitride, aluminum oxide, metal-matrix composites, PEAK, and silicon carbide arc ground with diamond wheels.

Cubic Boron Nitride (CBN) grinding is often recognized worldwide as a superior cutting tool for grinding difficult to cut ferrous-based metals. From their initial use in toolroom grinding applications. CBN wheels have made their presence felt in production grinding operations worldwide, where high technology CNC machines are revolutionizing the metal working industry. Conventional abrasives are ineffective, less productive, and uneconomical for use on these automatic computers controlled systems. Grinding wheels containing CBN abrasives last longer, provide more accurate parts, and require little or no reconditioning after initial truing and dressing. These wheels are more productive when grinding hardened steels, tool steels, and superalloys because of the properties of the CBN crystals. The CBN crystal is an extremely hard abrasive that is able to withstand the machining pressures and the heat of production grinding better than other abrasives. It has the toughness to match its hardness so that its cutting edges stay sharp longer and the crystal regenerates these edges to stay freer cutting over a longer period of time than conventional abrasives, Fig. 12.

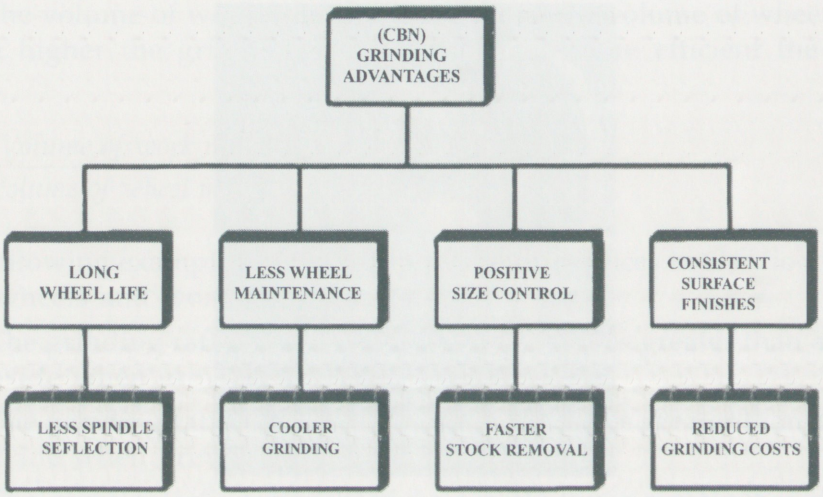


Figure 12. The advantages of grinding with CBN wheels.

3.1.8 Polycrystalline Tools

Up until 1973, Diamond and CBN, in abrasive grain form, were the only available superabrasive products. With the development of polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) blanks and inserts, a new generation of superabrasive cutting tools became available. These tool blanks consist of a .025 in. (0.63mm) layer of diamond or CBN bonded to a cemented carbide substrate (base). Polycrystalline diamond tools are used to cut abrasive nonferrous and nonmetallic materials, while polycrystalline CBN tools are used to cut hard, ferrous metals, superalloys, and certain cast irons, Table 1. The cutting edges of polycrystalline cutting tool blanks and inserts are more wear resistant than the cutting edges of conventional tools such as cemented carbides, even when removing material at much higher rates. As a result, these tools need to be indexed or changed far less often than carbide or ceramic tools. This reduces the amount of downtime and as a result increases productivity. Properly designed polycrystalline tools have high impact resistance and therefore can be used to machine parts that require severe interrupted cuts or the removal of tough, abrasive forging scales.

3.1.9 Machine Requirements

The performance of a superabrasive grinding wheel or polycrystalline cutting tool depends on the capabilities of the machine. Trying to use a superabrasive tool to make up for poor machine conditions will be doomed to failure right from the beginning. In order for superabrasive tools to work effectively, they *should be* used on machines that have the following characteristics:

- **Tight spindle bearings** and **snug machine** slides to prevent vibration and chatter that could shorten the tool life, produce a poor surface finish, and inaccurate work. Fig. 13.
- **Consistent spindle speeds,** to handle the torque required for high metal-removal rates, arc necessary to keep superabrasive tools operating at best efficiency. Loss of spindle speed reduces the efficiency of the cutting action and shortens the life of the tool.

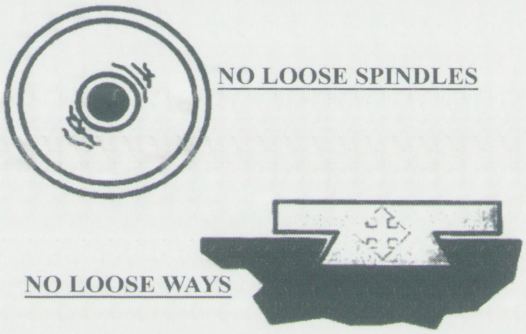


Figure 13. A machine with a tight spindle and snug ways is necessary for machining and grinding with superabrasives.

3.1.10 Grinding Wheels

The first application of the superabrasives, diamond and cubic boron nitride, was in grinding wheels. Although the applications for diamond and cubic boron nitride grinding wheels are very different, these two superabrasives contain four main properties that cutting tools must have to cut extremely hard or abrasive materials at high metal removal rates.

Diamond grinding wheels are used to grind a variety of nonferrous and nonmetallic materials. In the metalworking industries, diamond wheels are widely used to regrind various types of tungsten carbide tools.

Cubic boron nitride (CBN) grinding wheels arc recognized worldwide as superior cutting tools for grinding hard, abrasive ferrous-based metals. From their initial use in tool-room and cutter grinding applications. CBS wheels have made their presence felt in production grinding operations worldwide, where high technology CNC machines are revolutionizing the metalworking industry.

- Grinding wheels containing CBN abrasives last longer, provide more accurate pans, and require little or no conditioning after initial truing and dressing.
- These wheels are more productive when grinding hardened steels, tool steels, and superalloys, because of the properties of the CBN crystals.

- Not only is the CBN crystal an extremely hard abrasive, it is able to withstand the machining pressures and the heat of production grinding better than other abrasives.
- The CBN abrasive crystal has the toughness to match its hardness so that its cutting edges stay sharp longer, and the crystal resharpens itself to stay free cutting.

Superabrasive tools can be used effectively on conventional machines in good condition. Machine tool builders that have high speed and rigid spindles are now developing new machines specifically designed for superabrasives.

3.1.11 Applications of Superabrasives

Superahrasive tools are widely used in automotive, aerospace, and other manufacturing industries for turning and milling operations of hard, abrasive, and difficult-to-cut materials. Industry has found that these superabrasive cutting tools are among the most effective tools for production cost reduction and product improvement. In terms of the number of pieces per cutting edge, downtime and overall productivity, superabrasive tools have proven to be the most cost efficient tools available today.

General Applications Guidelines

To obtain the best tool performance and the most number of parts per cutting edge, the following guidelines should be closely followed.

- Use PCD cutting tools for machining and grinding nonferrous and nonmetallic materials.
- Select a rigid machine with good bearings and enough horsepower to maintain the cutting speed where PCD tools perform best.
- Use a speed three times faster than for a cemented tungsten carbide tool.
- Set speed and feed rates that give a good balance between productivity and long tool life.
- Use rigid toolholders and keep the tool overhang as short as possible to avoid deflection, chatter, and vibration.
- Use positive rake angles and the largest nose radius possible for better surface finishes and to spread the cutting force over a wider area.
- Establish the life of each cutting edge or tool (usually after a certain number of pieces arc cut) and change tools at the first sign of dullness.
- Use coolant wherever possible to reduce heat, promote free cutting, and flush away the abrasive chips from the finished work surface.

3.1.12 Polycrystalline Superabrasive Tools

With the development of polycrystalline diamond and polycrystalline cubic boron nitride (PCBN) tools in 1973, a new generation of cutting tools became available. Because of their excellent abrasion resistance and long wearing cutting edges, they greatly increase productivity while producing dimensionally accurate pans.

3.1.13 Manufacture of Polycrystalline Tools

A layer of diamond or CBN crystals is deposited onto a substrate, usually tungsten carbide, Fig. 14. The assembly is placed into a high pressure, high temperature apparatus. It is subjected to a heat of 2200°F (1204°C) and pressure of nearly 1,000,000 pounds per square inch. The crystals from a very strong bond to each other and the substrate.

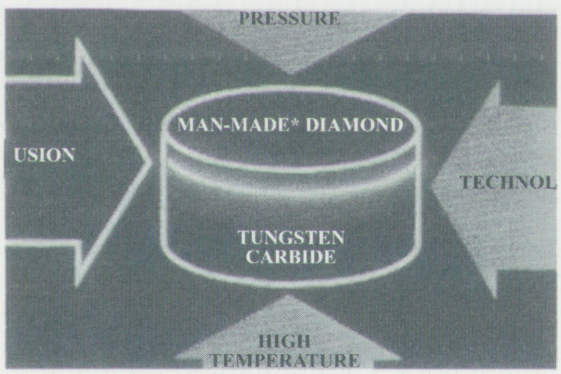


Figure 14. Polycrystalline tool blanks and inserts consist of a thin diamond or CBN layer bonded to a cemented carbide substrate.

3.1.14 Types of PCD and PCBN Inserts

A verity of PCD and PCBN tool blanks and inserts are shown in Fig. 15.

- ***Triangular,*** the most versatile tool shape. can be used to produce a wide range of shapes or forms on a workpiece
- ***Square,*** a strong insert that provides good support for the cutting edge. but cannot produce sharp corners on the workpiece
- ***Round,*** the strongest insert shape, provides more cutting edges than other shapes. but cannot produce corners on the workpiece

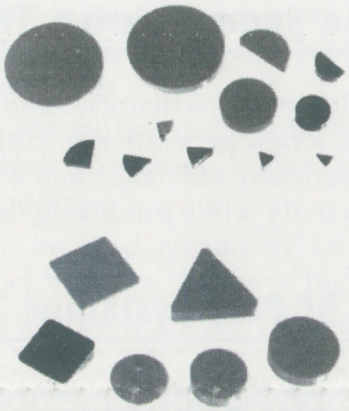


Figure 15. Polycrystalline tool blanks and inserts are available in a wide range of shapes and sizes.

3.1.15 Advantages of Polycrystalline Tools

The advantages that PCBN tools offer industry more than offset their initial higher cost, Fig. 16.

- ***Long Tool*** Life that consistently outperforms conventional tools from 10 to 700% and reduces tool wear, resulting in less machine downtime and dimensionally accurate workpieces.
- ***High Material Removal Rates*** that allow higher cutting speeds to be used because tools can withstand the heat and excessive wear encountered.
- ***Cuts Hard and Tough Materials*** including materials of Rc35 hardness and higher and, in some cases can replace grinding, which is a relatively slow material-removal process.
- ***High Quality Products*** that are produced faster and at reduced costs, that reduces the need for frequent inspections.
- ***Uniform Surface Finish,*** often in the single digit microinch range, because of reduced tool wear.
- ***Lower Tool*** Cost per Piece because tools stay sharp longer and cut efficiently, producing longer production runs.
- ***Reduced Machine Downtime*** that results in more machine time spent producing parts and less time spent changing and resetting cutting tools.

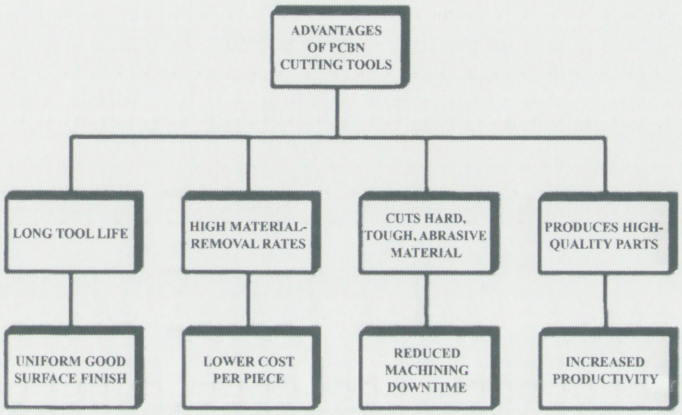


Figure 16. The main advantages of PCBN cutting tools.

3.1.16 Types of Materials Machined With PCD (Compax®) Tools

Polycrystalline diamond (PCD) tools are used for turning and milling nonferrous or nonmetallic materials, especially where the workpiece is hard and abrasive. The largest group of nonferrous metals is generally soft, but can have hard particles in them, such as silicon suspended in aluminum or glass fibers in plastic. These hard abrasive particles destroy the cutting edge of conventional tools. PCD tools often have a wear life of 100 times more than cemented carbide tools in such an abrasive machining application.

The materials most successfully machined with PCD tools fall into three general categories: nonferrous metals, nonmetallic materials, and composites, Table 2.

Table 2. The materials best suited for machining with PCD cutting tools.

PCD Cutting Tool Applications		
Nonferrous Metals	**Nonmetallic Materials**	**Composites**
Aluminum Alloys	Alumina Fired	Asbestos
Babbitt Alloys	Bakelite	Fiberglass Epoxy
Brass Alloys	Beryllia	Filled Carbons
Bronze Alloys	Ceramics	Filled Nylon
Copper Alloys	Epoxy	Filled Phenolic
Lead Alloys	Glass	Filled PVC.

Manganese Alloys	Graphite	Filled Silica
Silicon-Aluminum	Macor	Filled Teflon
Silver, platinum	Rubber, Hard	Wood, Manufactured
Tungsten Carbides	Various Plastics	
Zink Alloys		

3.1.17 Types of Materials Machined with PCBN (Borazon®) Tools

Polycrystalline cubic boron nitride (PCBN) tools are used for turning and milling operations on abrasive, and difficult-to-cut (DTC) materials. PCBN tools can remove material at much higher rates than conventional cutting tools, with far longer tool life. Wherever PCBN cutting tools were used to replace a grinding operation, machining time was greatly reduced because of the higher metal-removal rate.

The best applications for PCBN cutting tools are on materials where conventional cutting-tool edges of cemented carbides and ceramics are breaking down too quickly. Their long-lasting cutting edges are capable of transferring the accuracy of computer controlled machine tools and flexible manufacturing systems, thereby producing accurate pans, increasing productivity, and reducing expensive machine downtime.

3.1.18 Advantages of Superabrasives

The advantages of Superabrasive grinding wheels are more than extraordinary hardness, unparalleled performance, and longevity. These three features of Superabrasives are the core of many advantages manufacturers gain by an aggregation of services that normal abrasives simply cannot deliver.

These include,

- Less expensive tooling and fixturing costs
- More wheels on the spindle, smaller wheels, multiple operations
- Less floor space needed for manufacturing
- Virtual elimination of wheel wear
- Automated CNC machines, less labor intensive operations requiring less training
- Consistent surface speed from part to part
- Better overall throughput with fewer machines needed
- Improved Material Removal Rates, Lower Per Part Abrasive Costs and higher speeds

With Superabrasives, production increased by automated CNC equipment, industries have found one way to compensate for the lack of availability of skilled labor. With fewer machines needed, so is fewer workers. With Superabrasives CNC, automation is more concerned with defining a manufacturing process using machine capabilities and mechanization. There is less concern on operator technique. A properly defined process, combined with automatic loaders make for equipment that is almost running itself.

3.2 CARBIDE TOOLING

Among all the manufacturing processes that can be applied to shaping and forming of raw materials into useful products, the machining process has always been one of the most important operations. The fundamental cutting processes in machining, those of bringing the work into contact with the **cutting tool**, are still very much in evidence and should remain main-stays of the industry.

Cutting tool is any tool that is used to remove material from the work piece by means of shear deformation.

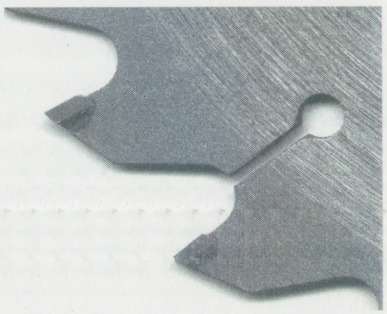
One of the most important components in the machining process is the cutting tool: its performance will determine the efficiency of the operation. Consequently, much attention has been directed to the selection of the tool materials, the cutting tool angles and their coating materials. Recent demands for high productivity combined with closer tolerance to machine heat resistant materials have made carbide tooling an important aspect of manufacturing technology.

3.2.1 Cemented Carbides

Cemented carbide is a hard material used extensively as cutting tool material, as well as other industrial applications. It consists of fine particles of carbide cemented into a composite by a binder metal. Cemented carbides commonly use tungsten carbide (WC), titanium carbide (TiC), or tantalum carbide (TaC) as the aggregate. Mentions of "carbide" or "tungsten carbide" in industrial contexts usually refer to these cemented composites.

Most of the time, carbide cutters will leave a better surface finish on the part, and allow faster machining than high-speed steel or other tool steels. Carbide tools can withstand higher temperatures at the cutter-workpiece

interface than standard high-speed steel tools (which is a principal reason for the faster machining). Carbide is usually superior for the cutting of tough materials such as carbon steel or stainless steel, as well as in situations where other cutting tools would wear away faster, such as high-quantity production runs.



Cemented carbides are produced by a powder metallurgy process. These cutting tools are largely composed of tiny pow-der particles of tungsten carbides (carburized tungsten), carbon powder, and cobalt (the binder), that are sintered together at temperatures between 2550 and 2730°F (1400-1500°C). The process for manufacturing cemented-carbide tools involves the steps shown in Fig. 17.

- ***Blending***: mixing the right amount of carbide powders and cobalt together for the type of cemented-carbide required.
- ***Compacting***: molding the green powder into size and shape in a press.
- ***Presintering***: heating the green compacts to approximately 1500°F (815°C) in a furnace to hold their size and shape.
- ***Sintering***: the final heating process, 2550 to 2730°F (1400 to 1500°C), to cement the carbide powders into a dense structure of extremely hard crystals.

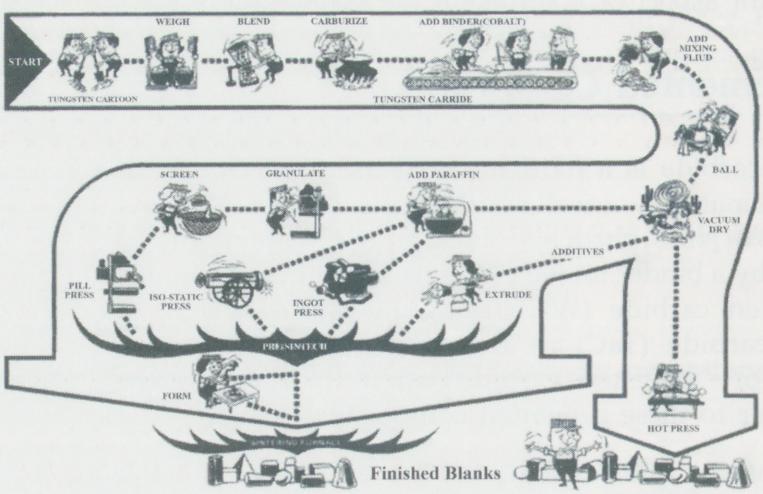


Figure 17. The power metallurgy process of manufacturing cemented-carbide tools.

The powder metallurgy process produces a wide variety of hard metals. Powdered metals such as titanium (Ti), columbium (Cb), tantalum (Ta), and niobium (Nb), are also used in manufacturing cemented carbide to provide cutting tools with various characteristics. Cutting tools made of cemented carbide can increase cutting speed about three to five times faster than those used for high-speed steel tools.

Table 3 shows the Valenite. Inc. system of uncoated carbide grades used for metal-removal operations on various applications, types of materials, cutting tool characteristics, and machining conditions. Although the coding system may vary from manufacturer to manufacturer, the characteristics and use of each carbide grade will be the same.

Table 3. Suggested uncoated carbide grades for metalcutting.

Uncoated Carbides					
Vilenite Grade	ISO class	Industry Class	Application	Materials	Working Methods & Conditions
VC2	M10-20 K10-20	C2	Timing. Boring & Milling	Cast-Iron, copper, brass, nonferrous alloys, high temperature exotics, stone and plastics.	General purpose grade of high toughness and resistance against flank wear at low to medium cutting speeds.
VC3	K10-05	C3, C4	Precision Turning, Boring, Milling	Cast iron, aluminum, high temperature exotics and nonferrous materials.	Wear-resistant grade for finishing cuts, low to medium feed rates under rigid conditions.
VC5	P20-30 M20-40	C5	Turning, Boring, & Milling	Steel, cast steel, malleable cast iron, 400/500 series stainless steels.	General purpose grade covering a wide range of applications, low to medium cutting speed, high feeds and depths of cut. Has good deformation resistance.
VC7	P05-15	C7	Tuning, Boring, Threading & Grooving	Steel, cast steel, malleable cast iron, 400/500 series stainless steels.	Light roughing to finishing at low to moderate feeds. Good crater and deformation resistance.

VC27	P15-30 M15-30 K20-30	C2	Timing, Milling	Steel, cast steel, alloyed cast irons, cast alloys, exotics.	General purpose fine grain grade with improved toughness and wear resistance for turning and milling.
VC28	M20-30 K15-30	C2	Milling	Cast and alloy irons.	General purpose grade for roughing to finishing in cast irons.
VC29	M10-20 K10-20	C2, C3	Turning, Boring & Milling	Stainless steels, irons, exotics and nonferrous materials.	Fine grain grade for finishing of exotic irons and nonferrous metals.
VC35	P20-35	C5	Milling	Carbon, alloy steel and stainless steel.	General purpose steel milling grade for moderate roughing to finishing.
VC101	M30-40 K30-40	Cl	Tuning, Boring & Milling	Iron, 200/300 stainless steel and exotics	Fine grain heavy-duty grade for roughing at low to moderate speeds.

3.2.2 Carbide Tool Identification

There are four basic groups of cutting tool materials used in metal-removal operations: tungsten carbide, cermet, ceramic, and polycrystalline. There are two basic tool types used in carbide cutting - indexable insert tool and standard brazed on insert tool. Indexable insert tools. Fig. 18 are the most economical and those commonly used all types of metal-cutting operations. The inserts provide a number of low cost, index-able cutting edges. After all cutting edges are worn, it is generally more economical to replace the insert than to have someone regrind the insert. Various methods are used to lock the insert in position. A cam-type lock pin, or a clamp, or combination of lock pin and clamp arc among the techniques used.

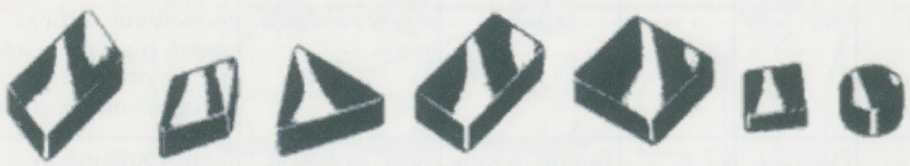


Figure 18. A variety of indexable carbide inserts.

Standard brazed-on tools, low in initial cost, can be used for special and some general-purpose machining operations. They are rarely used in manufacturing today because of the time it takes to recondition and reset a tool once it has become dull.

Indexable Carbide Tool Identification

Numerous manufacturers throughout the world make cemented carbide indexable inserts in a wide variety of shapes and sizes. The more inserts available, the more difficult it is for those in industry to select the correct tool insert consistently.

Turning Inserts

Most turning inserts today arc .187 in. (5mm) thick, .50 **in.** (13mm) IC (inscribed circle) radius with 35°. 55°, 60°, and 80° geometries. The 60° triangular insert, with six cutting edges, is a good *choice* for general-purpose machining. Fig. 19.

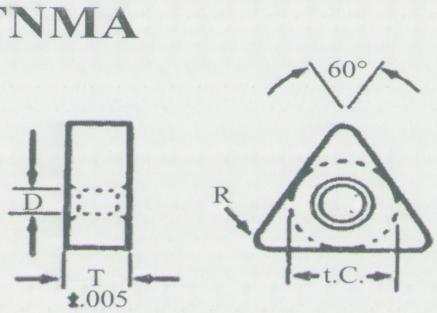


Figure 19. The triangular 60° insert with six cutting edges is used for general purpose machining.

- For turning steel, the Sandvik PR inserts have been developed to achieve good chip control especially during roughing cuts. These inserts have a positive insert geometry with the top rake increased to 22° to enable high productivity where toughness is required. Fig. 20.
- For heavy interrupted cuts or similar roughing operations, sturdier inserts such as the square or round inserts are recommended.

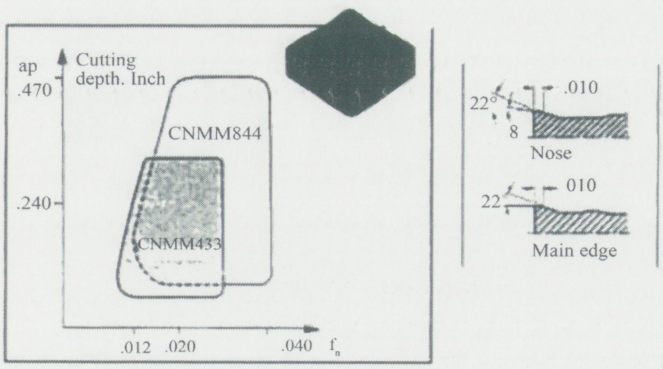


Figure 20. The positive 22° rake on the insert provides high productivity where toughness is required.

Milling Inserts

Carbide milling inserts are available in a wide variety of geometric shapes and sizes. The Sandvik CoroKey geometry insert codes are illustrated in Fig. 21.

Code: L ***or light operations***: Extra positive geometry for low cutting forces, suitable for small machines and sticky materials

M ***or medium operations***: Positive geometry for general use, has high edge toughness and is the basic insert for most materials

H **for heavy operations**: Reinforced cutting edge that allows the highest possible feed rate. reliable in operations where the recutting of chips may occur

In the midst of all these insert styles, the simple round insert is emerging as the first choice milling insert for a growing number of machinists, programmers, and engineering. Round carbide inserts are strong, versatile and economical. Despite the simple shape, that are complex and sophisticated cutting tools. Subtle changes in geometry, depth of cut, lead angle and rake can make a big difference.

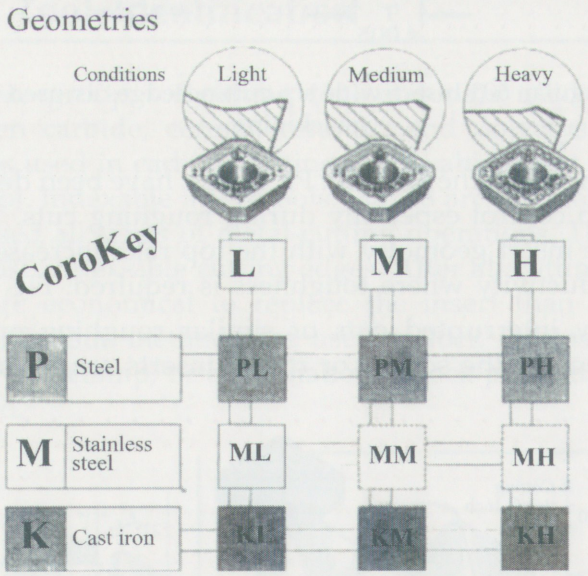


Figure 21. The Coro-Key insery codes cover various machining conditions.

3.2.3 Carbide Tool Advantages

- Excellent wear resistance
- Greater hardness than high-speed steel tools

- Ability to maintain a cutting edge under high-temperature conditions
- Inserts can be replaced quickly when they are dull and therefore minimize the amount of machine downtime
- Higher cutting speeds and feed rates can be used, increasing productivity

SUMMARY

- The superabrasives, Diamond and Cubic Boron Nitride, possess properties unmatched by conventional grinding wheels and cutting tools for grinders, lathes, and machining centers. The hardness, abrasion resistance, compressive strength, and thermal conductivity of superabrasives makes them the logical choice for many difficult grinding, sawing, lapping, machining, drilling, wheel dressing, and wire drawing applications.
- Superabrasive cutting tools are designed to meet the challenge of today by increasing productivity, producing better quality products, and reducing manufacturing costs.
- Superabrasives are tools used in precision grinding. Superabrasive materials attach to a wheel to make Superabrasive grinding wheels. The reason some abrasives are Superabrasives is due to their extraordinary hardness, unparalleled performance, and longevity.
- Diamond is used for truing and dressing grinding wheels and for the manufacture of diamonds' heels. The need for a reliable source of diamond during World War II was realized when natural diamond was not readily available.
- The RVG diamond abrasive can be coated to prevent the diamond crystals from being pulled out from the resin bond. Coatings, such as nickel and copper provide better retention (holding power) for the RVG crystal in the wheel bond.
- Diamond is used to machine and grind hard, abrasive nonferrous, nonmetallic, and composite materials. It is not recommended for grinding and machining ferrous materials because of the chemical characteristic known as carbon solubility potential, where steels will react with any source of carbon to absorb carbon into their surface.
- A major breakthrough in the precision high-production grinding of hard, difficult-to-grind ferrous metals, was the discovery and manufacture of cubic boron nitride. CBN is twice as hard as aluminum oxide, and its performance on hardened steels is far superior. CBN is cool cutting, chemically resistant to inorganic salts and organic compounds, and can withstand grinding temperatures up to 1832°F (1000°C) before breaking down. Because of the cool-cutting action of CBN wheels, there is little or no thermal (heat) damage to the surface of the part being ground.
- Diamond grinding wheels are used to grind a variety of nonferrous and nonmetallic materials. In the metalworking industries, diamond wheels are widely used to regrind tungsten carbide tools. Diamond wheels are also important in the production of electronic components from materials such as silicon, germanium, and ferrites.
- Superahrasive tools are widely used in automotive, aerospace, and other manufacturing industries for turning and milling operations of

hard, abrasive, and difficult-to-cut materials. Industry has found that these superabrasive cutting tools are among the most effective tools for production cost reduction and product improvement.

- Polycrystalline diamond (PCD) tools are used for turning and milling nonferrous or nonmetallic materials, especially where the workpiece is hard and abrasive. The largest group of nonferrous metals is generally soft, but can have hard particles in them, such as silicon suspended in aluminum or glass fibers in plastic.
- Polycrystalline cubic boron nitride (PCBN) tools are used for turning and milling operations on abrasive, and difficult-to-cut (DTC) materials. PCBN tools can remove material at much higher rates than conventional cutting tools, with far longer tool life.
- Cemented carbide is a hard material used extensively as cutting tool material, as well as other industrial applications. It consists of fine particles of carbide cemented into a composite by a binder metal.
- Cemented carbides are produced by a powder metallurgy process. These cutting tools are largely composed of tiny pow-der particles of tungsten carbides (carburized tungsten), carbon powder, and cobalt (the binder), that are sintered together at temperatures between 2550 and 2730°F (1400-1500°C).

REFERENCES

1. Childs, Thomas (2000). "A6.2 Cemented carbides and cermets". Metal Machining: Theory and Applications. Butterworth-Heinemann. pp. 388–9. ISBN 978-0-340-69159-5.
2. Crane, T. P.; Cowan, B. P. (2000). "Magnetic Relaxation Properties of Helium-3 Adsorbed on Hexagonal Boron Nitride". Physical Review B. 62 (17): 11359. Bibcode:2000PhRvB..6211359C. doi:10.1103/PhysRevB.62.11359.
3. Engler, M. (2007). "Hexagonal Boron Nitride (hBN) – Applications from Metallurgy to Cosmetics" (PDF). Cfi/Ber. DKG. 84: D25. ISSN 0173-9913.
4. Griggs, Jessica (2014-05-13). "Diamond no longer nature's hardest material". New Scientist. Retrieved 2018-01-12.
5. Haynes, William M., ed. (2011). CRC Handbook of Chemistry and Physics (92nd ed.). Boca Raton, FL: CRC Press. p. 5.6. ISBN 1439855110.
6. http://www.chasediamond.com/non-ferrous%20materials.htm
7. https://nptel.ac.in/courses/112105127/pdf/LM-16.pdf
8. https://www.cdtusa.net/blog/what-superabrasives-are-how-they-are-used
9. https://www.google.co.in/search?rlz=1C1NHXL_enIN806IN806&biw=1242&bih=597&ei=_gC2W6PgDtDazgLT85yABQ&q=Silicon-Aluminum%09Macor%09Filed+Teflon&oq=Silicon-Aluminum%09Macor%09Filed+Teflon&gs_l=psy-ab.3..0i71k1l8.690307.690307.0.690735.1.1.0.0.0.0.0.0..0.0....0...1.1.64.psy-ab..1.0.0....0.UEce6XVKyw4
10. Kawaguchi, M.; et al. (2008). "Electronic Structure and Intercalation Chemistry of Graphite-Like Layered Material with a Composition of BC6N". Journal of Physics and Chemistry of Solids. 69 (5–6): 1171. Bibcode:2008JPCS...69.1171K. doi:10.1016/j.jpcs.2007.10.076.
11. Kubota, Y.; et al. (2007). "Deep Ultraviolet Light-Emitting Hexagonal Boron Nitride Synthesized at Atmospheric Pressure". Science. 317 (5840): 932–4. Bibcode:2007Sci...317..932K. doi:10.1126/science.1144216. PMID 17702939.
12. Lan, J. H.; et al. (2009). "Thermal Transport in Hexagonal Boron Nitride Nanoribbons". Physical Review B. 79 (11): 115401. Bibcode:2009PhRvB..79k5401L. doi:10.1103/PhysRevB.79.115401.
13. Leichtfried, G.; et al. (2002). "13.5 Properties of diamond and cubic boron nitride". In P. Beiss; et al. Landolt-Börnstein – Group VIII Advanced Materials and Technologies: Powder Metallurgy Data. Refractory, Hard and Intermetallic Materials. 2A2. Berlin: Springer. pp. 118–139. doi:10.1007/b83029. ISBN 978-3-540-42961-6.

14. Pan, Z.; et al. (2009). "Harder than Diamond: Superior Indentation Strength of Wurtzite BN and Lonsdaleite". Physical Review Letters. 102 (5): 055503. Bibcode:2009PhRvL.102e5503P. doi:10.1103/PhysRevLett.102.055503. PMID 19257519.

15. Silberberg, M. S. (2009). Chemistry: The Molecular Nature of Matter and Change (5th ed.). New York: McGraw-Hill. p. 483. ISBN 0073048593.

16. Taniguchi, T.; et al. (2002). "Ultraviolet Light Emission from Self-Organized p–n Domains in Cubic Boron Nitride Bulk Single Crystals Grown Under High Pressure". Applied Physics Letters. 81 (22): 4145. Bibcode:2002ApPhL..81.4145T. doi:10.1063/1.1524295.

17. Tian, Yongjun; et al. (2013). "Ultrahard nanotwinned cubic boron nitride". Nature. 493 (7432): 385–8. Bibcode:2013Natur.493..385T. doi:10.1038/nature11728. PMID 23325219.

18. Watanabe, K.; Taniguchi, T.; Kanda, H. (2004). "Direct-Bandgap Properties and Evidence for Ultraviolet Lasing of Hexagonal Boron Nitride Single Crystal". Nature Materials. 3 (6): 404–9. Bibcode:2004NatMa...3..404W. doi:10.1038/nmat1134. PMID 15156198.

4

CHAPTER

SPECIAL MACHINES

INTRODUCTION

Machine, device, having a unique purpose, that augments or replaces human or animal effort for the accomplishment of physical tasks. This broad category encompasses such simple devices as the inclined plane, lever, wedge, wheel and axle, pulley, and screw (the so-called simple machines) as well as such complex mechanical systems as the modern automobile.

The operation of a machine may involve the transformation of chemical, thermal, electrical, or nuclear energy into mechanical energy, or vice versa, or its function may simply be to modify and transmit forces and motions. All machines have an input, an output, and a transforming or modifying and transmitting device.

Machines that receive their input energy from a natural source, such as air currents, moving water, coal, petroleum, or uranium, and transform it into mechanical energy are known as prime movers. Windmills, waterwheels, turbines, steam engines, and internal-combustion engines are prime movers. In these machines the inputs vary; the outputs are usually rotating shafts capable of being used as inputs to other machines, such as electric generators, hydraulic pumps, or air compressors. All three of the latter devices may be classified as generators; their outputs of electrical, hydraulic, and pneumatic energy can be used as inputs to electric, hydraulic, or air motors. These motors can be used to drive machines with a variety of outputs, such

as materials processing, packaging, or conveying machinery, or such appliances as sewing machines and washing machines. All machines of the latter type and all others that are neither prime movers, generators, nor motors may be classified as operators. This category also includes manually operated instruments of all kinds, such as calculating machines and typewriters

4.1 LINEAR MOTORS

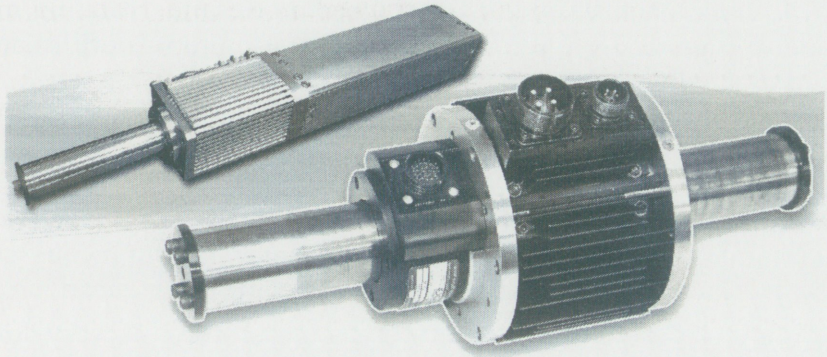
Sometimes referred to as a linear induction motor, the linear motor is a motor device that functions with the use of a multi-phase alternating current. As part of the design for the motor, the stator is in an unrolled position. This makes it possible for the linear motor to produce linear force along the length of the stator rather than the more common approach of producing rotation or torque.

Linear motors are usually classified as either low acceleration or high acceleration models. The low acceleration model works well for many ground transportation methods, such as with the use of commuter trains. In contrast, a high acceleration linear motor is ideal for locomotion that is not strictly considered ground transportation. The range of a high acceleration linear motor would include such entertainment devices as a roller coaster, as well as motors designed to aid in propelling spacecraft through the atmosphere of the earth and into open space.

The concept of electric drive linear motors actually precedes the invention of the automobile. The first designs for a working linear motor are attributed to Charles Wheatstone. Developed in the early 1840's while Wheatstone was associated with King's College in London, the model was workable but generally considered impractical for mass production.

Further technological advances in the 20th century made the idea of a linear motor for general usage more practical. During the first half of the century, designs were patented in the United States, the United Kingdom, Germany, and Japan. Along with use in transportation, the linear motor also proved to be workable in mining situations, as well as some manufacturing environments. The invention of a Lorentz-type actuator helped to broaden the usability and appeal of the linear motor as the century progressed.

Today, the linear motor is utilized as a matter of course in a number of settings. Aircraft commonly make use of the motor. In like manner, the motor is used with large aircraft carriers. Many companies around the world make use of the motor in digging operations, as well as some factory work. Even military weaponry may involve the use of a linear motor as part of the design.



4.1.1 The advantages and disadvantages of linear motors

A linear motor is a motor that converts electrical energy directly into linear motion without passing through any intermediate switching mechanism. The superiority of linear motor drives has been recognized by more and more people. So what are the advantages and disadvantages of linear motors? The text will detail the advantages and disadvantages of the linear motor.

Advantages of Linear Motors

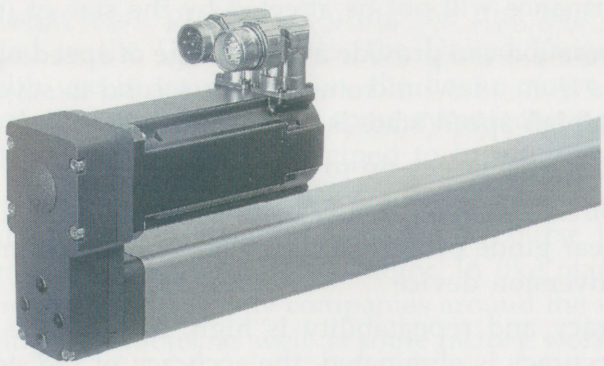
1. No mechanical contact, the transmission force is generated in the air gap, in addition to the linear motor rail without any other friction
2. The structure is simple, small size, by using fewer parts to achieve our linear drive, and this is only a moving part
3. The itinerary of the operation is theoretically unrestricted, and its performance will not be affected by the size of its itinerary
4. Its operation can provide a wide range of speed operating range, which covers from a few micrometers per second to several meters, especially in the high speed state is one of its outstanding advantages
5. Acceleration, larger up to 10g
6. Smooth movement, this is because in addition to supporting the role of linear guide or air bearing, there is no other mechanical connection or conversion device
7. Accuracy and repeatability is high, because the intermediate part of the accuracy is eliminated, the accuracy of the system depends on the position detection element, the appropriate feedback device can reach sub-micron level
8. Maintenance is simple, because the parts less, no mechanical contact when moving, thus greatly reducing the wear and tear parts, only little

or no maintenance, longer life. Linear motor and "rotating motor, ball screw" transmission performance comparison table performance rotary motor + ball screw linear motor.

Disadvantages of Linear Motors:

1. Linear motor power consumption, especially in the high load, high acceleration of the movement, the machine instantaneous current on the workshop power supply system to bring heavy load;
2. is high vibration, linear motor dynamic stiffness is very low, cannot play the role of buffer damping, in high-speed movement easily lead to other parts of the machine resonance;
3. is a large amount of heat, fixed at the bottom of the table motor is a high fever parts, the installation location is not conducive to natural heat, the machine temperature control caused great challenges;
4. Is not self-locking, in order to ensure safe operation, linear motor-driven movement axis, especially the vertical movement axis, must be equipped with additional locking mechanism, increasing the complexity of the machine.

With the rapid development of high-speed processing technology, the transmission and control system requirements are getting higher and higher, so that the linear motor drive technology research efforts gradually increased. Now many of the shortcomings of linear motors have been overcome, the linear motor power performance is more excellent. Linear drive technology research is both the trend of higher and faster development of technology, but also better meet the needs of the market, bring greater economic benefits, become the inevitable trend of future development.



4.1.2 Benefits of Linear Motors

Today, most motor technologies are set up to run in a rotary fashion. This can be a problem when the need to produce a straight move arises. To get linear

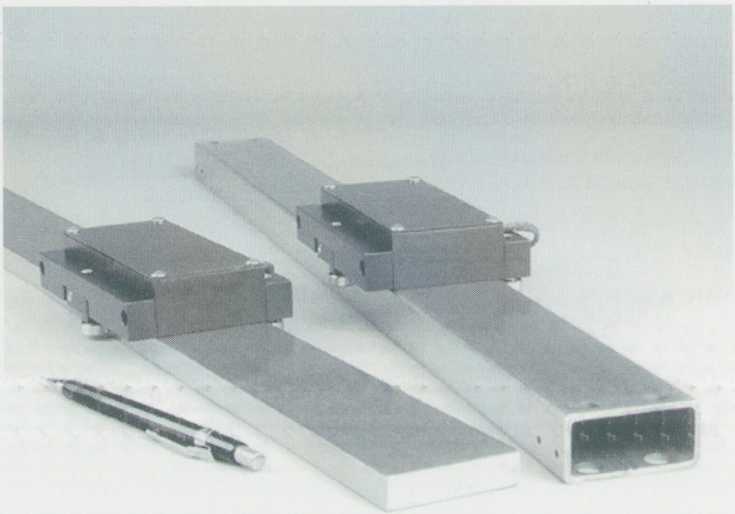
output you would be forced to buy and maintain additional components (such as pinion gears, belts, pulleys, etc.), thus wasting precious time and money. To solve this issue, many engineers opt to upgrade their system to use a linear motor. Linear motors run in a straight line and follow your instructions, all with a minimal number of components.

Performance Attributes of Linear Motors

- Straight Motion
  - Up / down
  - In / out
  - Push / pull
- Fast
  - Acceleration
  - Deceleration
  - Run speeds up to and beyond 100" per second
- Precise
  - Positioning with closed loop encoders built right onboard
  - Motion profile to follow your exact commands (in, out, sine/cos, vibrate at desired frequency, etc.)
  - Drive the brushless linear motor with the right amount of current to get exact force needed
- Robust
  - Simple two component construction - stator and rotor
  - Less components means less to fail = more engineering reliability
  - Non-contact magnet field creates motion
  - Long life bearing; require 1 minute of maintenance every 6 months

Moog's linear motors offer dynamic and precise linear motion positioning for **robotics**, factory automation, processing, packaging and other industrial applications. As a high force, direct drive solution, Moog's linear motors extend maintenance intervals and reduce the cost of ownership of any linear motion system. These devices are easy to install and have a rugged and durable design with built-in thermal and fault detection.

Robotics is an interdisciplinary branch of engineering and science that includes mechanical engineering, electronics engineering, information engineering, computer science, and others.



4.1.3 Designing with Linear Motor

Industrial linear motors offer design engineers the possibility of constructing machines in new ways. Fast, simple, and flexible, linear motors are easy to install and in many cases come with integrated sensors and bearings. Successful applications, however, require precise drive planning and a design that's appropriate for linear motors.

Physical limits

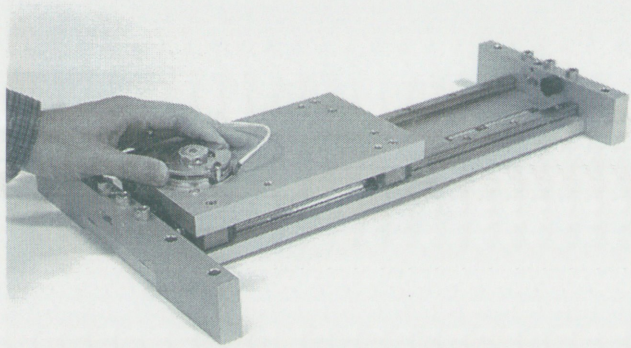
Linear motors also have weaknesses. The greatest disadvantage undoubtedly lies in their limited power and force densities. As with every electromagnetic drive, this limit is determined by magnetic saturation effects and the ohmic resistance in the electrical wiring (copper or aluminum).

Similarly, a linear motor with a particular volume can never produce the same force as a pneumatic or hydraulic cylinder of the same size. This comparison is not quite fair, however, as both the pneumatic and the hydraulic solutions require either an additional external compressed air source or oil preparation. Linear motors, on the other hand, represent an entirely electric solution.

Compared to rotating electrical motors, the power density of linear motors is basically the same. For many applications with rotary drives, however, step-down gears are often used. Speed is sacrificed for increased torque or higher force by using an additional spindle or belt. A high force can be produced, yet the dynamics are lost and all the additional disadvantages of mechanical conversion gears must be accepted.

Drive design for linear motors

The Achilles tendon of linear motors is that only a limited amount of force is available, which makes drive design extremely important. Today, modern design programs help with all necessary calculations, so that anyone can design a linear motor system.



Mechatronic design method

The suggested mechatronic construction method is *not* — on completion of the mechanical design — to simply select any old motor from any old catalog that is able to move the mechanics. It should *not* happen that the construction must be subsequently strengthened just because a more powerful (and heavier) motor had to be chosen. On the contrary, basic drive technology considerations must be part of the design process and should always aim to reduce the direct as well as indirect costs of the drive system.

Importance of mass in motion

The in-motion mass (gripper and working load) has, via the formula $F = ma$, a direct influence on the required driving force. A reduction of the mass in motion not only reduces the required driving power but, in general, also leads to simpler guiding systems and constructions. While the working load is dictated by either the process or the job at hand, most of the room to maneuver can be found in the areas of design and choice of materials for tool carriers, grippers, or other equipment in motion. Specific densities of several materials will need to be considered: steel — 7.9kg/dm^3; aluminum — 2.7 kg/dm^3; and Delrin/POM — 1.4 kg/dm^3.

In most cases, one of the aims of using linear motors is to produce fast movement. Because of the higher acceleration needed, mass has a larger "weighting" — as a result of the formula $F = ma$ — than in more slowly running

applications, such as in older machines. The reduction of in-motion mass is therefore very important.

It is not only a question of minimizing motor force and size, but also that the force *F* produced by the linear motor must be taken up by the motor's mounting, which can mean that complex mounting systems must be designed. If the importance of the sequence of events is realized — heavy gripper, high drive force necessary, powerful and heavy motor, heavy motor mounting — it is then easy to understand why fighting for every gram of in-motion mass is part of clever drive design.

For vertical applications, direct-acting drives like linear motors are not retained by friction. In such cases, this otherwise advantageous property means that a stationary linear motor must permanently produce a retention force corresponding to $F_h = mx9.8\ m/sec^2$. Consequently, a reduction of in-motion mass is even of great importance for slowly running vertical applications.

Movement times

When figuring cycle time, the starting point is once again F = ma. The force required depends on the acceleration needed, which depends to a large extent on the movement's time restrictions.

During the acceleration itself, the relationships $s(t) = 1/2at^2$ or $a = 2s/t^2$ are applicable. Due to the quadratic relationship between required acceleration and given time, it is worth fighting for every millisecond, in particular for short-stroke movements. Linear motor properties important during the optimization process include exact synchronization, fitting motion profiles, and the possibility of any asymmetric movement.

Any asymmetric movement possible

For linear motors, there is no particular reason to carry out movement symmetrically. For example, for a linear displacement from A to B, the forward movement without load can be allocated a different amount of time than the return movement with a load connected. In such a movement is computed for the symmetrical (each direction of the motion taking 100 msec) and the asymmetrical case. In the asymmetric case, movement with load mass was assigned 116 msec and that without load mass just 84 msec. The result is an approximately 26% lower peak force and a 15% lower average force (RMS force) for the same process cycle-time.

Exact synchronization

Linear motors are controlled in closed loop mode. This means that from the first to last repetition the movements are independent of temperature, age, and environmental factors and are always identical.

Consequently, intermeshing movements can be carried out without large safety margins. Follow-up movement can already be started while the first movement is still being carried out. As a result, either more time is available for the actual movement, or the process cycle time can be reduced.

Fitting motion profiles

Modern linear motor systems offer a choice of various optimized motion profiles. Depending on the particular application or movement, optimization with regard to freedom of shock, acceleration behavior, and speed is possible and thus various load conditions can be taken into account.

Why use a design program?

If the relationships may be simply explained by the formula $F = ma$, why use a design program for linear servo motors? For exact drive design, certain additional limiting conditions must be considered during calculation:

- The maximum feeding force produced by a linear motor is speed dependent and is influenced by the servo amplifier's properties. As in the case of rotational servomotors, where maximum torque is reduced with increasing rotation, linear motors suffer a reduction in maximum force with increasing speed due to the counter voltage. (shows how the design program computes this force limit depending on current speed in the force/time relationship and shows it as a border line in the diagram.)
- Long-stroke movements usually result in the drives running into a force limit during the acceleration and braking phases, where otherwise the limiting factor is maximum speed.
- For estimating whether or not a motor will overheat under given conditions, the continuous force required (RMS force) must be calculated.
- The choice of a suitable motor is an iterative process, as the mass of the *part of the motor in motion* is included in the *total mass in motio*n.

From an academic point of view, it can be very interesting to consider these factors in drive design. For most users, however, it is more sensible to invest time in design considerations and leave mathematical calculations to a program.

Design program basics

Using a design program is divided into four steps:

- Segmentation and definition of movement
- Input of global and segment-specific data

- Choice of the linear motor on the basis of computed force
- Testing of static and dynamic relationships (limits)

During the segmentation of movement, the complete motion is subdivided into individual integral movement sections, such as fast run-in, slow lowering, fast lifting, etc. Next, global data like mass of the gripper or the configuration (vertical, horizontal) are entered and then enhanced, as required, with local data such as load masses or counter-forces during individual movement segments.

Starting with this information, the program computes the required drive data, and the first drive may be freely chosen. The ratings, peak force, and RMS force computed are then used to select a suitable motor on the basis of the motor characteristics available. A subsequent look at the dynamic limits helps determine the correct servo controller. Depending on the application, this process must be run iteratively until the best solution is found.

A design program should not only be used to select a drive, but also to promote an integral way of looking at things: What happens if the load mass can be reduced by 10%? What effect does a reduction or increase of the movement times of individual segments have? Which movement profile is optimal for this application? These questions may be computed for different solution variants and displayed graphically by the design program in a few minutes.

4.2 TYPES OF LINEAR MOTORS

There are different types of linear motor classifications. The most common are:

- Voice coil
- Stepper Motor
- Induction motor (asynchronous)
- Permanent-magnet motor

4.2.1 Voice coil

A voice coil actuator, also known as a non-commutated DC linear actuator, is a type of direct drive linear motor. The name "voice coil" comes from one of its historically first applications: vibrating the paper cone of a loudspeaker. They are currently used for a wide range of applications, including moving much larger masses. It consists of a permanent magnetic field assembly (permanent magnets and ferrous steel) and a coil assembly. The current flowing through the coil assembly interacts with the permanent magnetic field and generates a force vector perpendicular to the direction of the current. The force vector can be reversed by changing the polarity of current flowing through the coil.

A non-commutated DC linear actuator, typically referred to as a voice coil, is capable of a displacement of up to 5 in., whereas most actuators have

displacements up to 2 in. Voice coils come in a range of sizes, from devices that generate a few ounces of force, to others that generate several hundred pounds of force. In addition, voice coil actuators can move bi-directionally, have a constant force over the stroke, and can be used for either open-loop applications or closed-loop position or force applications.

A voice coil actuator generates a force based on an interaction of current carrying conductors in a permanent magnetic field. The force generated by the voice coil is proportional to the cross product of the current flowing through the coil and the magnetic flux in the permanent magnetic field, as dictated by Lorentz' force equation:

- $F = B \times I$
  - F= Force (lbs or N)
  - B = Flux density (Tesla)
  - I = Current (Amps)

The force generated is relatively constant throughout the stroke of the actuator, with minor decreases in force at the beginning and end of the stroke.

Either the coil assembly or permanent magnetic field assembly can be used as the moving member in a voice coil actuator.

A voice coil actuator, also known as a non-commutated DC linear actuator, is a type of direct drive linear motor. The name "voice coil" comes from one of its historically first applications: vibrating the paper cone of a loudspeaker. They are currently used for a wide range of applications, including moving much larger masses. It consists of a permanent magnetic field assembly (permanent magnets and ferrous steel) and a coil assembly. The current flowing through the coil assembly interacts with the permanent magnetic field and generates a force vector perpendicular to the direction of the current. The force vector can be reversed by changing the polarity of current flowing through the coil.

A non-commutated DC linear actuator, typically referred to as a voice coil, is capable of a displacement of up to 5 in., whereas most actuators have displacements up to 2 in. Voice coils come in a range of sizes, from devices that generate a few ounces of force, to others that generate several hundred pounds of force. In addition, voice coil actuators can move bi-directionally, have a constant force over the stroke, and can be used for either open-loop applications or closed-loop position or force applications.

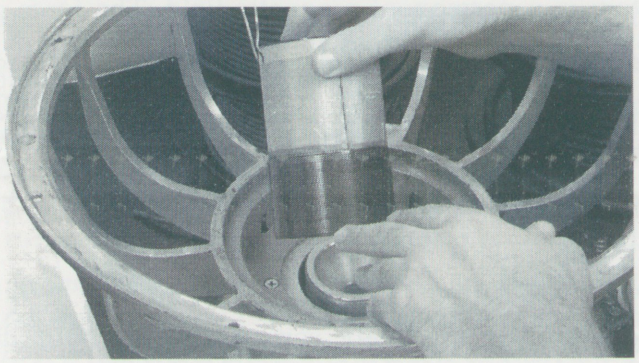
A voice coil actuator generates a force based on an interaction of current carrying conductors in a permanent magnetic field. The force generated by the voice coil is proportional to the cross product of the current flowing through the coil and the magnetic flux in the permanent magnetic field, as dictated by Lorentz' force equation:

- $F = B \times I$
  - F= Force (lbs or N)
  - B = Flux density (Tesla)

- I = Current (Amps)

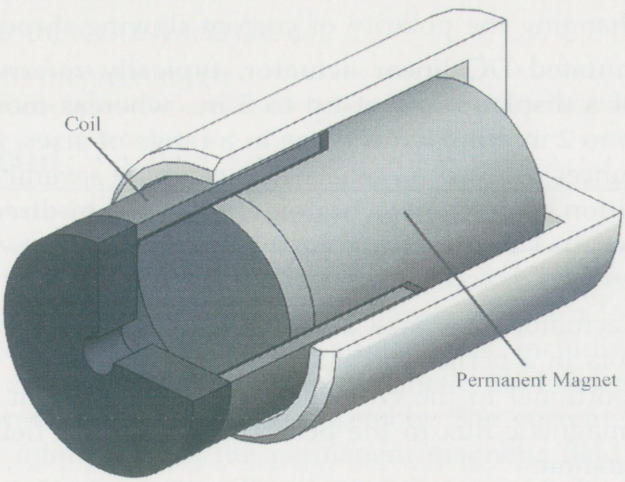
The force generated is relatively constant throughout the stroke of the actuator, with minor decreases in force at the beginning and end of the stroke.

Either the coil assembly or permanent magnetic field assembly can be used as the moving member in a voice coil actuator.



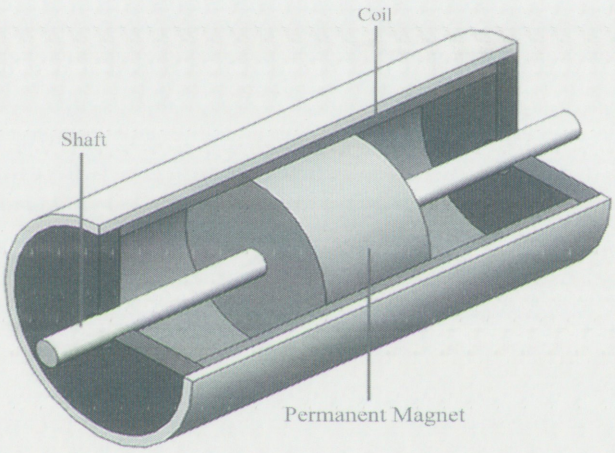
Moving Coil

Voice coil actuators come in a variety of packages. The standard type, which most people are familiar with, are moving coil type actuators. These typically involve a coil wound around a bobbin—which can be made from many non-magnetic materials—which moves in and out of a permanent magnetic field assembly consisting of a steel housing with a concentric permanent magnet assembly in the middle.



Moving Magnet

Another common type of actuator would be the moving magnet design, where the coil is fixed and magnet assembly moves. This construction change would prevent moving leads during operation. The package operates similarly, but instead of an exposed coil that moves in and out of the magnet assembly, the moving magnet style utilizes a permanent magnetic field assembly "piston" moving inside a cylindrical coil tube. This style often comes with the permanent field assembly attached to a shaft, and end caps containing bearings so that this style is most commonly supplied with an integrated bearing system.



There are variations on both common designs of either actuator design that allow for unique geometry, and the integration of voice coil actuators into several applications.

A few examples of customizations available are:

- Large radial clearances so that the voice coil can be used in limited rotation applications
- Designs that intentionally operate the voice coil motor in an arc (commonly referred to as a rotary voice coil actuator)
- Using low outgassing materials to enable use in vacuum environments
- Integration of feedback devices for closed loop control

Advantages of Voice Coil Actuators

Voice coil actuators are typically used in focusing applications, oscillatory systems, mirror tilting, and miniature position control. Their advantages include simple design and construction, a low hysteresis, being small in size for more efficient design footprint, high accelerations, and a lack of cogging or commutation.

Voice Coil Applications

Loudspeakers

Voice coil actuators received their name due to their common use in audio loudspeakers. Some of the earliest designs of voice coils also came from loudspeakers. The majority of loudspeakers are still constructed with voice coils. The design of a speaker system relies as much upon the speaker enclosure as the **speaker driver**.

Speaker Driver is an individual loudspeaker transducer that converts an electrical audio signal to sound waves.

When a voice coil is attached to a cone, the motion of the voice coil will make the cone reproduce sound waves according to input audio signals. The larger the magnet and the voice coil are, the greater the power and efficiency will be, if the loudspeaker is well made. The energy of the magnet is conducted through the pole plates and pole piece and concentrated (north - south) across the gap in which the voice coil is centered. The smaller the gap is, the more intense the magnetic field and the greater the efficiency are. However, normally, around 98% of the electrical energy becomes heat for cone speakers.

At bass frequencies, the voice coil has to move back and forth a long distance, especially at high power. During the movement, the percentage of voice coil in the gap must remain constant. So, either long voice coil plus thin pole plate or short voice coil plus thick pole plate can achieve the same purpose. At mid and high frequencies, movement of the voice coil is small, compared to the movement at bass frequencies. For this reason, the voice coil length and pole plate thickness are quite similar in mid and high frequency speakers cones.

Voice coil that has larger diameter has better control over the cone than voice coil with smaller diameter. This means that voice coil with larger diameter has better damping and linearity. However, it is more expensive to make a loud speaker with large voice coils

Hard Disk Drive Voice Coil Motor

A voice coil motor can serve as a servo motor, which is capable of moving to a precise and accurate angular or linear position according to a position feedback device such as hall-effect sensor. The voice coil motor keeps track on the pulse-wave width and move to the commanded position.

When the PWM signal is sent repeatedly, the motor will hold the position and resist t external forces.

One of the applications where voice coil motor serves as servo motor is hard disk drive voice coil motor. Computer hard drives use voice coils for the positioning of read/write heads through microcontroller.

Voice Coil Actuator for Vibrotactile Feedback

Vibration of voice coils can provide vibrotactile feedback for simulation of acoustic events. There are several applications utilizing this vibrotactile feedback.

Touch Flute: Normally, when performers play the acoustic instruments like woodwinds and brass instruments, the surfaces of the instruments vibrate. In order to simulate the vibration, D. Birnbaum's Touch Flute uses voice coil actuators on finger-control keys and hall-effect sensors under the keys for getting the binary position of the keys. The voice coils have a magnetic property that can activate hall-effect sensors, so no extra magnet is needed. When the performer's fingers are pressing the keys, the hall effect sensors control the voice coils actuators to give haptic signals to the performer's fingertips. Performers report that the vibration gives them warmth and familiarity with the instrument. This indicates that the vibrotactile feedback can improve players' performance experiences.

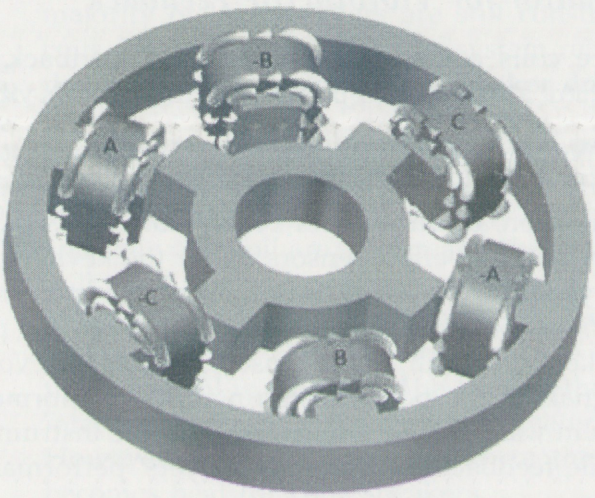
Vibrotactile Chair: Generally, through conductors like loudspeakers, it might not be possible to feel the physical vibration of sounds because the vibration generated by the conductors is not powerful enough. However, this kind of vibration can enhance musical experiences. In order to enhance the experiences, voice coils can be stored on a chair. When people sit on the chair, they will attach to the voice coils which are stored on the chair. When the voice coils vibrate, they can feel the vibration directly. The chair can help deaf people to experience music through haptic sensations as well.

Vibrotactile Stimulation for Performance Learning: The idea is to use full-body vibrotactile display as a tool to help performers to learn new music, so learners can learn from listening and haptic feelings. The study shows the benefits of multi-sensory learning. The device used by Giordana and Wanderley varies from the standard voice coil design in that the permanent magnet is the moving element and floats freely inside the coil.

4.2.2 Stepper Motor

A stepper motor is an electromechanical device it converts electrical power into mechanical power. Also it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps. The motor's position can be controlled accurately without any feedback mechanism, as long as the motor is carefully sized to the application. Stepper motors are similar to switched reluctance motors.

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. The stator has eight poles, and the rotor has six poles. The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives.



Types of Stepper Motor

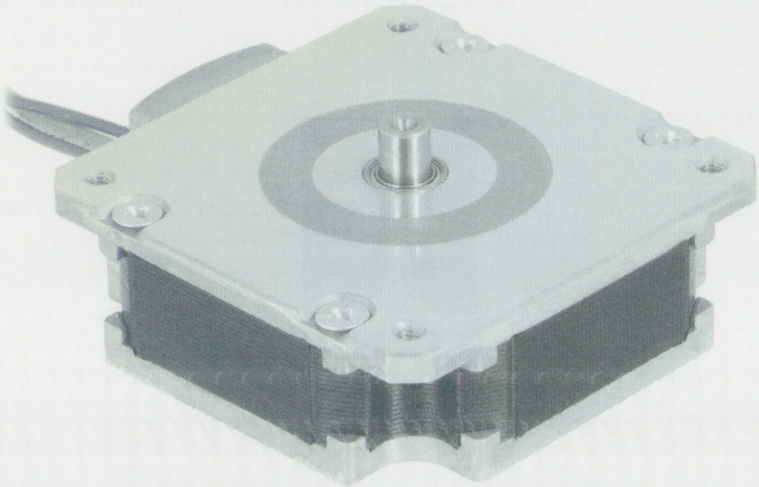
There are three main types of stepper motors, they are:

- Permanent magnet stepper
- Hybrid synchronous stepper
- Variable reluctance stepper

Permanent Magnet Stepper Motor: Permanent magnet motors use a permanent magnet (PM) in the rotor and operate on the attraction or repulsion between the rotor PM and the stator electromagnets.

Variable Reluctance Stepper Motor: Variable reluctance (VR) motors have a plain iron rotor and operate based on the principle that minimum reluctance occurs with minimum gap, hence the rotor points are attracted toward the stator magnet poles.

Hybrid Synchronous Stepper Motor: Hybrid stepper motors are named because they use a combination of permanent magnet (PM) and variable reluctance (VR) techniques to achieve maximum power in a small package size.



Advantages of Stepper Motor

- The rotation angle of the motor is proportional to the input pulse.
- The motor has full torque at standstill.
- Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non-cumulative from one step to the next.
- Excellent response to starting, stopping and reversing.
- Very reliable since there are no contact brushes in the motor. Therefore, the life of the motor is simply dependant on the life of the bearing.
- The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
- It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
- A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Applications

- **Industrial Machines** – Stepper motors are used in automotive gauges and machine tooling automated production equipments.
- **Security** – new surveillance products for the security industry.
- **Medical** – Stepper motors are used inside medical scanners, samplers, and also found inside digital dental photography, fluid pumps, respirators and blood analysis machinery.
- **Consumer Electronics** – Stepper motors in cameras for automatic digital camera focus and zoom functions.

And also have business machines applications, computer peripherals applications.

Operation of Stepper Motor

Stepper motors operate differently from DC brush motors, which rotate when voltage is applied to their terminals. Stepper motors, on the other hand, effectively have multiple toothed electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external control circuit, for example a microcontroller.

To make the motor shaft turn, first one electromagnet is given power, which makes the gear's teeth magnetically attracted to the electromagnet's teeth. The point when the gear's teeth are thus aligned to the first electromagnet, they are slightly offset from the next electromagnet. So when the next electromagnet is turned ON and the first is turned OFF, the gear rotates slightly to align with the next one and from there the process is repeated. Each of those slight rotations is called a step, with an integer number of steps making a full rotation. In that way, the motor can be turned by a precise. Stepper motor doesn't rotate continuously; they rotate in steps. There are 4 coils with 90° angle between each other fixed on the stator. The stepper motor connections are determined by the way the coils are interconnected.In stepper motor, the coils are not connected together. The motor has 90° rotation step with the coils being energized in a cyclic order, determining the shaft rotation direction. The working of this motor is shown by operating the switch. The coils are activated in series in 1 sec intervals. The shaft rotates 90° each time the next coil is activated. Its low speed torque will vary directly with current.

Stepper Motor Control by Varying Clock Pulses

Stepper motor control circuit is a simple and low-cost circuit, mainly used in low power applications. The circuit, which consist 555 timer's IC as stable multi-vibrator. The frequency is calculated by using below given relationship:

Frequency = 1/T = 1.45/(RA + 2RB)C Where RA = RB = R2 = R3 = 4.7 kilo-ohm and C = C2 = 100 μF.

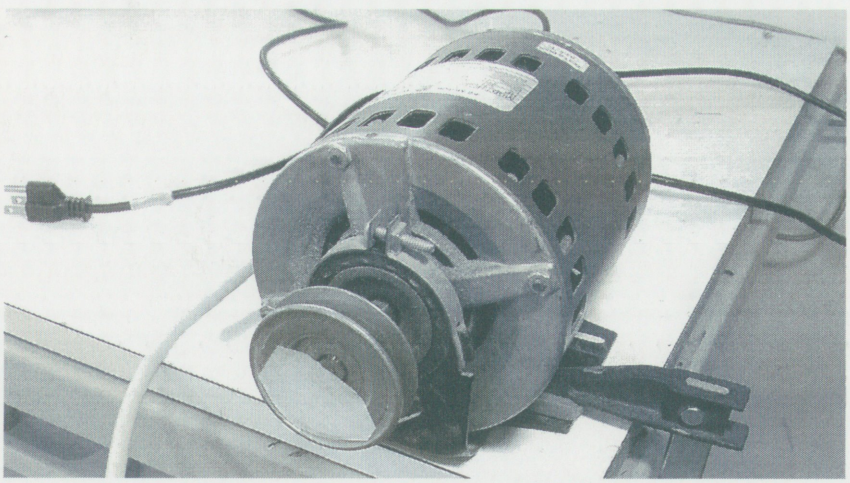
The output of timer is used as clock for two 7474 duals 'D' flip-flops (U4 and U3) configured as a ring counter. When power is initially switched on, only the first flip-flop is set (i.e. Q output at pin 5 of U3 will be at logic '1') and the other three flip-flops are reset (i.e. output of Q is at logic 0). On receipt of a clock pulse, the logic '1' output of the first flip-flop gets shifted to the second flip-flop (pin 9 of U3). Thus logic 1 output keeps shifting in a circular manner with every clock pulse. Q outputs of all the four flip-flops are amplified by Darling-ton transistor arrays inside ULN2003 (U2) and connected to the stepper motor windings orange, brown, yellow, black to 16, 15 ,14, 13 of ULN2003 and the red to +ve supply.

The common point of the winding is connected to +12V DC supply, which is also connected to pin 9 of ULN2003. The color code used for the windings is may vary form make to make. When the power is switched on, the control signal connected to SET pin of the first flip-flop and CLR pins of the other three flip-flops goes active 'low' (because of the power-on-reset circuit formed by R1-C1 combination) to set the first flip-flop and reset the remaining three flip-flops. On reset, Q1 of IC3 goes 'high' while all other Q outputs go 'low'. External reset can be activated by pressing the reset switch. By pressing the reset switch, you can stop the stepper motor. The motor again starts rotating in the same direction by releasing the reset switch.

4.2.3 Induction Motor

These motors operate by generating currents with two vector components. One component is for the coil currents (primary), the other induces currents in the secondary section, which encapsulates short circuit rods. The induced currents generate a magnetic flux, which interacts with the coil current to generate force.

The primary advantage of this type of linear motor is the low cost of its secondary. Its limitations are its large size (compared to an equivalent permanent magnet linear motor) and, for precision motion applications, it requires a complicated control algorithm. It functions best in positioning applications that require low-duty cycle, where high heat is not a problem, and where travel lengths are long.



Two Types of Induction Motors

Single phase induction motor: The single-phase induction motor is not self-starting. When the motor is connected to a single-phase power supply, the main winding carries an alternating current. It is logical that the least expensive, most

reduced upkeep sort engine ought to be utilized most regularly. These are of different types based on their way of starting since these are of not self-starting. Those are split phase, shaded pole and capacitor motors. Again capacitor motors are **start capacitor**, capacitor run and permanent capacitor motors.

Start Capacitor is an electrical capacitor that alters the current to one or more windings of a single phase AC induction motor to create a rotating magnetic field.

In these types of motors, the start winding can have a series capacitor and/or a centrifugal switch. When the supply voltage is applied, current in the main winding lags the supply voltage because of the main winding impedance. And current in the start winding leads/lags the supply voltage depending on the starting mechanism impedance. The angel between the two windings is sufficient phase difference to provide a rotating magnitude field to produce a starting torque. The point when the motor reaches 70% to 80% of synchronous speed, a centrifugal switch on the motor shaft opens and disconnects the starting winding.

Applications of Single Phase Induction Motor

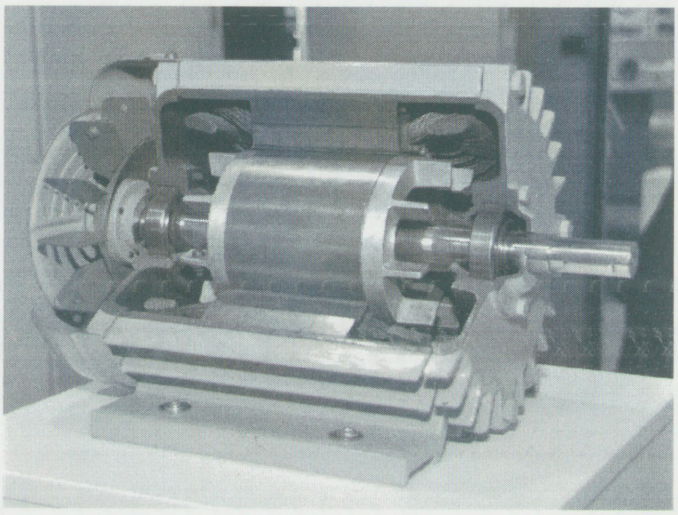
These are used in low power applications and widely used in domestic applications as well as industrial. And some of those are mentioned

- Pumps
- Compressors
- Small fans
- Mixers
- Toys
- High speed vacuum cleaners
- Electric shavers
- Drilling machines

Three-Phase Induction Motor: These motors are self-starting and use no capacitor, start winding, centrifugal switch or other starting device. Three-phase AC induction motors are widely used in industrial and commercial applications. These are of two types, squirrel cage and slip ring motors. Squirrel cage motors are widely used due to their rugged construction and simple design. Slip ring motors require external resistors to have high starting torque.

Induction motors are used in industry and domestic appliances because these are rugged in construction

requiring hardly any maintenance, that they are comparatively cheap, and require supply only to the stator.



Applications of Three Phase Induction Motor

- Lifts
- Cranes
- Hoists
- Large capacity exhaust fans
- Driving lathe machines
- Crushers
- Oil extracting mills
- Textile and etc.

Advantages of Induction Motor

The motor construction and the way electric power is supplied all give the induction motor several advantages.

Low cost: Induction machines are very cheap when compared to synchronous and DC motors. This is due to the modest design of induction motor. Therefore, these motors are overwhelmingly preferred for fixed speed applications in industrial applications and for commercial and domestic applications where AC line power can be easily attached.

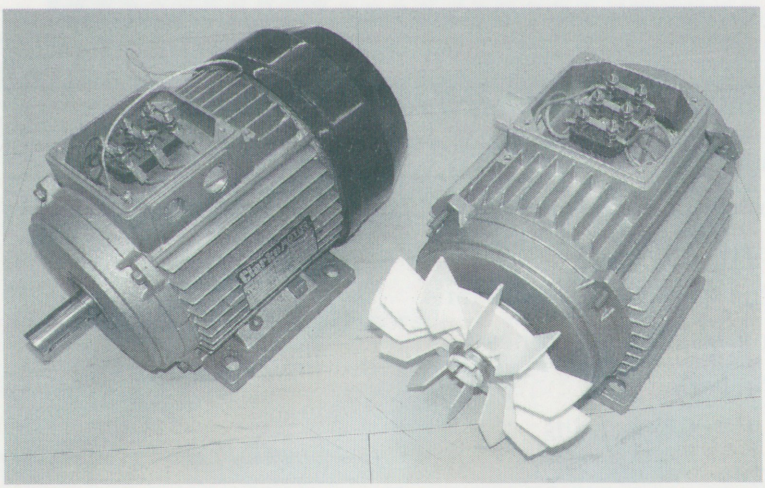
Low maintenance cost: Induction motors are maintenance free motors unlike dc motors and synchronous motors. The construction of induction motor is very simple and hence maintenance is also easy, resulting in low maintenance cost.

Ease of operation: Operation of induction motor is very simple because there is no electrical connector to the rotor that supply power and current is induced by the movement of the transformer performs on the rotor due to the low resistance of the rotating coils. Induction motors are self-start motors. This can result in reducing the effort needed for maintenance.

Speed Variation: The speed variation of induction motor is nearly constant. The speed typically varies only by a few percent going from no load to rated load.

High starting torque: The staring torque of induction motor is very high which makes motor useful for operations where load is applied before the starting of the motor.3 phase induction motors will have self-starting torque unlike synchronous motors. However, single-phase induction motors do not have self-starting torque and are made to rotate using some auxiliaries.

Durability: Another major advantage an induction motor is that it is durability. This makes it the ideal machine for many uses. This results the motor to run for many years with no cost and maintenance.



4.2.4 Permanent-magnet motor

These motors, also known as synchronous motors, are the most commonly used linear motor in high performance applications. Several versions are available:

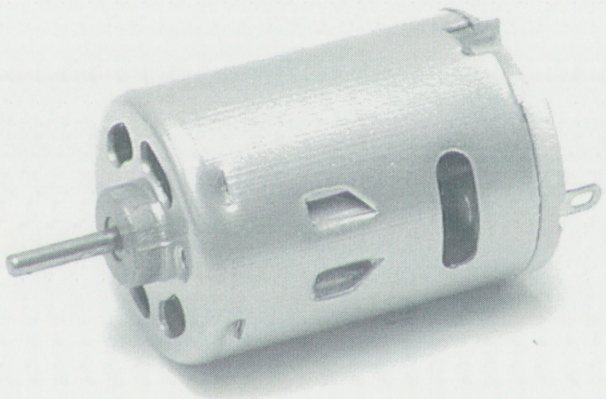
Brush type motors are the least expensive. Operating from direct current, each motor has a stationary coil assembly and moving magnets. The motor cable does not move in this configuration. Limitations include velocity, up to 1 m/sec; and acceleration, up to 0.5 g. These values there is excessive arcing and rapid deterioration of the brushes. These motors are excluded from clean room and vacuum applications.

Brushless, aluminum-core linear motor operates from three phase power, with a moving coil and cable. In applications requiring short travel lengths, though,

the coil can be stationary and the magnets moving. The core of the primary encloses the windings in aluminum. There is no magnetic attraction between the two motor parts. Therefore, it may require a double-sided magnet assembly to close the magnetic circuit effectively. This type of linear motor generates smooth motion.

Depending on the moving load, it can accelerate to 4 g's, but can also develop eddy currents at speeds over 1 m/sec. This motor is ideal for vacuum applications.

Brushless, epoxy-core linear motor is also non-ferrous with its epoxy-based core. It too, provides smooth motion. It has an advantage over aluminum in that it does not experience eddy currents at high speed. It has low stiffness (typically 35,000 N/mm) at high coil temperatures (to 125 C) and it tends to give off gases in high vacuum environments.



Brushless, steel-core linear motor uses steel lamination, in the main body of the primary, to enclose the copper windings. This motor uses a single-sided magnet assembly and is air or water cooled for high duty cycle applications. It functions well in applications that require such duty cycles and velocities up to 200 ips (5 m/sec). But this motor is subject to cogging. It can generate strong magnetic attraction between the two motor parts, which must be accounted for in the load carrying capacity of the bearing system. Typical applications are machine tools where high force, 5,000 lb (23,000 N), may be required, or in general automation where speed of several m/sec is needed 120 to 200 ips (3 to 5 m/sec).

Permanent magnet motor drives

In general, all electromechanical drives can be divided into constant-speed drives, servo drives and variable-speed drives.

A constant-speed drive usually employs a synchronous motor alone which can keep the speed constant without an electronic converter and feedback or any other motor when there is less restriction on the speed variation tolerance.

A servo system is a system consisting of several devices which continuously monitor actual information (speed, position), compare these values to desired outcome and make necessary corrections to minimize the difference. A servo motor drive is a drive with a speed or position feedback for precise control where the response time and the accuracy with which the motor follows the speed and position commands are extremely important.

Adjustable speed drive (ASD) describes equipment used to control the speed of machinery.

In a **variable-speed drive** (VSD) the accuracy and the response time with which the motor follows the speed command are not important, but the main requirement is to change the speed over a wide range.

In all electromechanical drives where the speed and position are controlled, a solid state converter interfaces the power supply and the motor. There are three types of PM motor electromechanical drives:

- d.c. commutator motor drives
- brushless motor drives (d.c. and a.c. synchronous)
- stepping motor drives

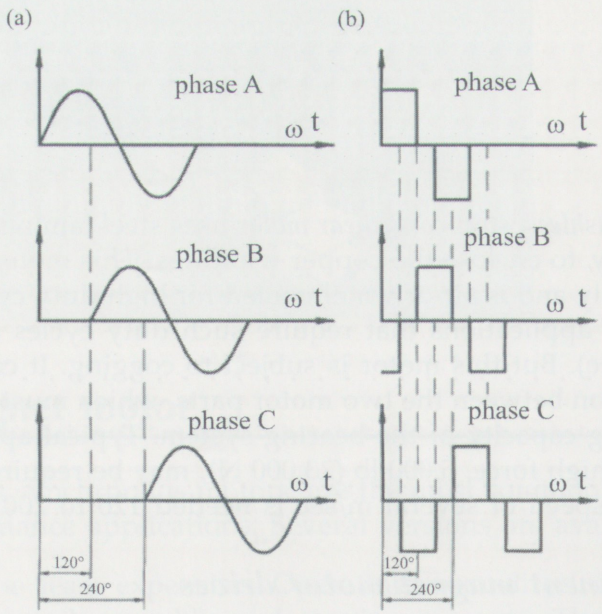
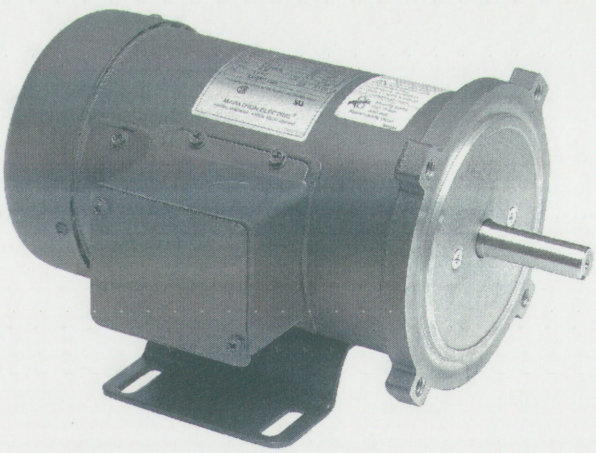


Figure 1: Basic armature waveforms for three phase PM brushless motors: (a) sinusoidally excited, (b) square wave.

Brushless motor drives fall into the two principal classes of sinusoidally excited and square wave (trapezoidally

excited) motors. Sinusoidally excited motors are fed with three-phase sinusoidal waveforms (Figure 1a) and operate on the principle of a rotating magnetic field. They are simply called sinewave motors or PM synchronous motors. All phase windings conduct current at a time. Square wave motors are also fed with three-phase waveforms shifted by 1200 one from another, but these wave shapes are rectangular or trapezoidal (Figure 1b). Such a shape is produced when the armature current (MMF) is precisely synchronized with the rotor instantaneous position and frequency (speed). The most direct and popular method of providing the required rotor position information is to use an absolute angular position sensor mounted on the rotor shaft. Only two phase windings out of three conduct current simultaneously. Such a control scheme or electronic commutation is functionally equivalent to the mechanical commutation in d.c. motors. This explains why motors with square wave excitation are called d.c. brushless motors. An alternative name used in power electronics and motion control is self-controlled synchronization.

Although stepping motor electromechanical drives are a kind of synchronous motor drive, they are separately discussed due to their different control strategies and power electronic circuits.



d.c. commutator motor drives

The d.c. commutator motor or d.c brush motor is still a simple and low cost solution to variable-speed drive systems when requirements such as freedom from maintenance, operation under adverse conditions or the need to operate groups of machines in synchronism are not supreme. Owing to the action of the mechanical commutator, control of a d.c. motor drive is comparatively

simple and the same basic control system can satisfy the requirements of most applications. For these reasons the d.c. electromechanical drive very often turns into the cheapest alternative, in spite of the cost of the d.c. commutator motor. In many industrial applications such as agitators, extruders, kneading machines, printing machines, coating machines, some types of textile machinery, fans, blowers, simple machine tools, etc., the motor is required only to start smoothly and drive the machinery in one direction without braking or reverse running. Such a drive operates only in the first quadrant of the speed-torque characteristic and requires only one controlled converter (in its rectifier mode) as shown in Figure 2a. At the expense of increased torque ripple and supply harmonics, a half-controlled rather than fully-controlled bridge may be used up to about 100 kW. If the motor is required to drive in both forward and reverse directions, and apply regenerative braking, a single fully controlled converter can still be used but with the possibility of reversing the armature current (Figure 2a).

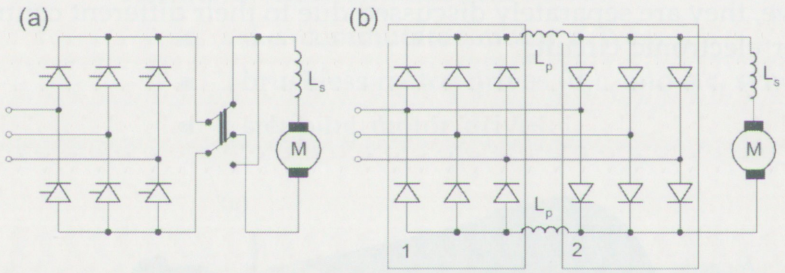


Figure 2: d.c. commutator motor drives: (a) one quadrant, fully-controlled, singleconverter drive, (b) four-quadrant, fully-controlled, dual converter drive; L_p are reactors limiting the currents circulating between the rectifying and inverting bridges, L_a is the armature circuit inductance.

Electromechanical drives such as for rolling mills, cranes and mine winders are subject to rapid changes in speed or in load. Similarly, in those textile, paper or plastics machines where rapid control of tension is needed, frequent small speed adjustments may request rapid torque reversals. In these cases a four-quadrant dual converter comprising two semiconductor bridges in antiparallel, as in Figure 2b, can be used. One bridge conducts when armature current is required to be positive, and the second bridge when it is required to be negative.

Natural or line commutation between successively conducting power semiconductor switches takes place when the instantaneous values of consecutive phase voltages are equal and cross each other. The phase with a decreasing voltage is suppressed, while that with an increasing voltage takes over the conduction. Natural commutation may not be possible in such situations when the armature inductance is very small, e.g., control of small d.c. motors. The normal phase

control would cause unacceptable torque ripple without substantial smoothing which, in turn, would impair the response of the motor. Power transistors, GTO thyristors or IGBTs can be turned off by appropriate gate control signals, but conventional thyristors need to be reverse biased briefly for successful turn off. This can be accomplished by means of a forced-commutation circuit, usually consisting of capacitors, inductors and, in some designs, auxiliary thyristors. Forced commutation is used mostly for the frequency control of a.c. motors by variable-frequency inverters and chopper control of d.c. motors.

Figure 3a shows the main components of a one-directional chopper circuit for controlling a PM or separately excited d.c. motor. Thyristors must be accompanied by some form of turn-off circuits or, alternatively, be replaced by GTO thyristors or IGBTs. When the mean value of the chopper output voltage is reduced the armature EMF, the direction of the armature current cannot reverse unless T2 and D2 are added. The thyristor T2 is fired after T1 turns off, and vice versa. Now, the reversed armature current flows via T2 and increases when T1 is off. When T1 is fired, the armature current flows via D2 back to the supply. In this way regenerative braking can be achieved.

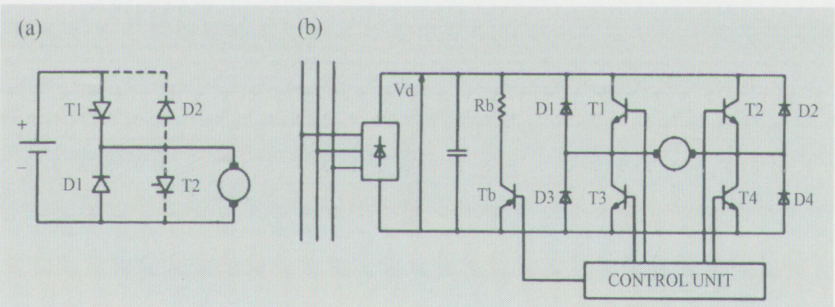
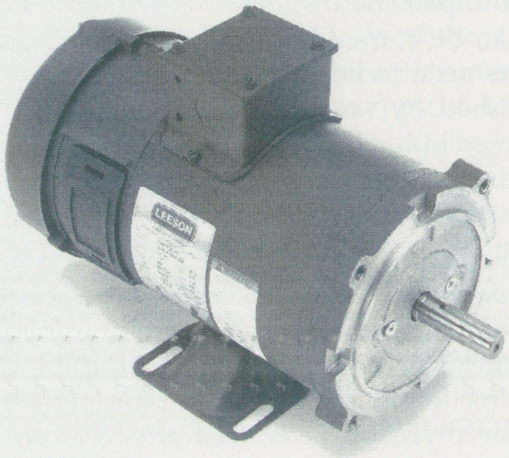


Figure 3: Chopper controlled d.c. motor drives: (a) one-directional with added regenerative braking leg, (b) four-quadrant chopper controller.

Full four-quadrant operation can be obtained with a bridge version of the chopper shown in Figure 3b. Transistors or GTO thyristors allow the chopper to operate at the higher switching frequencies needed for low-inductance motors. By varying the on and off times of appropriate pairs of solid switches, the mean armature voltage, and hence speed, can be controlled in either direction. Typical applications are machine tools, generally with one motor and chopper for each axis, all fed from a common d.c. supply.

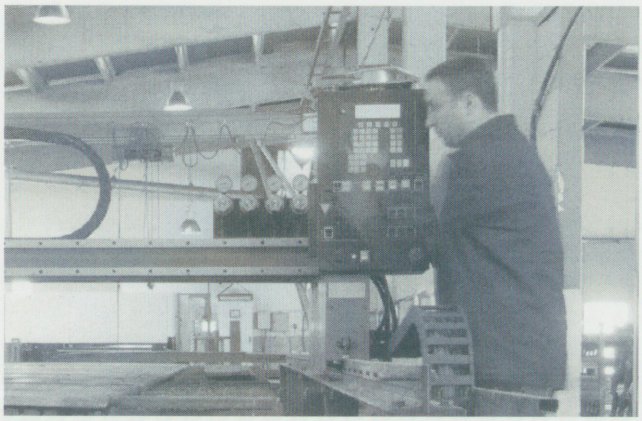


4.3 NON-CARTESIAN MACHINES

A Cartesian robot, also known as a Cartesian coordinate robot, is a common type of industrial robot. It has three "arms" that each function along linear axes of control. Each of these axes is at a right angle to the other two. A common application for the cartesian robot is a computer numerical control (CNC) machine, and it can have a multitude of uses, especially as either a milling or drawing machine.

The basic form of a cartesian robot consists of three "arms." Each arm can move only along a two dimensional axis — it can only move backward or forwards or, if the arm is vertical, up or down. Each arm is at a right angle to the other two, though, which allows the robot to utilize the motions of all three arms to reach various points in a three-dimensional space. These arms can vary tremendously in size, depending on the purpose of the robot. In some particularly large designs, the horizontal arm will have support on both ends. This is called a gantry robot.

The primary advantage that the cartesian robot has over other types of industrial robots is that all three of its axes of control are linear rather than rotational. Having a linear axis of control is an advantage because it greatly simplifies the robot's arm solution. In order to program a robot for a specific task, the programmer must be able to program the robot to move along its axes of control to reach the various desired positions. Determining this arm solution requires calculations to determine the desired positions relative to the robot's axes of control. Linear calculations are far easier to calculate, because the programmer can perform these calculations in a closed form using basic trigonometric principles.



As a result of the cartesian robot's ability to reach different points in a three-dimensional space with relative ease, its most common application is as a CNC machine. CNC machines use computer programs to extract the necessary commands to cause the robot to function in the desired manner and then to load these commands into the robot. They enable the robot to move very precisely and thus make cartesian robots suitable for different drawing and drafting functions. When a cartesian robot is used in this manner, a tool can be lowered onto or raised off of a surface while moving along the X and Y planes to create a specific design.

4.3.1 Different Types of Robots

Types of robots can be separated by the tasks that they are meant to perform, their role within society, their level of advancement and other criteria. In contemporary terms, types of robots are often separated into classes by the jobs that they perform, such as industrial, scientific, and consumer robots. Within the industrial sector, robots are also categorized further as to the types of capabilities and functions of which they are capable. Cartesian or gantry robots have an articulated arm that does various welding, assembly, and part-movement functions. Robots with other ranges of motion are labeled as cylindrical, spherical, and parallel depending on where they can reach and the level of dexterity and control that their arms possess for detailed work.

Aside from how a robot is physically designed, its degree of mobility and size is also an important factor in categorization. Especially within fields such as the military, combat robots can be autonomous flying drone aircraft, micro robots the size of insects build for surveillance, or large robotic systems built into land vehicles designed as logistical support or autonomous fighting machines. Some military machines are also semi-autonomous robots that can perform basic maneuvering functions on their own, but require special human control for complex actions.

Scientific robots are used in a laboratory setting to automate certain tasks, or in exploratory areas to which humans are unable or unwilling to go. This can include types of robots such as those carried by space probes to the surface of Mars or an asteroid, robots built to inspect the interior of nuclear reactor vessels, and robots that inspect suspicious vehicles or packages for the police in case they contain explosives. Laboratory or medical robots also can aid in the automation of mixing drugs or biological samples, as well as performing microsurgery under the guidance of a physician.

Humanoid robots are among the types of robots most often pictured in fiction or movies. They can serve educational or entertainment functions, and are often seen as a form of servant to people with a level of intelligence of their own that puts them on a par with the simple thinking of young children or pets. Where they get out of control, they are often a subject of debate about whether they should have been created in the first place. Types of robots built on the human model are the most challenging to create due to the fact that simulating how human beings walk is a very difficult task to do for a machine, as well as how human beings see the world or understand language so that they can effectively interact with each other.

As technology advances, robots become more and more a part of day-to-day life. Much of what they do remains hidden from society in general as they work in factories and remote regions, taking dangerous jobs once required of people. As industrial, scientific, and military robots become more advanced, however, these developments are being used to improve upon humanoid models that may one day exist and work alongside people on a routine basis.

4.3.2 Articulated Robots

An articulated robot is a robot which is fitted with rotary joints. Rotary joints allow a full range of motion, as they rotate through multiple planes, and they increase the capabilities of the robot considerably. An articulated robot can have one or more rotary joints, and other types of joints may be used as well, depending on the design of the robot and its intended function.

With rotary joints, a robot can engage in very precise movements. Articulated robots commonly show up on manufacturing lines, where they utilize their flexibility to bend in a variety of directions. Multiple arms can be used for greater control or to conduct multiple tasks at once, for example, and rotary joints allow robots to do things like turning back and forth between different work areas.

These robots can also be seen at work in labs and in numerous other settings. Researchers developing robots often work with articulated robots when they want to engage in activities like teaching robots to walk and developing robotic arms. The joints in the robot can be programmed to interact with each other in addition to activating independently, allowing the robot to have an even higher degree of control. Many next generation robots are articulated because this allows for a high level of functionality.

Articulated robots can have arms and legs which allow them to move and manipulate a wide variety of objects. Some are designed as console units with arms, where the unit remains in place in a fixed position and the arms are used to perform tasks. Others may wheel, slide, or move in other ways so that they can navigate spaces of varying sizes. In a medical lab, for example, an articulated robot might be used to deliver and carry samples around the lab.

Basic articulated robots are sometimes available in robotics kits, allowing people who are just starting to explore robotics to play with rotary joints and to get a feel for how they operate. More sophisticated robots may be built for a special purpose by robotics experts who design every component of the articulated robot from the ground up. Robots used on assembly lines and in similar settings are produced in various quantities by companies which develop manufacturing equipment. People who are interested in seeing an articulated robot in action can try doing a search for "articulated robot" on a site which collects videos from users.

Advantages

- High speed
- Large work envelope for least floor space
- Easier to align to multiple planes

Disadvantages

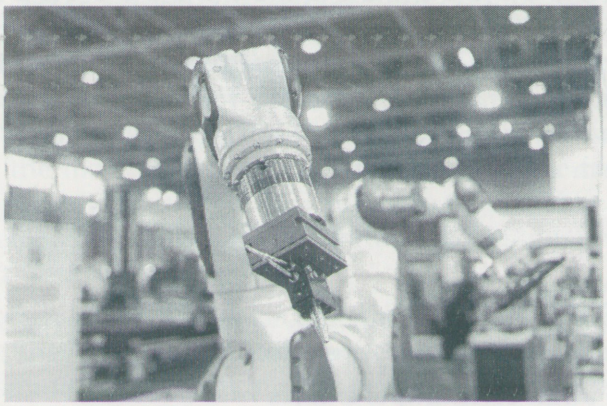
- Requires dedicated robot controller
- Complicated programming
- Complicated kinematics

Application

- Food packaging
- Arc welding
- Spot welding
- Material handling
- Machine tending
- Automotive assembly
- Steel bridge manufacturing
- Steel cutting
- Glass handling
- Foundry and forging application

4.3.3 Cartesian Robots

Cartesian robots are also called rectilinear or gantry robots and have a rectangular configuration. These types of industrial robots have three prismatic joints to deliver linear motion by sliding on its three perpendicular axes (X, Y and Z). They might also have an attached wrist to allow rotational movement. Cartesian robots are used in majority of industrial applications as they offer flexibility in their configuration which make them suitable for specific application needs.



Advantages

- Provides high positional accuracy
- Simple operation
- Easy to program offline
- Highly customizable
- Can handle heavy loads
- Less cost

Disadvantages

- Requires large operational and installation area
- Complex assembly
- Movement limited to only one direction at a time

Application

- Pick and place operations
- Loading and unloading
- Material handling

- Assembly and sub-assembly
- Nuclear material handling
- Adhesive applications

4.3.4 SCARA Robots

A SCARA robot is an assembly machine that installs parts or carries items. It is designed to mimic the action of a human arm and can be used in jobs from automobile factories to underwater construction. This tool is frequently utilized because of its speed, efficiency and low cost.



SCARA stands for Selective Compliant Assembly Robot Arm or Selective Compliant Articulated Robot Arm. A SCARA robot has a full range of motion on its X and Y axis but is bolted down and unable to move in the Y axis. It can be programed to perform precise jobs repetitively, such as installing a pin or carrying items from one location to another within its range of motion. In the field of robotics, the SCARA is considered more affordable than many of its competitors and is one of the most popular methods of automated assembly.

A SCARA robot is primarily used for assembly. They are used by manufacturers of everything from bulky automobiles to minuscule electronic items. It can be programmed to handle very precise installation work and cannot carry a great deal of weight, so the arm works best when handling small parts. These robots also can have their joints waterproofed in order to function in underwater construction. A SCARA's ability to be controlled remotely makes it a common feature of work sites that can be hazardous to humans, such as working with chemicals, or in environments with extreme conditions, such as a steel mill.

Considered to be relatively old in the constantly evolving world of robotics, the SCARA robot was developed in 1981 by the manufacturing company Sankyo Seiki. Since that time, it has become one of the most popular types of robots on an assembly line. Its closest competition is the Cartesian style robot. The Cartesian takes up much more space than a SCARA but can handle a heavier payload. The SCARA robot clearly does not excel at every job, but it gets high marks within its own niche.



SCARA robots are considered one of most important developments in assembly line technology because of their range of motion, speed and precision. By imitating the construction of the arm, elbow and wrist, the SCARA performs many tasks in a fraction of the time it would take a human. Whether constructing something intricate, such as a computer motherboard, or large and hulking, such as the frame of an 18-wheel semi truck, this tool helps increase production and lower costs because of its efficiency.

Advantages

- High speed
- Excellent repeatability
- Large workspace

Disadvantages

- Requires dedicated robot controller
- Limited to planar surfaces
- Hard to program offline

Application

- Assembly applications
- Semiconductor wafers handling

- Biomed applications
- Packaging
- Palletizing
- Machine loading

4.3.5 Parallel Robot

A parallel robot, also called a parallel manipulator, is a mechanism presenting very good performance in terms of stability, rigidity and accuracy to manipulate large loads. Parallel robots consist of three or more rotary or prismatic axes that function parallel to each other. They have been used in a number of applications such as flight simulators and astronomy, and they are growing in popularity in the machine-tool industry. Some examples of these types of robots are delta, hexapod and tricept robots.

Theoretical works by English and French geometricians that are related to parallel mechanisms, and in particular hexapods, date back many centuries. Homer described walking tripods in his epic work *The Illiad*. Aristotle envisioned such mechanisms that obeyed the will of others. The first parallel robot came only 17 years after the term "robot" was coined in 1921. Designed for automated spray painting, it is generally considered to be the first industrial parallel robot designed.

When it comes to robotics, an end effector is a rigid body at the end of a robotic arm. For each link of a robot, the connection degree is the number of rigid bodies attached to the link by a joint. In closed-loop kinematic chains, one of the links, but not the base, possesses a connection degree greater than or equal to three. Parallel robots are mechanisms where the end effector is connected to the base through several kinematic chains forming a closed loop.

Since the end effector of a parallel robot is supported in several places, this results in high structural stiffness. A number of legs connect the end effector to a base platform. Construction of a parallel robot is light. These features allow parallel robots to be capable of a wide range of motion. Their major drawback, however, is that they have a limited workspace because the legs can collide.

Used more frequently for industrial purposes is a robot known as a serial manipulator. It is constructed in such a way as to form the shape of an elbow, wrist and a shoulder. One of the major advantages of serial manipulators over parallel robots is their large workspace. Serial manipulators are the most common type of industrial robots.

Advances in robot kinematics, the study of the motion of robots, have led to applications in various fields, including surgery, manufacturing, locomotion and biomechanics. Robot kinematics can be divided into mobile robot kinematics, humanoid kinematics, parallel robot kinematics and serial manipulator kinematics.

Analyses of the velocity, acceleration and position of all of the links are calculated without taking into consideration the forces that cause the motion.

Another application of parallel robots is in high speed, high-accuracy positioning. An example of this is in the assembly of printed circuit boards. A parallel robot can also function as a micro manipulator for serial manipulators by being mounted on the end effector.

Advantages

- Very high speed
- High operational accuracy

Disadvantages

- Complicated operation
- Requires dedicated robot controller

Application

- Food industry
- Pharmaceutical industry
- Electronic industry
- Flight simulators
- Automobile simulators
- Optical fiber alignment

4.3.6 Polar Robots

Polar robots have a twisting joint connecting the arm with the base and a combination of two rotary joints and one linear joint connecting the links. These are also called as spherical robots, since it has a spherical work envelope and the axes form a polar co-ordinate system. These robots have a centrally pivoting shaft and an extendable rotating arm. The gun turret configuration of polar robots sweeps a large volume of space, but the access of the arm is restricted within its workspace.

Advantages

- Can reach all around
- Can reach above or below obstacles
- Large work volume
- Requires less floor space

Disadvantages

- Cannot reach above itself
- Short vertical reach
- Low accuracy and repeatability in direction of rotary motion
- Requires sophisticated control system
- Fallen out of favor and not common in new designs

Application

- Die casting
- Glass handling
- Stacking and unstacking
- Injection molding
- Forging
- Welding
- Material handling

4.3.7 Cylindrical Robots

Cylindrical robots have at least one rotary joint at the base and at least one prismatic joint connecting the links. These robots have a cylindrical workspace with a pivoting shaft and an extendable arm which moves vertically and by sliding. Thus, robots with cylindrical configuration offers vertical and horizontal linear movement along with rotary movement about the vertical axis. The compact design of the end of the arm allows the robot to reach tight work envelopes without any loss of speed and repeatability. It is mostly used in simple applications where materials are picked up, rotated and placed.

Advantages

- Simple operation and installation
- Minimal assembly
- Can reach all around itself
- Requires less floor space
- Can carry large payloads

Disadvantages

- Cannot reach around obstacles
- Low accuracy in direction of rotary motion

- Fallen out of favor and not common in new designs

Application

- Transport of LCD panels
- Assembly applications
- Coating applications
- Die casting
- Foundry and forging application
- Machine loading and unloading

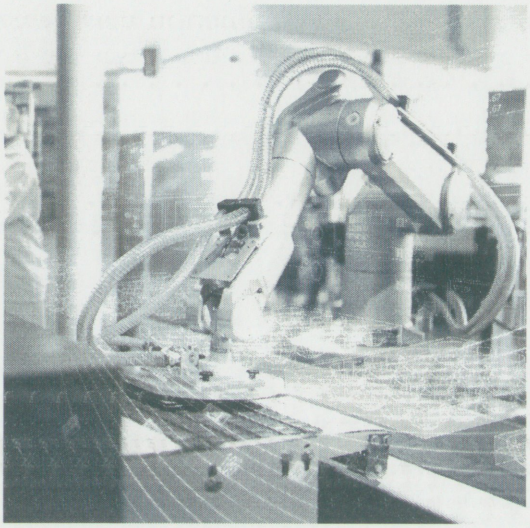
4.4 MANUFACTURING APPLICATIONS OF AUTOMATION AND ROBOTICS

One of the most important application areas for automation technology is manufacturing. To many people, automation means manufacturing automation. The types of automation are defined, and examples of automated systems used in manufacturing are described.

Three types of automation in production can be distinguished: (1) fixed automation, (2) programmable automation, and (3) flexible automation.

Fixed automation, also known as "hard automation," refers to an automated production facility in which the sequence of processing operations is fixed by the equipment configuration. In effect, the programmed commands are contained in the machines in the form of cams, gears, wiring, and other hardware that is not easily changed over from one product style to another. This form of automation is characterized by high initial investment and high production rates. It is therefore suitable for products that are made in large volumes. Examples of fixed automation include machining transfer lines found in the automotive industry, automatic assembly machines, and certain chemical processes.

Programmable automation is a form of automation for producing products in batches. The products are made in batch quantities ranging from several dozen to several thousand units at a time. For each new batch, the production equipment must be reprogrammed and changed over to accommodate the new product style. This reprogramming and changeover take time to accomplish, and there is a period of nonproductive time followed by a production run for each new batch. Production rates in programmable automation are generally lower than in fixed automation, because the equipment is designed to facilitate product changeover rather than for product specialization. A numerical-control machine tool is a good example of programmable automation. The program is coded in computer memory for each different product style, and the machine tool is controlled by the computer program. Industrial robots are another example.



Flexible automation is an extension of programmable automation. The disadvantage with programmable automation is the time required to reprogram and change over the production equipment for each batch of new product. This is lost production time, which is expensive. In flexible automation, the variety of products is sufficiently limited so that the changeover of the equipment can be done very quickly and automatically. The reprogramming of the equipment in flexible automation is done off-line; that is, the programming is accomplished at a computer terminal without using the production equipment itself. Accordingly, there is no need to group identical products into batches; instead, a mixture of different products can be produced one right after another.

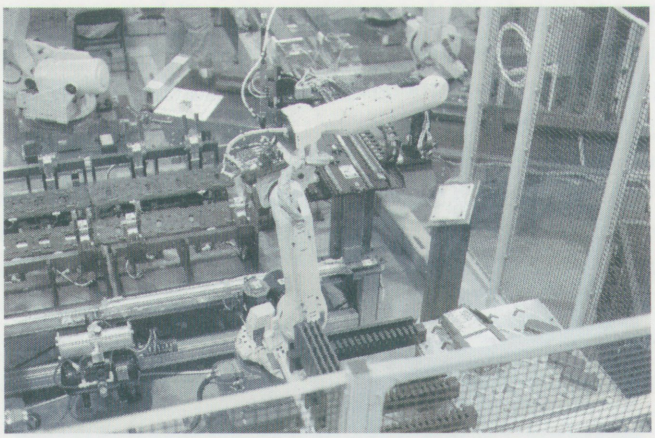


4.4.1 Automated production lines

An automated production line consists of a series of workstations connected by a transfer system to move parts between the stations. This is an example of fixed automation, since these lines are typically set up for long production runs, perhaps making millions of product units and running for several years between changeovers. Each station is designed to perform a specific processing

operation, so that the part or product is constructed stepwise as it progresses along the line. A raw work part enters at one end of the line, proceeds through each workstation, and emerges at the other end as a completed product. In the normal operation of the line, there is a work part being processed at each station, so that many parts are being processed simultaneously and a finished part is produced with each cycle of the line. The various operations, part transfers, and other activities taking place on an automated transfer line must all be sequenced and coordinated properly for the line to operate efficiently. Modern automated lines are controlled by programmable logic controllers, which are special computers that facilitate connections with industrial equipment (such as automated production lines) and can perform the kinds of timing and sequencing functions required to operate such equipment.

Automated production lines are utilized in many industries, most notably automotive, where they are used for processes such as machining and press working. Machining is a manufacturing process in which metal is removed by a cutting or shaping tool, so that the remaining work part is the desired shape. Machinery and motor components are usually made by this process. In many cases, multiple operations are required to completely shape the part. If the part is mass-produced, an automated transfer line is often the most economical method of production. The many separate operations are divided among the workstations. Transfer lines date back to about 1924.



Press working operations involve the cutting and forming of parts from sheet metal. Examples of such parts include automobile body panels, outer shells of major appliances (e.g., laundry machines and ranges), and metal furniture (e.g., desks and file cabinets). More than one processing step is often required to complete a complicated part. Several presses are connected together in sequence by handling mechanisms that transfer the partially completed parts from one press to the next, thus creating an automated press working line.

4.4.2 Numerical control

Numerical control is a form of programmable automation in which a machine is controlled by numbers (and other symbols) that have been coded on punched paper tape or an alternative storage medium. The initial application of numerical control was in the machine tool industry, to control the position of a cutting tool relative to the work part being machined. The NC part program represents the set of machining instructions for the particular part. The coded numbers in the program specify *x*-*y*-*z* coordinates in a Cartesian axis system, defining the various positions of the cutting tool in relation to the work part. By sequencing these positions in the program, the machine tool is directed to accomplish the machining of the part. A position feedback control system is used in most NC machines to verify that the coded instructions have been correctly performed.

Today a small computer is used as the controller in an NC machine tool, and the program is actuated from computer memory rather than punched paper tape. However, initial entry of the program into computer memory is often still accomplished using punched tape. Since this form of numerical control is implemented by computer, it is called computer numerical control, or CNC. Another variation in the implementation of numerical control involves sending part programs over telecommunications lines from a central computer to individual machine tools in the factory, thus eliminating the use of the punched tape altogether. This form of numerical control is called direct numerical control, or DNC.



Many applications of numerical control have been developed since its initial use to control machine tools. Other machines using numerical control include component-insertion machines used in electronics assembly, drafting machines that prepare engineering drawings, coordinate measuring machines that perform accurate inspections of parts, and flame cutting machines and similar devices. In these applications, the term numerical control is not always used explicitly, but the operating principle is the same: coded numerical data are employed to control the position of a tool or workhead relative to some object.

Printed Circuit Board (PCB) mechanically supports and electrically connects electronic components or electrical components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate.

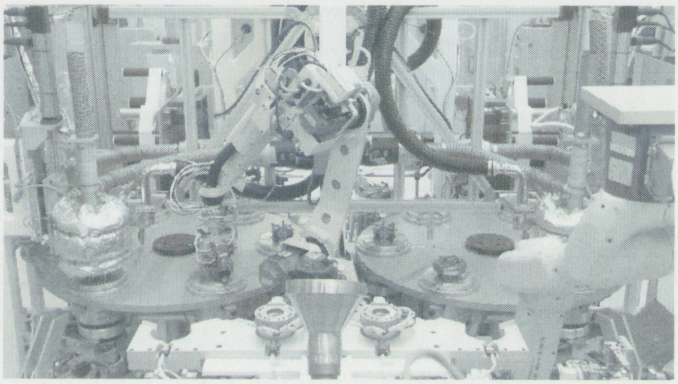
To illustrate these alternative applications of numerical control, the component-insertion machine will be considered here. Such a machine is used to position electronic components (e.g., semiconductor chip modules) onto a **printed circuit board (PCB)**. It is basically an x-y positioning table that moves the printed circuit board relative to the part-insertion head, which then places the individual component into position on the board. A typical printed circuit board has dozens of individual components that must be placed on its surface; in many cases, the lead wires of the components must be inserted into small holes in the board, requiring great precision by the insertion machine. The program that controls the machine indicates which components are to be placed on the board and their locations. This information is contained in the product-design database and is typically communicated directly from the computer to the insertion machine.

4.4.3 Automated assembly

Assembly operations have traditionally been performed manually, either at single assembly workstations or on assembly lines with multiple stations. Owing to the high labour content and high cost of manual labour, greater attention has been given in recent years to the use of automation for assembly work. Assembly operations can be automated using production line principles if the quantities are large, the product is small, and the design is simple (e.g., mechanical pencils, pens, and cigarette lighters). For products that do not satisfy these conditions, manual assembly is generally required.

Automated assembly machines have been developed that operate in a manner similar to machining transfer lines, with the difference being that assembly operations, instead of machining, are performed at the workstations. A typical assembly machine consists of several stations, each equipped with a supply of components and a mechanism for delivering the components into position for assembly. A work head at each station performs the actual attachment of the component. Typical work heads include automatic screwdrivers, staking or riveting machines, welding heads, and other joining devices. A new component is added to the partially completed product at each workstation, thus building up the product gradually as it proceeds through

the line. Assembly machines of this type are considered to be examples of fixed automation, because they are generally configured for a particular product made in high volume. Programmable assembly machines are represented by the component-insertion machines employed in the electronics industry.

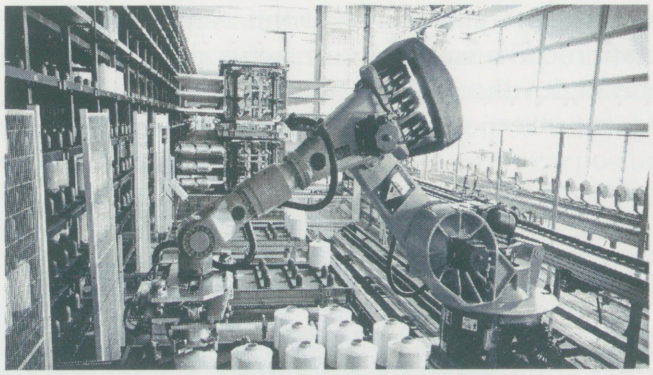


4.4.4 Robots in manufacturing

Today most robots are used in manufacturing operations; the applications can be divided into three categories: (1) material handling, (2) processing operations, and (3) assembly and inspection.

Material-handling applications include material transfer and machine loading and unloading. Material-transfer applications require the robot to move materials or workparts from one location to another. Many of these tasks are relatively simple, requiring robots to pick up parts from one conveyor and place them on another. Other transfer operations are more complex, such as placing parts onto pallets in an arrangement that must be calculated by the robot. Machine loading and unloading operations utilize a robot to load and unload parts at a production machine. This requires the robot to be equipped with a gripper that can grasp parts. Usually the gripper must be designed specifically for the particular part geometry.

In robotic processing operations, the robot manipulates a tool to perform a process on the work part. Examples of such applications include spot welding, continuous arc welding, and spray painting. Spot welding of automobile bodies is one of the most common applications of industrial robots in the United States. The robot positions a spot welder against the automobile panels and frames to complete the assembly of the basic car body. **Arc welding** is a continuous process in which the robot moves the welding rod along the seam to be welded. Spray painting involves the manipulation of a spray-painting gun over the surface of the object to be coated. Other operations in this category include grinding, polishing, and routing, in which a rotating spindle serves as the robot's tool.



Arc welding is a welding process that is used to join metal to metal by using electricity to create enough heat to melt metal, and the melted metals when cool result in a binding of the metals.

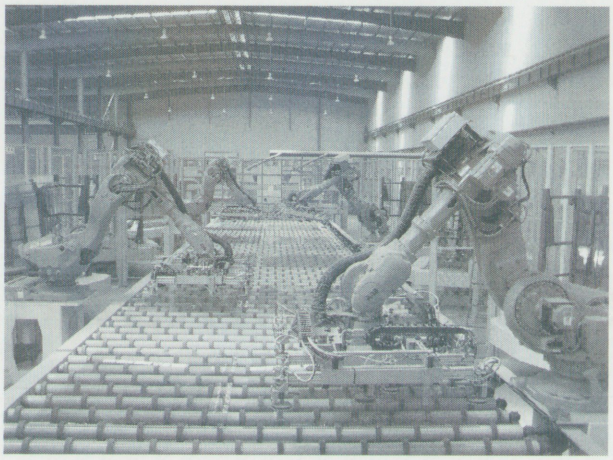
The third application area of industrial robots is assembly and inspection. The use of robots in assembly is expected to increase because of the high cost of manual labour common in these operations. Since robots are programmable, one strategy in assembly work is to produce multiple product styles in batches, reprogramming the robots between batches. An alternative strategy is to produce a mixture of different product styles in the same assembly cell, requiring each robot in the cell to identify the product style as it arrives and then execute the appropriate task for that unit.

The design of the product is an important aspect of robotic assembly. Assembly methods that are satisfactory for humans are not necessarily suitable for robots. Using a screw and nut as a fastening method, for example, is easily performed in manual assembly, but the same operation is extremely difficult for a one-armed robot. Designs in which the components are to be added from the same direction using snap fits and other one-step fastening procedures enable the work to be accomplished much more easily by automated and robotic assembly methods.

Inspection is another area of factory operations in which the utilization of robots is growing. In a typical inspection job, the robot positions a sensor with respect to the work part and determines whether the part is consistent with the quality specifications.

In nearly all industrial robotic applications, the robot provides a substitute for human labour. There are certain characteristics of industrial jobs performed by humans that identify the work as a potential application for robots: (1) the operation is repetitive, involving the same basic work motions every cycle; (2) the operation is hazardous or uncomfortable for the human worker (*e.g.*, spray painting, spot welding, arc welding, and certain machine loading

and unloading tasks); (3) the task requires a work part or tool that is heavy and awkward to handle; and (4) the operation allows the robot to be used on two or three shifts.



4.4.5 Flexible manufacturing systems

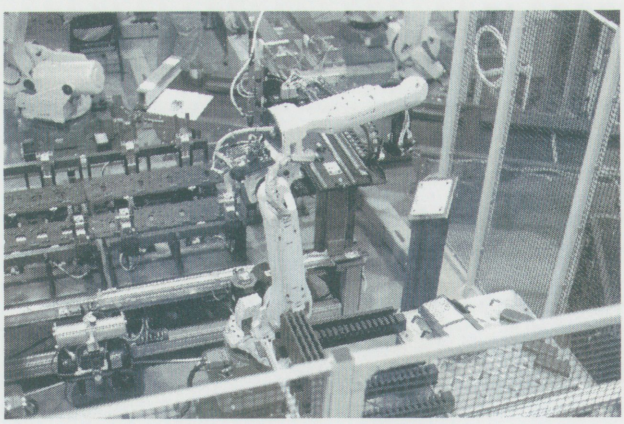
A flexible manufacturing system (FMS) is a form of flexible automation in which several machine tools are linked together by a material-handling system, and all aspects of the system are controlled by a central computer. An FMS is distinguished from an automated production line by its ability to process more than one product style simultaneously. At any moment, each machine in the system may be processing a different part type. An FMS can also cope with changes in product mix and production schedule as demand patterns for the different products made on the system change over time. New product styles can be introduced into production with an FMS, so long as they fall within the range of products that the system is designed to process. This kind of system is therefore ideal when demand for the products is low to medium and there are likely to be changes in demand.

The components of an FMS are (1) processing machines, which are usually CNC machine tools that perform machining operations, although other types of automated workstations such as inspection stations are also possible, (2) a material-handling system, such as a conveyor system, which is capable of delivering work parts to any machine in the FMS, and (3) a central computer system that is responsible for communicating NCpart programs to each machine and for coordinating the activities of the machines and the material-handling system. In addition, a fourth component of an FMS is human labour. Although the flexible manufacturing system represents a high level of production automation, people are still needed to manage the system, load and unload parts, change tools, and maintain and repair the equipment.



4.4.6 Computer process control

In computer process control, a digital computer is used to direct the operations of a manufacturing process. Although other automated systems are typically controlled by computer, the term computer process control is generally associated with continuous or semicontinuous production operations involving materials such as chemicals, petroleum, foods, and certain basic metals. In these operations the products are typically processed in gas, liquid, or powder form to facilitate flow of the material through the various steps of the production cycle. In addition, these products are usually mass-produced. Because of the ease of handling the product and the large volumes involved, a high level of automation has been accomplished in these industries.



The modern computer process control system generally includes the following: (1) measurement of important process variables such as temperature, flow rate, and pressure, (2) execution of some optimizing strategy, (3) actuation of such

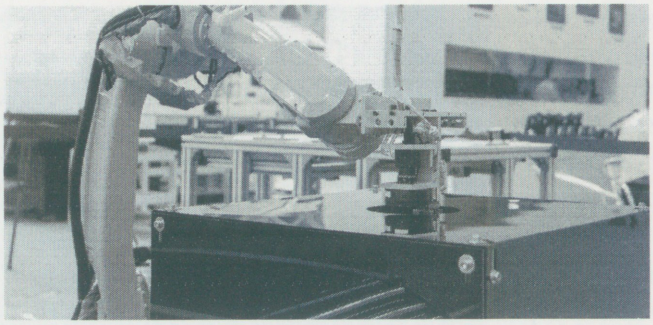
devices as valves, switches, and furnaces that enable the process to implement the optimal strategy, and (4) generation of reports to management indicating equipment status, production performance, and product quality. Today computer process control is applied to many industrial operations, two of which are described below.

The typical modern process plant is computer-controlled. In one petrochemical plant that produces more than 20 products, the facility is divided into three areas, each with several chemical-processing units. Each area has its own process-control computer to perform scanning, control, and alarm functions. The computers are connected to a central computer in a hierarchical configuration. The central computer calculates how to obtain maximum yield from each process and generates management reports on process performance.

Each process computer monitors up to 2,000 parameters that are required to control the process, such as temperature, flow rate, pressure, liquid level, and chemical concentration. These measurements are taken on a sampling basis; the time between samples varies between 2 and 120 seconds, depending on the relative need for the data. Each computer controls approximately 400 feedback control loops. Under normal operation, each control computer maintains operation of its process at or near optimum performance levels. If process parameters exceed the specified normal or safe ranges, the control computer actuates a signal light and alarm horn and prints a message indicating the nature of the problem for the technician. The central computer receives data from the process computers and performs calculations to optimize the performance of each chemical-processing unit. The results of these calculations are then passed to the individual process computers in the form of changes in the set points for the various control loops.

Substantial economic advantages are obtained from this type of computer control in the process industries. The computer hierarchy is capable of integrating all the data from the many individual control loops far better than humans are able to do, thus permitting a higher level of performance. Advanced control algorithms can be applied by the computer to optimize the process. In addition, the computer is capable of sensing process conditions that indicate unsafe or abnormal operation much more quickly than humans can. All these improvements increase productivity, efficiency, and safety during process operation.

Like the chemical-processing industries, the basic metals industries (iron and steel, aluminum, etc.) have automated many of their processes by computer control. Like the chemical industries, the metals industries deal in large volumes of products, and so there is a substantial economic incentive to invest in automation. However, metals are typically produced in batches rather than continuously, and it is generally more difficult to handle metals in bulk form than chemicals that flow.



Computer-aided design (CAD) is the use of computer systems (or workstations) to aid in the creation, modification, analysis, or optimization of a design.

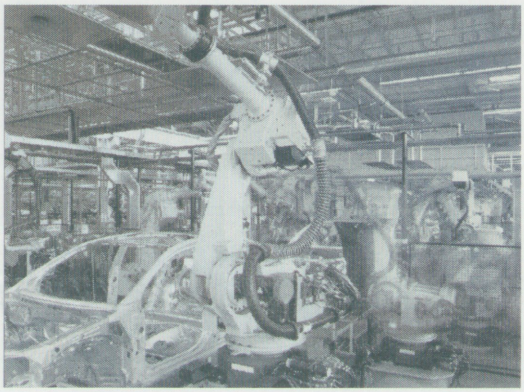
An example of computer process control in the metals industry is the rolling of hot metal ingots into final shapes such as coils and strips. This was first done in the steel industry, but similar processing is also accomplished with aluminum and other metals. In a modern steel plant, hot-rolling is performed under computer control. The rolling process involves the forming of a large, hot metal billet by passing it through a rolling mill consisting of one or more sets of large cylindrical rolls that squeeze the metal and reduce its cross section. Several passes are required to reduce the ingot gradually to the desired thickness. Sensors and automatic instruments measure the dimensions and temperature of the ingot after each pass through the rolls, and the control computer calculates and regulates the roll settings for the next pass.

In a large plant, several orders for rolled products with different specifications may be in the mill at any given time. Control programs have been developed to schedule the sequence and rate at which the hot metal ingots are fed through the rolling mills. The production control task of scheduling and keeping track of the different orders requires rapid, massive data gathering and analysis. In modern plants this task has been effectively integrated with the computer control of the rolling mill operations to achieve a highly automated production system.

4.4.7 Computer-integrated manufacturing

Since about 1970 there has been a growing trend in manufacturing firms toward the use of computers to perform many of the functions related to design and production. The technology associated with this trend is called CAD/CAM, for computer-aided design and computer-aided manufacturing. Today it is widely recognized that the scope of computer applications must extend beyond design and

production to include the business functions of the firm. The name given to this more comprehensive use of computers is computer-integrated manufacturing (CIM).



CAD/CAM is based on the capability of a computer system to process, store, and display large amounts of data representing part and product specifications. For mechanical products, the data represent graphic models of the components; for electrical products, they represent circuit information; and so forth. CAD/CAM technology has been applied in many industries, including machined components, electronics products, and equipment design and fabrication for chemical processing. CAD/CAM involves not only the automation of the manufacturing operations but also the automation of elements in the entire design-and-manufacturing procedure.

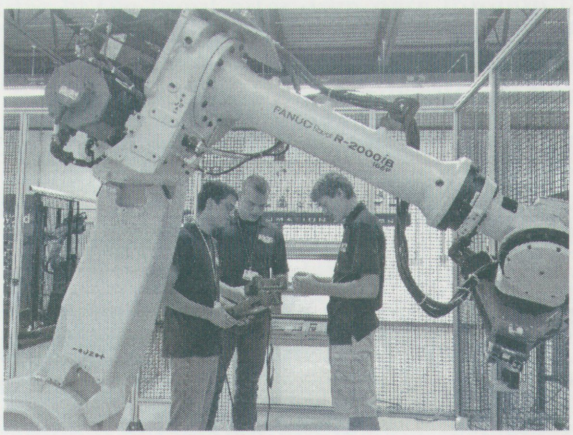
Computer-aided design (CAD) makes use of computer systems to assist in the creation, modification, analysis, and optimization of a design. The designer, working with the CAD system rather than the traditional drafting board, creates the lines and surfaces that form the object (product, part, structure, etc.) and stores this model in the computer database. By invoking the appropriate CAD software, the designer can perform various analyses on the object, such as heat transfer calculations. The final object design is developed as adjustments are made on the basis of these analyses. Once the design procedure has been completed, the computer-aided design system can generate the detailed drawings required to make the object.

Computer-aided manufacturing (CAM) involves the use of computer systems to assist in the planning, control, and management of production operations. This is accomplished by either direct or indirect connections between the computer and production operations. In the case of the direct connection, the computer is used to monitor or control the processes in the factory. Computer process monitoring involves the collection of data from the factory, the analysis of the data, and the communication of process-performance results to plant management. These measures increase the efficiency of plant operations. Computer process control entails the use of the computer system to execute control actions to operate the plant automatically. Indirect connections between the computer

system and the process involve applications in which the computer supports the production operations without actually monitoring or controlling them. These applications include planning and management functions that can be performed by the computer (or by humans working with the computer) more efficiently than by humans alone. Examples of these functions are planning the step-by-step processes for the product, part programming in **numerical control**, and scheduling the production operations in the factory.

Numerical control (NC) is the automated control of machining tools by means of a computer, in which a NC machine operates on a piece of material to transform it to precise specifications.

Computer-integrated manufacturing includes all the engineering functions of CAD/CAM and the business functions of the firm as well. These business functions include order entry, cost accounting, employee time records and payroll, and customer billing. In an ideal CIM system, computer technology is applied to all the operational and information-processing functions of the company, from customer orders through design and production (CAD/CAM) to product shipment and customer service. The scope of the computer system includes all activities that are concerned with manufacturing. In many ways, CIM represents the highest level of automation in manufacturing.



SUMMARY

- Sometimes referred to as a linear induction motor, the linear motor is a motor device that functions with the use of a multi-phase alternating current. As part of the design for the motor, the stator is in an unrolled position.
- A stepper motor is an electromechanical device it converts electrical power into mechanical power. Also it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps.
- These motors operate by generating currents with two vector components. One component is for the coil currents (primary), the other induces currents in the secondary section, which encapsulates short circuit rods.
- These motors, also known as synchronous motors, are the most commonly used linear motor in high performance applications.
- A Cartesian robot, also known as a Cartesian coordinate robot, is a common type of industrial robot.
- Types of robots can be separated by the tasks that they are meant to perform, their role within society, their level of advancement and other criteria.
- An articulated robot is a robot which is fitted with rotary joints. Rotary joints allow a full range of motion, as they rotate through multiple planes, and they increase the capabilities of the robot considerably.
- Cartesian robots are also called rectilinear or gantry robots and have a rectangular configuration. These types of industrial robots have three prismatic joints to deliver linear motion by sliding on its three perpendicular axes (X, Y and Z).
- A SCARA robot is an assembly machine that installs parts or carries items. It is designed to mimic the action of a human arm and can be used in jobs from automobile factories to underwater construction.
- A parallel robot, also called a parallel manipulator, is a mechanism presenting very good performance in terms of stability, rigidity and accuracy to manipulate large loads.
- Polar robots have a twisting joint connecting the arm with the base and a combination of two rotary joints and one linear joint connecting the links.
- Cylindrical robots have at least one rotary joint at the base and at least one prismatic joint connecting the links.
- One of the most important application areas for automation technology is manufacturing. To many people, automation means manufacturing automation.
- An automated production line consists of a series of workstations connected by a transfer system to move parts between the stations.

- Numerical control is a form of programmable automation in which a machine is controlled by numbers (and other symbols) that have been coded on punched paper tape or an alternative storage medium.
- Assembly operations have traditionally been performed manually, either at single assembly workstations or on assembly lines with multiple stations.
- A flexible manufacturing system (FMS) is a form of flexible automation in which several machine tools are linked together by a material-handling system, and all aspects of the system are controlled by a central computer.
- In computer process control, a digital computer is used to direct the operations of a manufacturing process.

REFERENCES

1. B.S. Dhillon, A.R.M. Fashandi, K.L. Liu: Robot systems reliability and safety: a review, J. Qual. Mainten.
2. E. Westkämper: Strategic development of factories under the influence of emergent technologies, CIRP Ann. Manuf. Technol.
3. G. Hirzinger, N. Sporer, A. Albu-Schaffer, M. Hahnle, R. Krenn, A. Pascucci, M. Schedl: DLR's torque-controlled light weight robot III – are we reaching the technological limits now?, Proc. IEEE Int. Conf. Robot. Autom. (ICRA), Vol. 2 (Washington 2002)
4. http://www.moog.com/news/blog-new/the-benefits-of-linear-motors.html
5. http://www.tmmotion.com/english/newsshow_253.html
6. https://www.elprocus.com/induction-motor-types-advantages/
7. https://www.etel.ch/linear-motors/direct-drive/
8. https://www.wisegeek.com/what-is-a-cartesian-robot.htm
9. J.N. Pires, A. Loureiro, G. Bolmsjö: Welding Robots (Springer, London 2006)
10. M.P. Groover: Automation, Production Systems, and Computer-Integrated Manufacturing, 2nd edn. (Prentice Hall, Upper Saddle River 2000)
11. The International Federation of Robotics (IFR): World Robotics 2007. Statistics, Market Analysis, Forecasts, Case Studies and Profitability of Robot Investment (IFR Statistical Department, Frankfurt 2007)
12. W. Townsend: The BarrettHand grasper – programmable flexible part handling and assembly, Ind.

5

CHAPTER

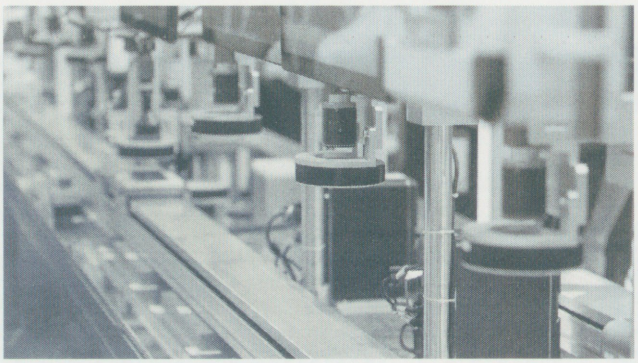
MANUFACTURING SYSTEM

INTRODUCTION

A manufacturing system is an approach to making products that is based upon several factors. These include how much of the product is needed, how quickly the product must be produced and how unique the product must be to ensure sufficient sales. Manufacturing systems include custom, assembly, flexible, intermittent, reconfigurable, just-in-time and lean manufacturing systems.

Custom manufacturing is the original form of production. It is the making of unique items, one at a time, by employing the skills of a single craftsman. Craftsmen might work alongside one another, but they do not work together as a team, because one person completes the manufacture of an individual item.

This is in contrast with an assembly manufacturing system, in which each worker contributes one or more actions that are required in the manufacturing process. This action might be repeated every few seconds or for longer intervals, depending on the complexity of the task. This also is referred to as a mass-production manufacturing system, and it typically values speed and uniformity. The drawbacks to mass-production manufacturing systems are the difficulty of assuring the correct supply of products in real time and being unable to provide customized product offerings.



Flexible manufacturing proposes a solution to producing too much or too little of the product. This method also enables a manufacturer to respond to consumer demand for customized products. It is more expensive to tool a flexible manufacturing system.

Intermittent manufacturing, in which the same item is made repeatedly, might employ a reconfigurable manufacturing system. This is so that different items can be mass-produced one type of item at a time. There is a trade-off with flexible manufacturing systems. The redundancy of functions in tooling systems adds costs in exchange for flexibility, so the initial capital outlay might be higher.

The goal of just-in-time production is to eliminate inventory. Carrying more inventory than is needed adds to overhead costs. For example, producing too many of a particular model of automobile results in unsold vehicles depreciating on the car seller's lot. The storage of unsold items also can be costly in terms of space and money. Conversely, running out of inventory adversely affects sales because customers will go to a competitor if a particular item is not available when the customer is ready to buy.

Lean manufacturing is often employed in tandem with just-in-time production methods. Although it is a manufacturing system, lean manufacturing is actually a strategy that focuses on eliminating unnecessary or wasteful elements of the manufacturing process and achieving maximum efficiency. This strategy can be used in tandem with other manufacturing systems to varying degrees, depending upon the system.

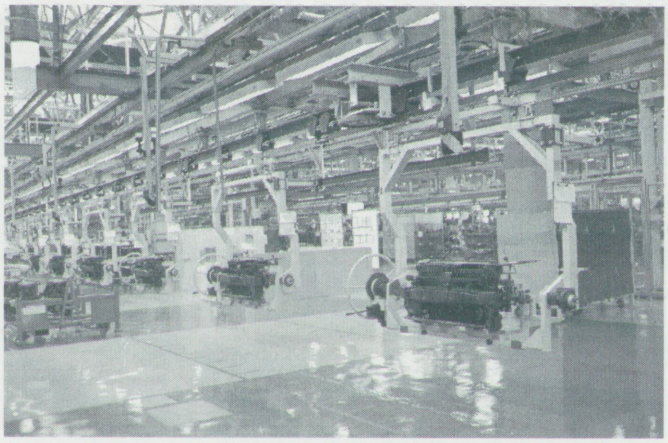
5.1 LEAN MANUFACTURING

Ever since Henry Ford invented the assembly line, industrial innovators have constantly focused on improvement through a variety of different manufacturing strategies. Lean manufacturing is a manufacturing strategy that seeks to produce a high level of throughput with a minimum of inventory.

Originally a Japanese methodology known as the Toyota Production System designed by Sakichi Toyoda, lean manufacturing centers around placing small stockpiles of inventory in strategic locations around the assembly line, instead

of in centralized warehouses. These small stockpiles are known as kanban, and the use of the kanban significantly lowers waste and enhances productivity on the factory floor.

In addition to eliminating waste, lean manufacturing seeks to provide optimum quality by building in a method whereby each part is examined immediately after manufacture, and if there is a defect, the production line stops so that the problem can be detected at the earliest possible time. The lean method has much in common with the Total Quality Management (TQM) strategy. Both strategies empower workers on the assembly line, in the belief that those closest to production have the greatest knowledge of how the production system should work.



In a lean manufacturing system, suppliers deliver small lots on a daily basis, and machines are not necessarily run at full capacity. One of the primary focuses of lean systems is to eliminate waste; that is, anything that does not add value to the final product gets eliminated. In this respect, large inventories are seen as a type of waste that carries with it a high cost. A second major focus is to empower workers, and make production decisions at the lowest level possible.

Additionally, supply chain management factors heavily into lean manufacturing, and a tight partnership with suppliers is necessary; this facilitates the rapid flow of product and parts to the shop floor.

Lean manufacturing strategies can save millions of dollars and produce excellent results. Advantages include lower lead times, reduced set-up times, lower equipment expense, and of course, increased profits. It gives the manufacturer a competitive edge by reducing costs and increasing quality, and by allowing the manufacturer to be more responsive to customer demands.

5.1.1 Purpose of Lean Manufacturing

Lean manufacturing concepts eliminate wasteful practices while delivering increased value to the customer. These principles are simple to apply but require

full employee participation and relentless attention to detail. Even a partial implementation can benefit manufacturing operations and improve performance by reducing waste.

The broad purpose of lean manufacturing is to increase the value of products delivered to the customer to solve the customer's problems. Achieving this aim helps improve your company's competitiveness by reducing your costs. You can create more value in your manufacturing process by identifying activities that don't directly contribute to the creation of high-quality products. If you analyze every step of your production line, you can eliminate unnecessary procedures and achieve the overarching purpose of lean manufacturing.

Eliminating Waste

A basic step in implementing lean manufacturing is to eliminate direct waste, such as wait times and moving goods and materials unnecessarily. Direct waste results in unproductive work hours for employees, underutilization of machines and a slow production line. Lean manufacturing principles call for the synchronization of manufacturing tasks to ensure that one finishes as the next is ready to receive the material. Workers only move products and material when it is directly required as part of a particular manufacturing step. Examining each manufacturing step for wait times and material movement allows you to streamline your production.

Just in Time

Reducing inventory to a minimum decreases costs and supports the purpose of delivering top value. You can apply the lean manufacturing just-in-time principle to the inventory of materials you are using in manufacturing, as well as your inventory of finished products. Ideally your materials inventory is large enough to supply items to the manufacturing line at just the right moment when they are needed. Finished products roll off the line just as customers order them. A continuous process minimizes materials and finished products waiting to be used or shipped.

Eliminate Mistakes

Elimination of mistakes is one of the most important purposes of lean manufacturing. When products don't meet customer specifications or quality requirements, you have to make corrections or rework the item. In addition to using extra manpower and materials, you disrupt the manufacturing line and create outputs of questionable quality. To improve your process, analyze each mistake, find out exactly what caused it and correct the causes to eliminate repeat errors. Doing this on a continuous basis eventually eliminates errors on the production line while reducing costs and raising quality.

5.1.2 The Business Impact of Lean Manufacturing

Because lean manufacturing reduces waste and increases the efficiency of your production line, it has an impact on other parts of the business. Converting to the new system requires adjustments within your company and changes in your **supply chain**. Before implementing a lean manufacturing program, you have to plan for these effects to get the full benefit of the lean manufacturing initiative.

Quality

Lean manufacturing methods result in products of increased quality because they impose a design and manufacturing process that identifies problems at the source. This technique impacts your business by reducing testing requirements, warranty claims and customer service calls. You focus your resources to design quality products and set up your manufacturing process to build them without defects. This allows you to reduce spending in other areas that don't add value directly to your products.

Supply chain is a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer.

Waste

Production lines use consumable material as well as generate off-cuts and defective parts. Lean manufacturing reduces such waste to a minimum. Wherever the manufacturing line produces waste, lean manufacturing methods look for ways to recycle the material or eliminate the source of the waste. Design changes minimize off-cuts, and quality controls reduce defective pieces. The remaining defective material is re-integrated into the production line and re-manufactured if possible. Reduced waste decreases your costs and either increases profitability or makes your products more competitive.

Efficiency

The parts of a manufacturing process operate at different speeds, resulting in wait times. Lean manufacturing methods identify wait times and reduce them to a minimum. Using these methods, you analyze the speeds at which the different sections of the production line operate and match them to

eliminate bottlenecks. Manufacturing takes less time, and costs generated by wait times are reduced -- saving you money and impacting your bottom line.

Inventory

When waiting times are reduced, the need to keep inventory decreases. Your streamlined production line performs more reliably, and you can better forecast your material requirements. Lean manufacturing is often partnered with a just-in-time delivery process that optimizes your supply chain. The ideal target for this process is to provide material as it is needed at every stage of production and to finish products as customers place orders. This concept impacts your supply chain from raw material suppliers to sales and marketing as you have to integrate the entire organizational structure to work seamlessly together.

5.1.3 Key Factors in Lean Manufacturing

The margin between success and failure in the global economy is wafer thin. To stay competitive, organizations must closely monitor every aspect of their operations to produce lower costs and deliver better and better products. The most popular methodology used by industry is known as lean manufacturing, a system that originated within the auto industry. The key factors of lean manufacturing as described below provide managers with powerful tools for continuously improving to staying ahead of the competition.

Lean Basics

Lean manufacturing traces its origins back to Henry Ford and the first modern auto assembly line, but really came of age in the mid-1940s at Toyota Motor Corporation. Engineer Taaichi Ohno developed an operating system focused on eliminating waste, reducing errors, shrinking inventory and ordering parts or supplies "just-in-time," thus reducing warehousing costs. These principles make up what is today known as the Toyota Production System and have been studied and replicated around the world – even in office settings.

Streamlining Processes

The basic idea behind lean manufacturing is to create streamlined processes that deliver products "just in time" – exactly when the customer needs them, without the products spending any time on a shelf as inventory. The idea of "just in time" applies both to the end product and the raw materials for that product within the plant – for instance, delivering a set of screws for one product exactly when they are needed. Just in time seeks to implement a "pull" philosophy that maximizes product flow across the length of the factory.

Eliminating Waste

Fundamental to becoming a lean manufacturer is the elimination of waste from all aspects from an operation. But waste doesn't only refer to producing too many unwanted products. Engineers have identified at least seven forms of waste, including waste in unnecessary motion, transportation and over-processing. The first step in any lean system is a process inventory that identifies the wasteful areas. Reduction of waste saves money and allows workers to turn their attention to more value-creating activities.

Reducing Defects

Perhaps the most damaging form of waste is manufacturing defective products. Lean manufacturing calls on its followers to "do it right the first time" – not just to save money, but as part of an overall mindset dominated by quality. Lean encourages adherents to work toward a system in which quality is a given, whether in a part, a product, a package or an accounting process. Lean is often associated with Six Sigma, which is a measurement that is considered as close to zero defects as is possible.

Continuous Improvement

Lean manufacturing is not considered a one-time, flavor-of-the-month program. It is a never-ending mindset – a journey aimed at widening the margin between success and failure. Once done with the steps of lean manufacturing, organizations are supposed to return to the beginning and start again. As one lean expert describes it, lean manufacturing involves the pursuit of perfection.

5.1.4 Improve Quality with Lean Manufacturing

Lean manufacturing is a production theory that emphasizes the elimination of waste in all forms. Resource expenditures that do not contribute to the value of a product are wasteful in a lean manufacturing environment. When waste elimination is the goal, the results are an improvement in customer service, efficiency and the quality of the products a business manufactures.

Customer Focus and Continuous Improvement

Lean organizations develop a focus on customer value. In an effort to reduce costs to end customers, businesses using lean manufacturing principles will strive to eliminate defects to reduce the added cost of reworking parts and components. The first step in adopting a lean manufacturing system is to create a customer-focused environment. In addition to a focus on the customer, lean manufacturing stresses continuous improvement, which is a system of small

incremental changes to improve efficiency and eliminate waste. Some businesses use quality circles or quality improvement teams to identify, resolve and eliminate waste in the company.

Waste Identification

To eliminate waste, such as quality defects, it is necessary to identify it. One of the tools a lean manufacturing business may use is value stream mapping. Value stream mapping creates a visual image of how materials and information flow through the organization from the time a customer places an order until the shipping department ships it out the door. The mapping process highlights inefficiencies in the production flow and provides opportunities for continuous improvement projects. The identification of waste affects the quality of a product by showing where the defects occur in the process.

Root Cause Analysis

Once a quality team identifies a defect or inefficiency, members can begin working on a root cause analysis. While some businesses implement inspection processes to remove defective material from production, lean organizations conduct a root cause analysis to resolve the problem and stop the defects from ever occurring. Root cause analysis traces the cause of a defect back to its origin. Causes may include machinery failure, human error, raw material defects or a problem with the work process. Lean manufacturing principles include a zero defect policy that encourages workers to create error-free products.

Implement a Solution

When a business has a clearly defined problem and the root cause has been identified, the next step is to implement a solution. Using a team approach to solving the problem allows businesses to extract input from workers in all areas of the manufacturing process. Teams may implement a solution and collect data to ensure the problem is resolved.

5.1.5 Lean Manufacturing Pros & Cons

Lean manufacturing aims to incorporate processes and attitudes to increase efficiency and streamline operations and overhead, resulting in cost savings, increased profits and an engaged, motivated workforce. Despite an underlying philosophy of constant improvement, lean principles can be pushed past the point of effective return, reversing the improvements these meant to achieve.

Cost Savings

Every business owner, large or small, is interested in ways to improve the bottom line. Lean principles promote reduced waste and increased productivity, so training staff in the techniques of lean manufacturing usually pays dividends with implementation of the principles. Cost savings are realized through reduced raw material supplies and fewer labor hours, while these efficiencies increase the capacity of a business, saving storage and production space and gaining worker time to turn toward other parts or projects.

Positive Workforce Effects

Lean strategies often are based around worker initiatives, assuming that those doing the work are the best source for ideas about improving the way it is done. With acceptance and buy-in from production staff, a business owner realizes the benefits of a previously hidden resource. In turn, having influence and input into their work and how it is done, workers are more apt to feel involved and satisfied about themselves, their workplace and the work they do, particularly when they feel they have the support of you, the business owner.

False Economies

Care must be taken to implement reasonable expectations from lean manufacturing principles. A company may see large savings at the onset of starting a lean program. While further improvements are usually possible, these will likely be on a smaller scale. The drive for further improvements may become counterproductive. For example, if your business used a machine that produces 40 parts an hour, increasing the speed of the machine may improve the output, but this may come at a cost of increased waste.

Negative Workforce Effects

Relentless push for change and improvement by management may be poorly received by workers. Even in the case of businesses where lean implementation is successful, continuous improvement drives may be frustrating for workers. This is particularly dangerous when workers perceive an owner is placing all the lean burden on them. Leading by example is key for owners and managers, to show that lean principles are accepted and implemented at all levels, not simply operations.

5.1.6 Key Issues for the Implementation of a Lean Manufacturing System

Lean manufacturing centers around minimizing waste and reducing costs through automation and continuous improvements in operational efficiency. Lean manufacturing relies on integrated technological systems, smaller workforces of highly trained employees and a radical shift in company culture. Each of these elements can present distinct challenges that must be overcome to achieve a truly efficient lean manufacturing system. Understanding these key issues is a vital building block for developing your own lean implementation plan.

Project managers are first point of contact for any issues or discrepancies arising from within the heads of various departments in an organization before the problem escalates to higher authorities.

Supply Chain Issues

Lean manufacturing includes the minimization or near elimination of storage time for incoming materials and outgoing products. Implementing a just-in-time ordering system is necessary to ensure that raw materials are constantly coming in at the perfect rate to meet operational demand. This requires close coordination with suppliers, even going as far as integrating automated ordering and order-fulfillment systems between your two companies. This kind of close operational cooperation can introduce a host of issues, since **project managers** in both companies must coordinate with each other while managing their own side of the implementation project. The same can be true on the outgoing end, as well. Serving business customers with just-in-time ordering systems can require your business to act as a just-in-time supplier, filling orders frequently and automatically.

Employee Development

Implementing lean manufacturing methodologies in an existing business creates a talent gap that must be crossed. The technological infrastructure required to manage supply-chain issues while maintaining automated production and quality-control systems requires more-educated and -trained employees than traditional assembly line setups. Lean manufacturers require highly skilled and educated employees to inspect, repair and design the layout of automated production technology regularly. Technical

employees will likely require safety certifications and special licenses to operate and maintain such systems, and they demand much higher compensation than general-labor employees.

Cultural Issues

Going lean introduces a revolutionary shift in the way work is done in a manufacturing organization. Implementing lean manufacturing requires a smaller number of employees to take on a wider range of responsibilities, blurring the lines between formal job descriptions. It involves a strict and meaningful commitment to waste reduction, which can mean changing employees' familiar work processes. It should involve reworking incentives and bonus structures to reward behavior and ideas that reduce costs, production time and waste. This requires true buy-in at all levels of a company, from senior managers to front-line machine operators. Successfully developing lean manufacturing processes requires true commitment from everyone involved.

Technological Challenges

Lean manufacturing can require a significant upfront investment in technology, from new production systems to statistical analysis software for monitoring quality improvement on assembly lines. Choosing the right systems is crucial for success as a lean manufacturer, since you will be relying on your systems for the continued efficient operation of your business. One of the tenets of lean business practices is to automate as much as possible, making you more reliant on technology than you may have been in the past.

5.2 FLEXIBLE MANUFACTURING SYSTEM

A flexible manufacturing system (FMS) is a type of industrial process that allows equipment to be used for more than one purpose, though they may be somewhat related. The equipment is often used to make customized parts, or make different parts for different models of product. This type of system may be changed by hand, but is more likely to be controlled by a computer, and changed through an entirely automated process.

The main goal of a flexible manufacturing system is to offer the speed needed to change with market conditions quickly, but not sacrifice any quality. Equipment that does this most effectively is likely designed for two or more purposes. While it may be possible to modify or retrofit some types of industrial equipment to do a job adequately, most FMS are designed for more than one purpose from the very outset.

Though the equipment for a flexible manufacturing system may initially be more expensive than traditional equipment, the overall goal is to reduce expenses.

Manufacturers can save money by using the same equipment to essentially perform two or more functions. With traditional equipment, manufacturing two different products may not only require different pieces of equipment, but also two different lines and perhaps two different facilities. Therefore, this type of system may reduce overhead, despite higher start-up costs initially.

One of the most common examples of a flexible manufacturing system can be seen in the manufacturing of automobiles. Certain equipment is used to attach doors to a sedan. With just a few simple adjustments, that same line and equipment may be used to attach doors to a sport utility vehicle or some other type of vehicle. Often, the switchover can take place with very little disruption to the line, and may even happen during shifts.

In fact, the automobile industry can potentially save a substantial amount of money using a flexible manufacturing system. A report in 2004 indicated that Ford Motor Company saved approximately $2.5 billion US Dollars by putting flexible systems in at five manufacturing plants. The company estimated it can save at least half of the cost of manufacturing updated models using the systems.

In some cases, the machines may not only be used to produce or assemble different parts for different models, but to make customizations. These customizations, without a flexible system in place, would take much longer, and be much more expensive for the customer. Using machines with the ability to be flexible can not only speed the process up, but can improve customer satisfaction by bringing down the price.

5.2.1 Organizational Structure for Flexible Manufacturing Systems

In a manufacturing setting, the flexibility concept denotes the ability to produce high quality customized products that are reasonably priced and can be delivered quickly to customers. This is often achieved by a flexible manufacturing system, an arrangement of machines interconnected by a transport system and controlled by a central computer. FMS allows you to change the line to produce new product types as well as change the order of operations to be executed on a part. FMS also enables routing flexibility: You can deploy multiple machines for the same operation on a part in addition to accommodating large-scale changes.

Computer Control

At the heart of the FMS structure is a central computer that controls both the machines and the transport system. The computer coordinates workflow by performing several functions: It schedules the jobs onto the machine tools and downloads part programs that give detailed instructions to the machines on how to produce the various parts. The computer also sends specific instructions to the automated transport system on how, where and when to deliver items. The

FMS communication protocol supports real-time data traffic consisting of both large machining data files and short messages.

Work Machines

A flexible manufacturing system relies on machine flexibility, or their ability to adapt to a variety of products and circumstances. An industrial FMS typically consists of numerical controlled machines or computer-controlled machines, instrumentation devices and stand-alone systems such as inspection equipment. Complementing these in the production segment are several machine tools along with tool and part handling devices such as robots. The robots usually are arranged to handle any family of parts for which they are designed, to enable optimal utilization and to achieve high volumes of productivity.

Material Handling System

FMS requires material handling flexibility, determined by the system's ability to transport and properly position different part types at the various machine tools on the production line. The central control computer directs the movement of product parts from the load station to the processing stations via the transport system. Once the part processing ends, finished parts are routed to automatic inspection nodes and subsequently offloaded from the FMS. Common material handling systems include conveyors and automatic guided vehicles -- rail-guided, free-roving or guided by wires embedded in the floor.

FMS Implementation

FMS ensures high flexibility in managing manufacturing resources such as time and effort and is suitable for mass production. It has many advantages. Automated control ensures reduced errors, rework, repairs and rejects, yielding consistent and better quality. Programming precision ensures proper planning, reducing inventory. You incur lower direct labor cost as it minimizes human numbers and improves capital utilization due to faster, lower-cost changes from one part to another. However, it has some drawbacks: It is expensive to implement, requiring a high capital outlay, and it demands substantial pre-planning activity, translating to personnel with specialized training.

5.2.2 Flexible Manufacturing Systems and Today Factories

A flexible manufacturing system (FMS) is a manufacturing system in which there is some amount of flexibility to react in the case of changes, whether predicted or unpredicted. This flexibility can be divided into two categories:

- Machine flexibility, covers the system's ability to be changed to produce new product types, and ability to change the order of operations executed on a part, and
- Routing flexibility, this consists of the ability to use multiple machines to perform the same operation on a part, as well as the system's ability to absorb large-scale changes, such as in volume, capacity, or capability.

Most FMS systems consist of three main systems.

- The work machines which are often using computerized machines,
- Material handling system to optimize parts flow, and
- The central control computer which controls material movements and machine flow.

An Industrial Flexible Manufacturing System (FMS) consists of robots, Computer-controlled Machines, Numerical controlled machines (CNC), instrumentation devices, computers, sensors, and other stand-alone systems such as inspection machines as shown in Figure 1.

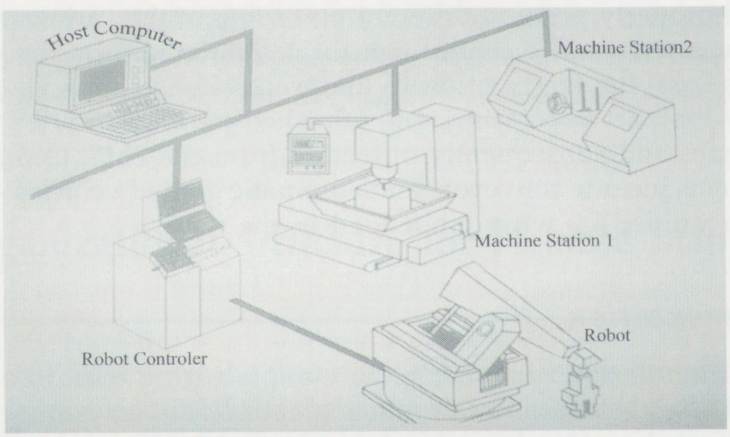


Figure 1. Illustration of FMS

The use of robots in the production segment of manufacturing industries promises a variety of benefits ranging from high utilization to high volume of productivity. Each Robotic cell or node will be located along a material handling system such as a conveyor or automatic guided vehicle as shown in Figure 2.

The production of each part or work-piece will require a different combination of manufacturing nodes. The movement of parts from one node to another is done through the material handling system. At the end of part processing, the finished parts will be routed to an automatic inspection node, and subsequently unloaded from the Flexible Manufacturing System.

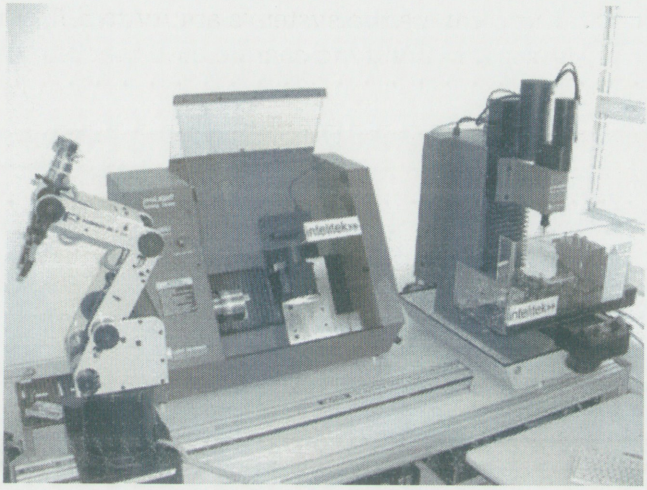


Figure 2. Robotic located along a material handling system.

The FMS data traffic consists of large files and short messages, and mostly come from nodes, devices and instruments. The message size ranges between a few bytes to several hundreds of bytes. Executive software and other data, for example, are files with a large size, while messages for machining data, instrument to instrument communications, status monitoring, and data reporting are transmitted in small size. There is also some variation on response time. Large program files from a main computer usually take about seconds to be down loaded into each instrument or node at the beginning of FMS operation. Messages for instrument data need to be sent in a periodic time with deterministic time delay. Other type of messages used for emergency reporting is quite short in size and must be transmitted and received with almost instantaneous response.

The demands for reliable FMS protocol that support all the FMS data characteristics are now urgent. The existing IEEE standard protocols do not fully satisfy the real time communication requirements in this environment. The delay of CSMA/CD is unbounded as the number of nodes increases due to the message collisions. Token Bus has a deterministic message delay, but it does not support prioritized access scheme which is needed in FMS communications. Token Ring provides prioritized access and has a low message delay, however, its data transmission is unreliable. A single node failure which may occur quite often in FMS causes transmission errors of passing message in that node. In addition, the topology of Token Ring results in high wiring installation and cost.

A design of FMS communication protocol that supports a real time communication with bounded message delay and reacts promptly to any emergency signal is needed. Because of machine failure and malfunction due to heat, dust, and electromagnetic interference is common, a prioritized mechanism and immediate transmission of emergency messages are needed so that a suitable recovery procedure can be applied. A modification of standard Token Bus to implement a prioritized access scheme was proposed to allow transmission of

short and periodic messages with a low delay compared to the one for long messages.

5.2.3 Flexibility and Its Types

Flexibility is an attribute that allows a mixed model manufacturing system to cope up with a certain level of variations in part or product style, without having any interruption in production due to changeovers between models. Flexibility measures the ability to adapt "to a wide range of possible environment". To be flexible, a manufacturing system must possess the following capabilities:

- Identification of the different production units to perform the correct operation
- Quick changeover of operating instructions to the computer controlled production machines
- Quick changeover of physical setups of fixtures, tools and other working units

Computer numerical control is the automated control of machining tools by means of a computer, in which a NC machine operates on a piece of material to transform it to precise specifications.

These capabilities are often difficult to engineer through manually operated manufacturing systems. So, an automated system assisted with sensor system is required to accomplish the needs and requirements of contemporary business milieu. Flexible manufacturing system has come up as a viable mean to achieve these prerequisites. The term flexible manufacturing system, or FMS, refers to a highly automated GT machine cell, consisting of a group of **computer numerical control (CNC)** machine tools and supporting workstations, interconnected by an automated material handling and storage system, and all controlled by a distributed computer system. The reason, the FMS is called flexible, is that it is capable of processing a variety of different part styles simultaneously with the quick tooling and instruction changeovers. Also, quantities of productions can be adjusted easily to changing demand patterns.

The different types of flexibility that are exhibited by manufacturing systems are given below:

1. **Machine Flexibility.** It is the capability to adapt a given machine in the system to a wide range of production operations and part styles. The greater the range of operations and part styles the greater will be the machine flexibility. The various factors on which machine flexibility depends are:

- Setup or changeover time
- Ease with which part-programs can be downloaded to machines
- Tool storage capacity of machines
- Skill and versatility of workers in the systems

2. **Production Flexibility.** It is the range of part styles that can be produced on the systems. The range of part styles that can be produced by a manufacturing system at moderate cost and time is determined by the process envelope. It depends on following factors:
   - Machine flexibility of individual stations
   - Range of machine flexibilities of all stations in the system
3. **Mix Flexibility.** It is defined as the ability to change the product mix while maintaining the same total production quantity that is, producing the same parts only in different proportions. It is also known as process flexibility. Mix flexibility provides protection against market variability by accommodating changes in product mix due to the use of shared resources. However, high mix variations may result in requirements for a greater number of tools, fixtures, and other resources. Mixed flexibility depends on factors such as:
   - Similarity of parts in the mix
   - Machine flexibility
   - Relative work content times of parts produced
4. **Product Flexibility.** It refers to ability to change over to a new set of products economically and quickly in response to the changing market requirements. The change over time includes the time for designing, planning, tooling, and fixturing of new products introduced in the manufacturing line-up. It depends upon following factors:
   - Relatedness of new part design with the existing part family
   - Off-line part program preparation
   - Machine flexibility
5. **Routing Flexibility.** It can define as capacity to produce parts on alternative workstation in case of equipment breakdowns, tool failure, and other interruptions at any particular station. It helps in increasing throughput, in the presence of external changes such as product mix, engineering changes, or new product introductions. Following are the factors which decides routing flexibility:
   - Similarity of parts in the mix
   - Similarity of workstations
   - Common tooling
6. **Volume Flexibility.** It is the ability of the system to vary the production

volumes of different products to accommodate changes in demand while remaining profitable. It can also be termed as capacity flexibility. Factors affecting the volume flexibility are:

- Level of manual labor performing production
- Amount invested in capital equipment

7. **Expansion Flexibility.** It is defined as the ease with which the system can be expanded to foster total production volume. Expansion flexibility depends on following factors:
   - Cost incurred in adding new workstations and trained workers
   - Easiness in expansion of layout
   - Type of part handling system used

Since flexibility is inversely proportional to the sensitivity to change, a measure of flexibility must quantify the term "penalty of change (POC)", which is defined as follows:

POC = penalty x probability

Here, penalty is equal to the amount up to which the system is penalized for changes made against the system constraints, with the given probability. Lower the value of POC obtained, higher will be the flexibility of the system.

5.2.4 FMS and its Rule in CIM Environment

FMS ensures quality product at lowest cost while maintaining small lead-time. So, firms adopt FMS as a means of meeting burgeoning requirements of customized production. Main purpose of FMS is to achieve efficiency of well-balanced transfer line while retaining the flexibility of the job shop. A flexible manufacturing system (FMS) has four or more processing workstations connected mechanically by a common part handling system and electronically by a distributed computer system. It covers a wide spectrum of manufacturing activities such as machining, sheet metal working, welding, fabricating, scheduling and assembly. Advantages of processes involved in flexible manufacturing system over the conventional methods are:

Table 1. Comparison between attributes of flexible and conventional manufacturing systems.

Item	Flexible	Conventional
Set-up	Defined	Varies
Volume	Low-Medium	Medium-High
WIP (work-in-process)	Low	High
Flexibility	High	Low
Scrap	Low	Unpredictable
Labor	Low	High
Equipment cost	High (short term)	Low (short term)
Equipment ROI	Low	High
Plant ROI	High	Low
Queuing	Low	High
Automation	High level	Low level
Future	Lead to integration	Dead end
Quality	Controlled	Varies
Inspection	Automatic tie-in	Doesn't flow
Tooling and fixturing	Flexible	Rigid
Market changes	Flexible	Rigid
Equipment utilization	Optimized	Low
Production control	Predictable	Unpredictable
Lead time	Low	High
Engineering changes	Easier	Equipment and time constraints

Another strategic advantage of FMS is that it is able to handle the risk caused by uncertainty about the future. It can be done through planning in a way that maintains flexibility of the environment. Although it is impossible to predict the future, one can make estimates of probabilities and proceed in ways to accord with the future. The simple decision tree in figure 3 illustrates the decision-making in case of FMSs governing the choices among three different options depending upon the nature of the market.

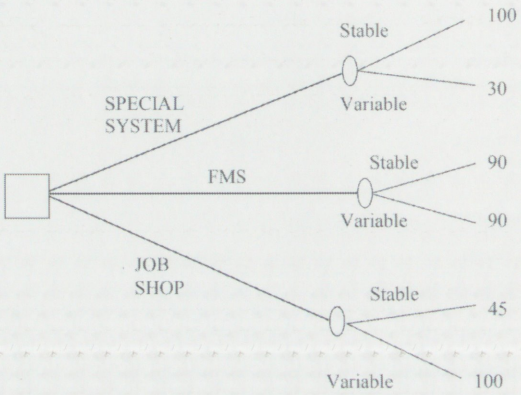


Figure 3. Simple Decision Tree.

The first option is a specialized manufacturing system that performs well in stable market (payoff = 100) but will perform poorly (payoff = 30) if the market is variable. The second option, the FMS, will perform fairly well (payoff = 90) regardless of the type of market. The third option is the job shop that will perform well in variable (payoff = 100). From the example it is clear that an FMS performs less well than a specific option in specific market but proves to be a fairly good performer when the nature of market is not defined. As a conclusion, FMS technology can be termed as an evolutionary step beyond transfer lines that enables the industries to accommodate the growing customer demand and maintain the quick delivery of customized products. It is the newest wave in attaining greater productivity with instant positive response to both adversities and new opportunities.

5.2.5 Advantages and disadvantages of FMSs implementation

Advantages

- Faster, lower- cost changes from one part to another which will improve capital utilization
- Lower direct labor cost, due to the reduction in number of workers
- Reduced inventory, due to the planning and programming precision
- Consistent and better quality, due to the automated control
- Lower cost/unit of output, due to the greater productivity using the same number of workers
- Savings from the indirect labor, from reduced errors, rework, repairs and rejects

Disadvantages

- Limited ability to adapt to changes in product or product mix (ex. machines are of limited capacity and the tooling necessary for products, even of the same family, is not always feasible in a given FMS)
- Substantial pre-planning activity
- Expensive, costing millions of dollars
- Technological problems of exact component positioning and precise timing necessary to process a component
- Sophisticated manufacturing systems

5.3 GROUP TECHNOLOGY / CELLULAR MANUFACTURING

Group Technology is a manufacturing technique by which parts having similarities in design attributes or manufacturing processes are grouped together in Part Families. Cellular Manufacturing is a method of designing the plant layout which takes advantage of Group Technology to form Machine Cells to process parts lying within a particular part family.

The cellular manufacturing system, often called lean manufacturing, is a fairly recent development in global manufacturing processes. One of the first, and today, the most common cellular, or lean manufacturing systems is the Kaizen system. Originally conceived by the Toyota Corporation in Japan, Kaizen utilizes technology and cellular manufacturing to reduce the waste of time, effort, money, and resources in the production process.

A cellular manufacturing layout is in direct contradiction to the traditional production line. In the production line, numerous workers are needed to service a single production line running from receiving of raw material to shipping of finished product. A breakdown in staffing or machinery in any part of the line nearly always resulted in the entire process being idled until the specific difficulty in the line was repaired, or re-crewed. With cellular manufacturing, production is divided among groups, or cells, of workers and production machinery. Thus, the breakdown of one cell, due to equipment malfunction or staffing problems, does not radically affect the rest of the production process.

Though very technical and detailed, the concept of cellular production is basically simple; get a finished product from raw materials to shipment as efficiently, and as profitably as possible. Cellular manufacturing systems and layouts essentially separate the production line into segments, or cells, sometimes called modules. Each cell, consisting of both workers and production machinery, is dedicated to a particular component of the manufactured product. Ideally, workers and equipment comprising a particular cell are trained and configured to be able to take over the processes of another cell when necessary, thus minimizing downtime and wastage of raw material.

Obviously, a significant investment in time and money is necessary to implement a lean, or cellular, system of manufacturing, especially in an established production facility. The process of modulating the production process usually involves both re-training workers and re-tooling equipment. This process becomes much less expensive and time-consuming when implemented as part of a start-up manufacturing enterprise. In established facilities, the process of implementation usually takes several months, while new facilities will incorporate cellular manufacturing procedures into the construction and employee training process.

Six Sigma is a disciplined, statistical-based, data-driven approach and continuous improvement methodology for eliminating defects in a product, process or service.

Technology and cellular manufacturing have combined to streamline the production processes of numerous established and start-up manufacturing facilities worldwide. Lean systems, such as Kaizen, and **Six Sigma**, to name just two, though very often high in startup cost, provide both a short- and long-term benefit in reducing the waste common to the traditional production line. The bottom line in any manufacturing enterprise is profit. Cellular manufacturing has been proven to dramatically increase profits.

5.3.1 Historical Development

As early as in the 1920ies it was observed, that using product-oriented departments to manufacture standardized products in machine companies lead to reduced transportation. This can be considered the start of Group Technology (GT). Parts are classified and parts with similar features are manufactured together with standardized processes. As a consequence, small "focused factories" are being created as independent operating units within large facilities. More generally, Group Technology can be considered a theory of management based on the principle that "similar things should be done similarly". In our context, "things" include product design, process planning, fabrication, assembly, and production control. However, in a more general sense GT may be applied to all activities, including administrative functions. The principle of group technology is to divide the manufacturing facility into small groups or cells of machines. The term cellular manufacturing is often used in this regard. Each of these cells is dedicated to a specified family or set of part types. Typically, a cell is a small group of machines (as a rule of thumb not more than five). An example would be a machining center with inspection and monitoring

devices, tool and Part Storage, a robot for part handling, and the associated control hardware. The idea of GT can also be used to build larger groups, such as for instance, a department, possibly composed of several automated cells or several manned machines of various types. If volumes are very small, and parts are very different, a functional layout (job shop) is usually appropriate. In the intermediate case of medium-variety, medium-volume environments, group configuration is most appropriate.

GT can produce considerable improvements where it is appropriate and the basic idea can be utilized in all manufacturing environments:

- To the manufacturing engineer GT can be viewed as a role model to obtain the advantages of flow line systems in environments previously ruled by job shop layouts. The idea is to form groups and to aim at a product-type layout within each group (for a family of parts). Whenever possible, new parts are designed to be compatible with the processes and tooling of an existing part family. This way, production experience is quickly obtained, and standard process plans and tooling can be developed for this restricted part set.
- To the design engineer the idea of GT can mean to standardize products and process plans. If a new part should be designed, first retrieve the design for a similar, existing part. Maybe, the need for the new part is eliminated if an existing part will suffice. If a new part is actually needed, the new plan can be developed quickly by relying on decisions and documentation previously made for similar parts. Hence, the resulting plan will match current manufacturing procedures and document preparation time is reduced. The design engineer is freed to concentrate on optimal design.

In this GT context a typical approach would be the use of composite Part families. Consider e.g. the parts family shown in Figure 4.

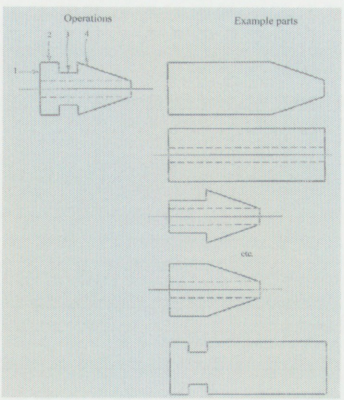


Figure 4. Composite Group Technology Part.

The parameter values for the features of this single part family have the same allowable ranges. Each part in the family requires the same set of machines and tools; in our example: turning/lathing, internal drilling, face milling, etc. Raw material should be reasonably consistent (e.g. plastic and metallic parts require different manufacturing operations and should not be in the same family). Fixtures can be designed that are capable of supporting all the actual realizations of the composite parts within the family. Standard machine setups are often possible with little or no changeover required between the different parts within the family (same material, same fixture method, similar size, same tools/machines required).

In the functional process (job shop) layout, all parts travel through the entire shop. Scheduling and material control are complicated. Job priorities are difficult to set, and large WIP inventories are used to assure reasonable capacity utilization. In GT, each part type flows only through its specific group area. The reduced setup time allows faster adjustment to changing conditions. Often, workers are cross-trained on all machines within the group and follow the job from Start to finish. This usually leads to higher job satisfaction/motivation and higher efficiency. For smaller-volume part families it may be necessary to include several such part families in a machine group to justify machine utilization. One can identify three different types group layout:

- In a GT flow line concept all parts assigned to a group follow the same machine sequence and require relatively proportional time requirements on each machine. The GT flow line operates as a mixed product assembly line system; see Figure 5a. Automated transfer mechanisms may be possible.

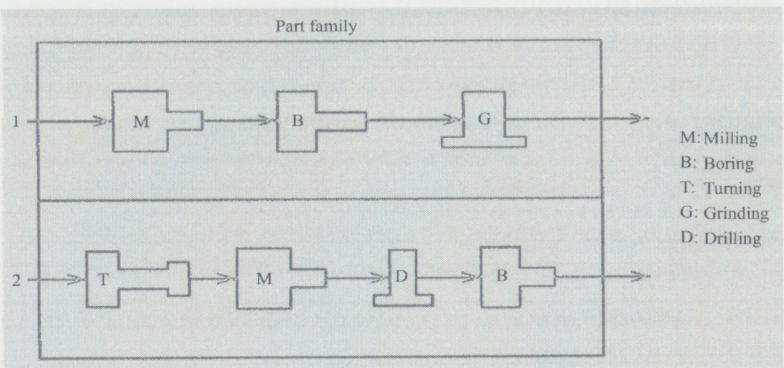


Figure 5a. GT flow line

- The classical GT cell allows parts to move from any machine to any other machine. Flow is not unidirectional. However, since machines are located in close proximity short and fast transfer is possible.

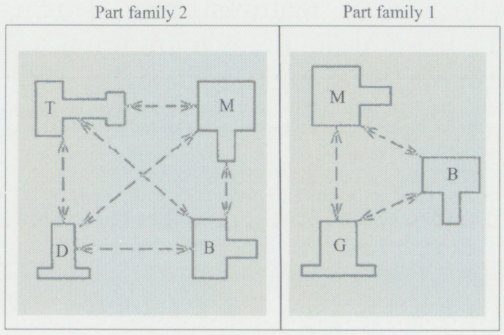
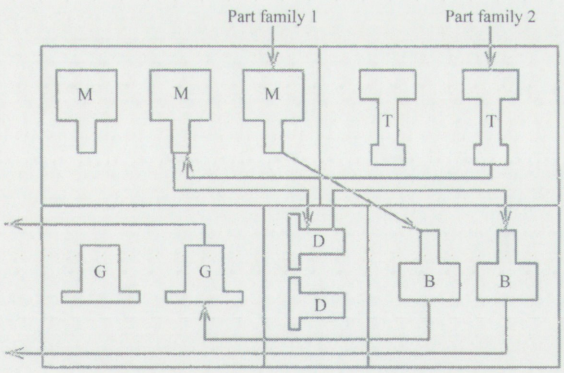


Figure 5b. GT cell

- The GT center may be appropriate when
  - Large machines have already been located and cannot be moved, or
  - Product mix and part families are dynamic and would require frequent relay out.

Then, machines may be located as in a process layout by using functional departments (job shops), but each machine is dedicated to producing only certain Part families. This way, only the tooling and control advantages of GT can be achieved. Compared to a GT cell layout, increased material handling is necessary.



- **Figure 5c.** GT center

GT offers numerous benefits w.r.t. throughput time, WIP inventory, materials handling, job satisfaction, fixtures, setup time, space needs, quality, finished goods, and labor cost.

In general, GT simplifies and standardizes. The approach to simplify, standardize, and internalize through repetition produces efficiency. Since a work center will work only on a family of similar parts generic fixtures can be developed and used. Tooling can be stored locally since parts will always be processed through the same machines. Tool changes may be required due to tool wear only, not part changeovers (e.g. a press may have a generic fixture that

can hold all the parts in a family without any change or simply by changing a part specific insert secured by a single screw. Hence setup time is reduced, and tooling cost is reduced. Using queuing theory (M/M/1 model) it is possible to show that if setup time is reduced, also the throughput time for the system is reduced by the same percentage.

5.3.2 Production Flow Analysis (PFA)

To group machines, part routings must be known. Section this presents a method for clustering part operations onto specific machines to provide this routing information.

The basic idea is:

- Identify items that are made with the same processes / the same equipment
- These parts are assembled into a part family
- Can be grouped into a cell to minimize material handling requirements.
- The clustering methods can be classified into:
- Part family grouping: Form part families and then group machines into cells
- Machine grouping: Form machine cells based upon similarities in part routing and then allocate parts to cells
- Machine-part grouping: Form part families and machine cells simultaneously.

The most typical methods are the machine-part grouping ones. Typically one starts with a matrix that shows which part types require which machine types. The aim is to sort the part types and machines such that some kind of block diagonal structure is obtained:

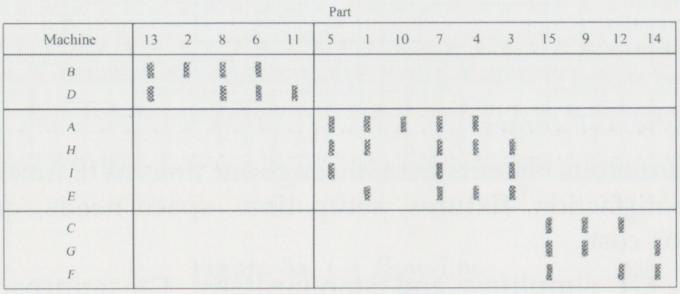


Figure 6. Matrix of machine usage

In case of the example in Figure 6, it is easy to build groups:

- Group 1: parts {13, 2, 8, 6, 11 }, machines {B, D}

- Group 2: parts { 5, 1, 10, 7, 4, 3}, machines {A, H, I, E}
- Group 3: parts { 15, 9, 12, 14}, machines {C, G, F}

But the question is how this sorting can be done. Various heuristic and exact methods have been developed. The simplest one is binary ordering, also known as rank order clustering or King's algorithm

Binary Ordering (Rank Order Clustering, King's Algorithm)

This is done in three steps

- Interpret rows and columns as binary numbers
- Sort rows w.r.t. decreasing binary numbers
- Sort columns w.r.t. decreasing binary numbers

This will be illustrated in a simple example with 6 parts and 5 machines:

	part					
machine	*1*	*2*	*3*	*4*	*5*	*6*
A	-	1	-	1	-	-
B	1	-	1	-	1	1
C	-	1	1	1	-	1
D	1	-	-	-	1	1
E	-	-	-	1	1	-

First, the rows are interpreted as binary numbers and sorted

	part						
machine	*1*	*2*	*3*	*4*	*5*	*6*	value
A	-	1	-	1	-	-	
B	1	-	1	-	1	1	
C	-	1	1	1	-	1	
D	1	-	-	-	1	1	
E	-	-	-	1	1	-	
2^x	*32*	*16*	*8*	*4*	*2*	*1*	

This gives a new ordering of the machines: B – D – C – A – E. Next, we sort columns w.r.t. decreasing binary numbers (note the new order of rows here):

	part						
machine	*1*	*2*	*3*	*4*	*5*	*6*	2^x
B	1	-	1	-	1	1	*16*
D	1	-	-	-	1	1	*6*
C	-	1	1	1	-	1	*4*
A	-	1	-	1	-	-	*2*
E	-	-	-	1	1	-	*1*
value							

This gives a new ordering of parts: 6-5-1-3-4-2.

The matrix with rows and columns in the new order is:

	part					
machine	*6*	*5*	*1*	*3*	*4*	*2*
B	1	1	1	1	-	-
D	1	1	1	-	-	-
C	1	-	-	1	1	1
A	-	-	-	-	1	1
E	-	1	-	-	1	-

Now 2 groups can be formed

- Group 1: parts {6, 5, 1}, machines {B, D}
- Group 2: parts { 3, 4, 2}, machines {C, A, E}

Parts 1, 4, and 2 can be produced in one cell. The remaining items 6, 5, and 3 are outside the bold rectangles (indicating the block diagonal structure) and cause problems. There are, in principle 3 possibilities:

- These parts produced in both cells, i.e. Part 6 is mainly produced in cell 1 but for operation on machine c it has to be transported to cell 2
- Machines b, c, and e have to be duplicated, so that all parts can be produced within one cell
- Some parts that do not fit at all could also be given to subcontractors
- Binary Ordering is a simple heuristic ⇒ no guarantee that optimal ordering is obtained.

Sometimes a better block-diagonal structure is obtained by repeating the Binary Ordering until there is no change anymore. In the above example this yields the final form of the matrix

	part						
machine	*6*	*5*	*1*	*3*	*4*	*2*	value
B	1	1	1	1	-	-	60
D	1	1	1	-	-	-	56
C	1	-	-	1	1	1	39
E	-	1	-	-	1	-	3
A	-	-	-	-	1	1	18
value	28	26	24	20	7	5	

Hence, repeated Binary Ordering did not help in this example.

Single-Pass Heuristic Considering Capacities

All machines have sufficient capacity to produce all products that need to go on this machine, i.e. we ignored capacity. The following algorithm by Askin and Standridge extends the model by introducing capacity considerations.

We make the following assumptions:

- All parts must be processed in one cell (machines must be duplicated, if off-diagonal elements occur in the matrix)
- All machines have capacities (normalized to be 1)
- There are constraints on number of identical machines in a group
- There are constraints on total number of machines in a group

Example: We will demonstrate the methods in an example with 7 parts and 6 machines. At most 4 machines can be in a group and not mot than one copy of each machine is allowed in each group. The following matrix contains the processing times (incl. set up times) for typical lot size of parts on machines (i.e., the entries in matrix are not just 0/1 for used/not used). All times are normalized as percentage of total machine capacity:

	part								
machine	*1*	*2*	*3*	*4*	*5*	*6*	*7*	sum	min. # machines
A	0.3	-	-	-	0.6	-	-	0.9	1
B	-	0.3	-	0.3	-	-	0.1		
C	0.4	-	-	0.5	-	0.3	-		
D	0.2	-	0.4	-	0.3	-	0.5		
E	-	0.4	-	-	-	0.5	-		
F	-	0.2	0.3	0.4	-	-	0.2		

By summing up all entries in a row we obtain total machine utilization. If this value exceeds one, at least two machines are needed. More generally, this number must be rounded up to the next integer to give the minimum number of machines needed. It should be noted, that this minimum number of machines is a lower bound. It may be necessary to use more copies of some machines than this minimum number suggests.

Summing up the minimum number of machines for all machine types we obtain, that at least 9 machines are needed. Since not more than 4 machines are permitted in a group, we know that at least 9/4 = 2,25 groups are needed. Since only integer numbers of groups make sense, this must be rounded up to obtain the lower bound on the number of groups: at least 3 groups.

For binary sorting treat all entries as 1s. The result is the matrix

	part						
machine	1	5	7	3	4	6	2
D	0.2	0.3	0.5	0.4	-	-	-
C	0.4	-	-	-	0.5	0.3	-
A	0.3	0.6	-	-	-	-	-
F	-	-	0.2	0.3	0.4	-	0.2
B	-	-	0.1	-	0.3	-	0.3
E	-	-	-	-	-	0.5	0.4

Hence, the parts are considered in the following order: D – C – A – F – B – E.

Iteration	part chosen	group	assigned machines	remaining capacity
1	1			
2	5			
3	7			
4	3			
5	4			
6	6			
7	2			

The final solution consists of the three cells:

- Group 1: parts {1, 5}, machines {D, C, A}
- Group 2: parts {7, 3, 4}, machines {D, F, B, C}
- Group 3: parts {6, 2}, machines {C, E, F, B}

We can compare the machines used with the theoretical minimum numbers computed earlier:

	part									
machine	1	2	3	4	5	6	7	sum	min. #	**Single-Pass Heuristic**
A	0.3	-	-	-	0.6	-	-	0.9	**1**	**1**
B	-	0.3	-	0.3	-	-	0.1	0.7	***1***	***2***
C	0.4	-	-	0.5	-	0.3	-	1.2	***2***	***3***
D	0.2	-	0.4	-	0.3	-	0.5	1.4	**2**	**2**
E	-	0.4	-	-	-	0.5	-	0.9	**1**	**1**
F	-	0.2	0.3	0.4	-	-	0.2	1.1	**2**	**2**

Apparently, we need one more copy of machine B (2 instead of 1) and one more copy of machine C (3 instead of 2).

We should note, that the Single-pass heuristic of Askin und Standridge is a simple heuristic. Hence, it gives not necessarily an optimal solution (min possible number of machines).

5.4 JUST-IN-TIME MANUFACTURING

Just-in-time manufacturing is a strategy used in the manufacturing industry to reduce costs by reducing the in-process inventory level. It is driven by a series of signals that tell the production line to make the next piece for the product and when it is needed. The signals used are usually simple visual signals, such as the absence or presence of a piece that is needed in the **manufacturing process**.

Manufacturing process are the steps through which raw materials are transformed into a final product.

In just-in-time manufacturing, reorder levels for certain inventory items are set, and new stock is ordered only when those levels are reached. There is no overstocking of parts or items, which saves on space in the warehouse. This manufacturing strategy can lead to improvements in quality and efficiency. It also can lead to higher profits and a larger return on the company's investment.

Although this specific manufacturing strategy was created by the Toyota company in Japan during the 1970s, previous businesses used manufacturing processes that were based on similar concepts. One of the first was created by Henry Ford, whose automobile company bought materials only for its immediate needs in the manufacturing process. Ford bought only the amount of material that was needed in the plan of production and planned the transportation of materials so that the flow of the product would be smooth. This created a rapid turnover and decreased the amount of money that was tied up in raw materials.

Ford's manufacturing process was adopted by many other car manufacturers. Toyota used the process with satisfactory results and modified it to overcome some of its weaknesses, which led to what is now known as just-in-time manufacturing. The process allowed Toyota to reduce costs and build cars more quickly. Many vehicles were built to order, which reduced the threat that they would be built and not sold, thus eliminating a risk to the company.

Quality Assurance (QA) is the process of verifying whether a product meets required specifications and customer expectations. It is a process-driven approach that facilitates and defines goals regarding product design, development and production.

Unlike some other types of manufacturing processes, with just-in-time manufacturing, assemblers do not have a choice of which parts to use; every part has to fit correctly. This means that the use of multiple suppliers usually is avoided, and **quality assurance** is higher. The parts used are all of the same quality, which means that line stops for quality checks are almost eliminated, leading to higher productivity rates. Just-in-time manufacturing principles have been applied to many industries and businesses with successful results.

One potential flaw in just-in-time manufacturing is that it relies on an accurate anticipation of demand. Manufacturers need to gauge the levels of materials and parts that they need based on their previous or current sales figures. If there is a rise or fall in demand for the product, it could have serious effects on the just-in-time manufacturing process. Manufacturers have to make sure that they have a reliable sales forecast in place to allow for these fluctuations in sales, or they could have problems with inventory or with the manufacturing process.

The operations planning and control system is an information system running throughout the manufacturing environment. Although there is a common system framework. Systems run in different ways in different environments. For example, dedicated special facilities are used in make-to-stock environments; general purpose machines are used in make-to-order environments. Dedicated production lines can be designed in a balanced way with minimal setups in order to maximize the flow rate of the materials, while a general purpose machine must be set up before producing a specific item. In setup operations, the material flow is interrupted.

Manufacturing environments can be changed to make planning and control systems simpler and more effective. For example, products are designed to have high similarity in processing and are mixed in a dedicated production line with negligible setups. Since lead-times are shortened, this

turns a make-to-stock product into a make-to-order product. Just-in-time is not only a control technique, but also a way to improve the manufacturing environment. JIT control systems are only effective in JIT environments. Introducing kanban systems into a non-JIT environment means nothing to a company.

JIT Control can be incorporated into an ERP system as a control part with a condition that the system has to be in a JIT environment. The JIT philosophy guides the development of the JIT environment. The JIT environment provides the foundation for implementing the JIT control techniques. The JIT philosophy, JIT environment, and the JIT technique can be expressed in Figure 7.

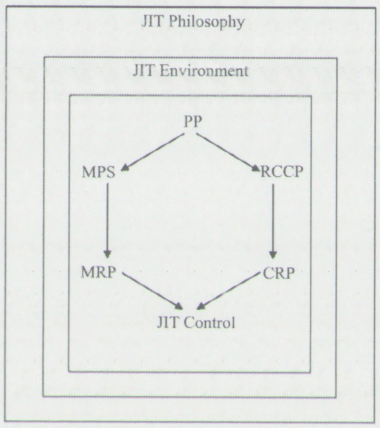


Figure 7: JIT Concept

5.4.1 JIT as a Philosophy

Elimination of waste

Any activity that does not add value to the product or service in the eyes of the customer is a waste. Poor product design such as the inclusion of fancy functions not required by the customer is a waste. A product design causing difficulty in manufacturing is a waste. Standardization reduces the planning and control efforts, the number of parts, and the inventory required. A poor product design without enough standardization leads to waste. In addition to waste resulting from poor design, Toyota identifies seven examples of waste resulting from poor manufacturing methods.

1. Waste of overproduction. Overproduction is the production of goods more than what are immediately needed. Overproduction causes extra material handling, quality problems, and unnecessary inventories. Consuming materials for unnecessary products may cause a shortage of material for other products that are needed. Never overproduce

products to keep men and machines busy. If the required loading is less than the capacity, leave it alone. The labor can be switched to other departments, cleaning or maintaining the machines, accepting training and education, etc.

2. Waste of waiting. A material waiting in queue is a waste. An operator waiting for material or instruction and having no productive work to do is a waste.
3. Waste of movement. Poor plant layout results in materials having to be moved extra distances and cause unnecessary material handling costs. Work centers should be close to each other in order to reduce the move distance. Someone may say that close work centers provide no room for WIP inventories. That is fine! No room for WIP inventory forces the WIP to decrease.
4. Waste of inventories. Inventory causes costs of interest, space, record keeping, and obsolescence. Moreover, inventory can mask problems which could cause more inventory buildup. For example, WIP inventory between work centers can hide the symptoms of an unbalanced production rate. Finished goods inventory can mask poor forecasting, poor quality, and poor production control. Inventory is not an asset; it is a waste!
5. Waste of motion. Improper methods of performing tasks by the operators cause wasted motions. Reaching far for materials or machine buttons is a waste of motion. Searching for tools is a waste of motion. Any activity that does not add value to the products should be eliminated. Bad layout or training causes waste of motion.
6. Waste of making defects. The cost of scraps is a waste. But it is the least important compared with other wastes caused by making defects. Defects interrupt the smooth flow of materials in the production line. If the scrap is not identified, next workstation will try using it to produce more wastes, or waste time waiting for good materials.
7. Waste of process itself. Bad process design is a waste. For example, wrong type or size of machines, wrong tools, and wrong fixtures are wastes.

The principle of eliminating the wastes includes:

1. All waste should be eliminated.
2. Waste can gradually be eliminated by removing small amounts of inventory from the system, correcting the problems that ensue, and then, removing more inventory.
3. The customers' definitions of quality should drive product design and manufacturing system.
4. Manufacturing flexibility is essential to maintain high quality and low cost with an increasingly differentiated product line.

5. Mutual respect and support should exist among an organization, its employees, its suppliers, and its customers.
6. A team effort is required to achieve world class manufacturing capability.
7. The employee who performs a task is the best source of suggested improvements.

Continuous improvement/One Less at a Time

As we have mentioned before, JIT improves the manufacturing system gradually rather than drastically, as in **business process reengineering (BPR)**. This gradual continuous improvement is defined by APICS Dictionary as "one less at a time": a process of gradually reducing the lot size of the number of items in the manufacturing pipeline to expose, prioritize, and eliminate waste. "One less at a time" is a constant, step-by-step methodology for making JIT work in any manufacturing environment. JIT is a never-ending series of small, controlled steps, not one great leap forward. In the JIT philosophy, not the same product is produced over and over again; instead, the same process is used repeatedly to produce different products.

Business process reengineering (BPR) is the practice of rethinking and redesigning the way work is done to better support an organization's mission and reduce costs.

The procedure of "one less at a time" is as follows:

1. If the inventory is equal to zero then stop, else
2. Select the most prioritized process to be improved.
3. Improve the process.
4. Is the process economical? If no, go to step 3.
5. Reduce the inventory by a small amount.
6. Go to step 1

The third step "Improve the process" in the above procedure can be broken down into following steps:

1. Observe the existing method and collect related data on the selected process.
2. Investigate and analyze the data to generate alternatives to improve the process.
3. Evaluate the alternatives to determine the new method for the process.
4. Install the new method and educate the operator.
5. Maintain the new method.

The effects of "One inventory less" can be expressed as in Figure 8. Reducing inventory forces the setup times to decrease for more frequently the products have to be produced to maintain lower inventory level. In order to have shorter setup times, processes must be designed to be more flexible and workers must be trained to do multiple jobs. The need for shorter setup times also demands that the number of items be fewer. The number of items can be reduced through a design of more common parts and modules in different products. Shorter setup times lead to smaller lot sizes and shorter lead times. Shorter lead times result in more frequent product delivery and decrease the need for accurate forecasting and planning which increase the schedule stability. More frequent distribution forces people to reduce paper work and material move distance, and to develop more efficient material handling and transportation systems. Less inventory demands a higher quality level, zero defect process, and better preventive maintenance. Less inventory also requires better communication between departments, customers, and suppliers, and hence requires a smaller number of suppliers.

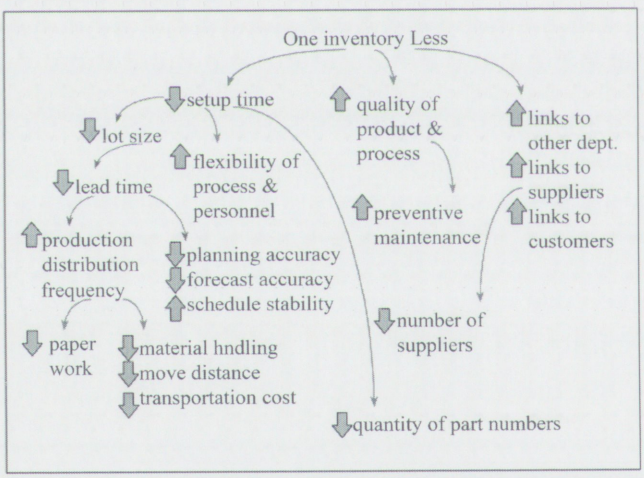


Figure 8: Effects of Less Inventory

Problems as opportunities

JIT philosophy sees the problems as the opportunities. A problem is an opportunity to improve. JIT exposes problems rather than covering them.

Quality at the source

Defects may occur at the design stage, any workstation in the production line, or the suppliers' plants. Quality does not come from inspection. It does not come from manufacturing either. Quality comes from good design. The quality of a

product is determined at the design stage, including product design and process design. A poor design will never result in good quality. In a production line, it is not adequate to inspect the products at the end the line. Inspections should be executed by the operators themselves at each step of the line before the parts are passed on to the following process. The operator in the next workstation has no obligation to inspect an incoming part. A defect must be screened out immediately after it occurs. For purchased parts, the inspection should be completed before delivery. Incoming inspection is not required.

Simplification

Simplicity is a key to successful manufacturing. Products should be designed to be easy to manufacture, install, and repair. Only 2 or 3 levels should exist in the bill of material. Suppliers deliver the materials regularly and purchase orders are not required. Materials are stored at the point of use (POU), and picking orders are not required. Work centers produce the items when they are consumed and shop orders are not required. Material inventory records are not updated until the finished goods are reported complete. Simplifying the system is central to the philosophy of JIT.

Visual Control

Visible control tools are used wherever possible. Cards attached to the materials, containers at sight, tags in stock indicating order points, etc. are examples of visual control tools. These signals are processed by human intelligence at the speed of light, and are superior to any computer in the world. JIT philosophy reminds us that natural human senses are effective tools but are frequently ignored.

Focus on Customer Needs

In JIT philosophy, only values in customers' eyes are real values. Values perceived by engineers but not accepted by customers are wastes. All activities from production design, material procurement, fabrication, assembly, distribution to after service, focus on customer needs. Any motion of the operator on the shop floor not adding value to customer needs is a waste.

Production to Customer Demand

In JIT philosophy, only immediate customer demands are produced. Extra items not required immediately by the customers are not put into production. Without customer demand, there should be no production.

Respect for Individual

Each individual in a company is an important asset. Education and training are frequently conducted to enhance the capability of the employees. Employee involvement and empowerment are part of JIT philosophies. Employee involvement is the concept of using the experience, creativity, and intelligence of all employees by treating them with respect, keeping them informed, and including them and their ideas in decision making processes. Employee empowerment is the practice of giving non-managerial employees the responsibility and power to make decisions that can effect their jobs or tasks. It allows employee to take responsibility for tasks normally associated with staff specialists, such as scheduling, inspection, etc.

5.4.2 JIT as an Environment

In addition to philosophical concepts, JIT also provides an environment in which products are manufactured in a simpler way.

Repetitive Manufacturing

Assemble to order (ATO) is a business production strategy where products ordered by customers are produced quickly and are customizable to a certain extent.

Repetitive manufacturing is the production of discrete items in a production line with fixed routings. The items can be a product or a family of products. The product is standard or made from standard modules. The manufacturing environment is make-to-order (MTO) or **assemble-to-order (ATO)**. The production line consists of workstations located close together and in sequence. Materials flow from a workstation to the next at a relatively constant rate. Material handling systems are normally used to move the materials from process to process in the production line. Normally, the capacity of the production line is kept sufficient. The repetitive manufacturing is based on an uninterrupted flow of materials.

Total Quality Management (TQM)

Total quality management is a management approach used to achieve quality improvement and long-term success

through customer satisfaction. TQM involves all members of the organization, and is meant to improve the quality of all processes, products, services, operations, and corporate culture.

TQM activities follow a plan-do-check-action (PDCA) cycle to improve the quality. In the "plan" step, the problem is defined, the symptoms are explained, and the key performance measures are determined. In the "do" step, the cause of the symptoms is identified. The causes of the causes are also investigated until the root cause is uncovered. Then, an approach to solve the problem is developed and implemented. The performance measures can be changed in this step. In the "check" step, the effectiveness of the proposed approach is observed by using the performance measures. In the "action" step, the results are studied to determine what was learned and what can be predicted. The improvement process is standardized to apply to similar problems. In the PDCA cycle, the steps are not necessarily followed strictly sequentially. For example, if we find a proposed approach is not affirmative in "check" step, we may jump to the "do" stage to revise the approach.

Total Productive Maintenance (TPM)

"Preventive maintenance" is a restrictive term which mentally prohibits us from thinking more broadly. TPM means preventive maintenance and continuing efforts to adapt, modify, and refine equipment in order to increase flexibility, reduce material handling, and promote continuous flows. It is operator-oriented maintenance involving all qualified employees in all maintenance activities.

Total Employee Involvement (TEI)

Elimination of waste and continuous improvement are the central ideas of the JIT philosophy. They can be accomplished only when employees are cooperative. A successful JIT environment should have the cooperation and involvement of everyone in the organization. Traditionally, operators take orders from management and do what they are asked to do, while management is in charge of planning, supervising, inspecting, etc. In a JIT environment, operators take responsibility for controlling the equipment, inspecting for quality, correcting the deviations, maintaining the machines, and improving the processes. Many of the tasks traditionally done by the management become the duties of the line workers under JIT. Managers are not playing the game; they are coaches and the line workers are the players. The mission of a coach is to train the players.

Supplier Partnership

In order to establish a smooth flow of materials into the factory, a close and reliable relationship with the suppliers is very important. Supplier partnership is the establishment of a working relationship with a supplier whereby the two

organizations act as one. Relationships with the suppliers should be based on mutual trust, cooperation, and long-term commitment.

5.4.3 JIT as a Control Technique

In daily operations, JIT provides useful control methods. The characteristics of a JIT control technique include uniform loading, repetitive processes, pull system, using production cards, and synchronized production.

Pull System

JIT control pulls materials from the previous workstation. The workstation replenishes any materials consumed by its following workstation. Since only the consumed materials are produced, the inventories between workstations never accumulate. For the first workstation of the factory, the supplier is its preceding workstation. For the last workstation in a factory, the customer is its following workstation. Customers pull the products from the factory, and factory pulls the materials from the suppliers.

Uniform Loading

The loads for jobs in every workstation are equal. This makes the pull system possible. If uneven loading exists, the following workstation may have to wait for the materials from the preceding workstation. Uniform loading allows the materials to flow through the production line smoothly. Every workstation runs at a constant rate. If the demand increases, the production rates in all workstation increase together. If the demand drops, all workstations may have the same level of idleness.

Production Card

JIT control uses various cards to transmit production signals. During the production, these cards are attached to and detached from the materials. Production signals are transmitted from the following workstation back to the preceding workstation. The cards have various shapes and colors to indicate different purposes. Sometimes material containers or the material itself are themselves the signals.

Synchronized Production

Synchronized production is a manufacturing practice in which production activities in each workstation are synchronized with certain control signals. The production rates of workstations are related to each other, and the work-in-

process inventories are limited to a predetermined level. Synchronized production can be seen in JIT environments or theory-of-constraints (TOC) environments. The control signals are carried by kanbans in a JIT environment. In the TOC environment, drum-buffer-rope (DBR) is used to synchronize the workstations.

5.4.4 Differences between JIT & Lean Manufacturing

The terms lean manufacturing and "just in time," or JIT, are often used as if they're the same thing, but they aren't identical concepts. Just-in-time manufacturing is focused on efficiency, while lean manufacturing is focused on using efficiency to add value for your customer. It's not a question of either-or: Just-in-time manufacturing can be practiced on its own, or as one step in your lean manufacturing process.

Just-in-Time Manufacturing

Before JIT was introduced by Toyota, most manufacturers kept large amounts of inventory available just in case they needed it. Taiichi Ohno of the Toyota Corporation developed a production system of ordering parts in small quantities, based on short-term production cycles. The process was designed to ensure that a part would arrive just in time to be used, eliminating the need to keep it in inventory. Toyota found that the just-in-time system reduced lead time on orders by one third and reduced production costs by 50 percent, and the system eventually spread too many other companies.

Lean Manufacturing

Lean manufacturing takes the concept of JIT and reexamines in the light of customer value. The first step in the lean manufacturing process is to consider what the real value of your product is for the customer. For instance, if your customer is buying a stereo speaker, he might be looking for sound quality, durability and affordability. The first principle of lean manufacturing is that every step in the production process must add something of value that the customer actually wants.

The Value Stream

The next step in the lean process is to examine every activity involved in manufacturing your product, to understand which activities add value and which don't. Then, redesign your manufacturing process to remove activities that don't add value, as far as it's possible. For instance, if your stereo speaker customer is looking for affordability, sound quality and durability, using high-quality parts would add value by improving the durability and sound quality of the product. Transporting parts from a distant warehouse to the manufacturing

plant would not. Switching to a just-in-time manufacturing process would reduce transportation and warehousing costs, making the speakers more affordable. The new process adds value by increasing efficiency.

Flow and Pull

Once everything that does not add value has been removed from the value stream, your manufacturing process should flow more efficiently. At this stage in the process, lean manufacturing and just in time are identical. The next step in leaning manufacturing is to only manufacture what your customer orders or requests, so that customer demand or "pull" drives your production. This is similar to just in time in that new parts are ordered based on short-term requirements, but the driving force behind the efficiency of the process is customer value rather than cost reduction.

5.4.5 High Velocity Manufacturing

Traditionally, a manufacturing business competes on price, quality, variety, after service, etc. Now, these conditions are merely prerequisites. Few businesses exist today without offering low prices, high quality, and good service. The key competitive factor has become speed. All else being equal, the faster a business responds to its customers, the more profitable it is. The shorter the lead-time in which a manufacturer can supply its products, the higher the probability that it will survive. High velocity manufacturing is a common goal for all manufacturing businesses. In high velocity manufacturing, everything is moving. Machines, people, funds and materials are constantly moving. Therefore, inventories in storage or on the shop floor are moving inventories rather than sitting inventories. Inventories are stocked only for a very short time, and will move to other locations only moments after being stocked. The conditions of high velocity manufacturing include flow manufacturing, line balancing, level schedule, and linearity.

Flow Manufacturing

A product or a group of similar products are processed through a series of workstations arranged in a fixed sequence. The materials flow through each workstation at a constant production rate.

Line balancing

Line balancing is required in high velocity manufacturing. Under this condition, tasks must be designed so that the work assigned to each workstation will require about the same amount of time to complete. There is no bottleneck and

no buildup of **work-in-process (WIP)** inventories. For cases where bottlenecks are unavoidable, the theory of constraints (TOC) is applied.

Work in process (WIP) are a company's partially finished goods waiting for completion and eventual sale or the value of these items. These items are either just being fabricated or waiting for further processing in a queue or a buffer storage.

Level Schedule

The schedule sets the flow of material coming into and passing through the manufacturing system. Since the flow of materials must be even in a high velocity manufacturing system, the schedules are designed to be level.

Linearity

Linearity refers to production at a constant rate or the use of resources at a level rate that is measured at least daily.

SUMMARY

- A manufacturing system is an approach to making products that is based upon several factors. These include how much of the product is needed, how quickly the product must be produced and how unique the product must be to ensure sufficient sales.
- Custom manufacturing is the original form of production. It is the making of unique items, one at a time, by employing the skills of a single craftsman. Craftsmen might work alongside one another, but they do not work together as a team, because one person completes the manufacture of an individual item.
- Flexible manufacturing proposes a solution to producing too much or too little of the product. This method also enables a manufacturer to respond to consumer demand for customized products. It is more expensive to tool a flexible manufacturing system.
- A basic step in implementing lean manufacturing is to eliminate direct waste, such as wait times and moving goods and materials unnecessarily. Direct waste results in unproductive work hours for employees, underutilization of machines and a slow production line.
- Lean manufacturing is a production theory that emphasizes the elimination of waste in all forms. Resource expenditures that do not contribute to the value of a product are wasteful in a lean manufacturing environment.
- Lean manufacturing centers around minimizing waste and reducing costs through automation and continuous improvements in operational efficiency.
- A flexible manufacturing system (FMS) is a type of industrial process that allows equipment to be used for more than one purpose, though they may be somewhat related.
- A flexible manufacturing system (FMS) is a manufacturing system in which there is some amount of flexibility to react in the case of changes, whether predicted or unpredicted.
- Flexibility is an attribute that allows a mixed model manufacturing system to cope up with a certain level of variations in part or product style, without having any interruption in production due to changeovers between models.
- FMS ensures quality product at lowest cost while maintaining small lead-time. So, firms adopt FMS as a means of meeting burgeoning requirements of customized production. Main purpose of FMS is to achieve efficiency of well-balanced transfer line while retaining the flexibility of the job shop.
- Group Technology is a manufacturing technique by which parts having similarities in design attributes or manufacturing processes are grouped

together in Part Families. Cellular Manufacturing is a method of designing the plant layout which takes advantage of Group Technology to form Machine Cells to process parts lying within a particular part family.

- Just-in-time manufacturing is a strategy used in the manufacturing industry to reduce costs by reducing the in-process inventory level. It is driven by a series of signals that tell the production line to make the next piece for the product and when it is needed.
- Repetitive manufacturing is the production of discrete items in a production line with fixed routings. The items can be a product or a family of products. The product is standard or made from standard modules.
- Line balancing is required in high velocity manufacturing. Under this condition, tasks must be designed so that the work assigned to each workstation will require about the same amount of time to complete.

REFERENCES

1. Aghazadeh, S. (2003), "JIT inventory and competition in tlie global environment: a comparative study of American and Japanese values in auto industry", Cross Cultural Management, Vol. 10 No.4, pp.29-42
2. Cheng, L., D. E. Cantor, M. Dresner and C. M. Grimm. 2012. The impact of contract manufacturing on inventory performance: An examination of U.S. manufacturing industries. Decision Sciences 43(5): 889-928.
3. Clottey, T., W. C. Benton Jr. and R. Srivastava. 2012. Forecasting product returns for remanufacturing operations. Decision Sciences 43(4): 589-614.
4. http://keu92.org/uploads/Search%20engineering/Flexible%20Manufacturing%20Systems.pdf
5. http://www.ignou.ac.in/upload/UNIT6-55.pdf
6. http://www.lancer.com.tw/attachments/367_ErpBook(8).pdf
7. https://prolog.univie.ac.at/teaching/LVAs/Layout_und_Design/SS09/Skript%20insel.pdf
8. https://smallbusiness.chron.com/differences-between-jit-lean-manufacturing-75614.html
9. https://smallbusiness.chron.com/organizational-structure-flexible-manufacturing-systems-81099.html
10. https://smallbusiness.chron.com/purpose-lean-manufacturing-69380.html
11. https://www.wisegeek.com/what-is-a-flexible-manufacturing-system.htm
12. https://www.wisegeek.com/what-is-a-manufacturing-system.htm
13. https://www.wisegeek.com/what-is-cellular-manufacturing.htm
14. https://www.wisegeek.com/what-is-just-in-time-manufacturing.htm
15. https://www.wisegeek.com/what-is-lean-manufacturing.htm

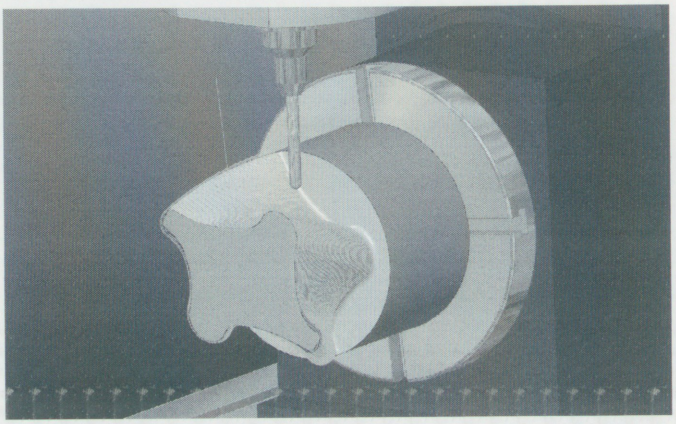
6

CHAPTER

CNC AND CAD MANUFACTURING

INTRODUCTION

CNC (Computer Numerical Control) Machining is a process used in the manufacturing sector that involves the use of computers to control machine tools. Tools that can be controlled in this manner include lathes, mills, routers and grinders. The CNC in CNC Machining stands for Computer Numerical Control. CAD is the use of computer technology for design and design documentation. CAD/CAM applications are used to both design a product and program manufacturing processes, specifically, CNC machining. Computer-aided manufacturing (CAM) is the use of software to control machine tools and related ones in the manufacturing of work pieces. CAM is used in many schools alongside Computer-Aided Design (CAD) to create objects. CAD (computer-aided design) software is used by architects, engineers, drafters, artists, and others to create precision drawings or technical illustrations. CAD software can be used to create two-dimensional (2-D) drawings or three-dimensional (3-D) models. CNC-computer numeric control, used for guiding the tool as required by use of programming, it can be used in turning, milling, laser cutting, etc.



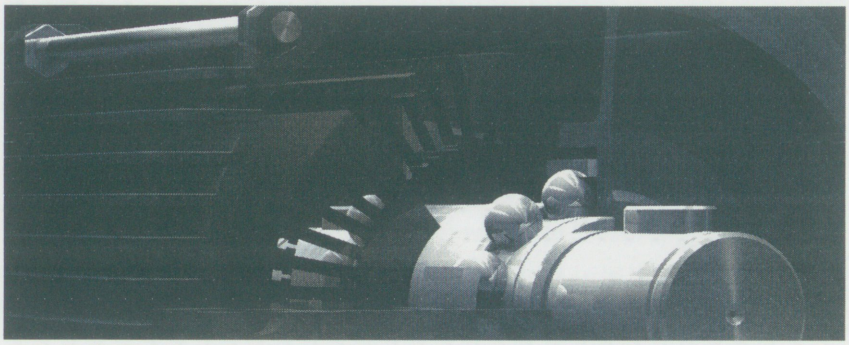
6.1 CONCEPT OF CNC

What is CNC? CNC is a Computer Numerical Control. CNC is the automation of machine tools that are operated by precisely programmed commands encoded and played by a computer as opposed to controlled manually via hand wheels or levers. In modern CNC systems, end-to-end component design is highly automated using **Computer-Aided Design (CAD)** and Computer-Aided Manufacturing (CAM) programs. The series of steps needed to produce any part is highly automated and produces a part that closely matches the original CAD design.

CAD (computer-aided design) software is used by architects, engineers, drafters, artists, and others to create precision drawings or technical illustrations.

In the CNC machines the role of the operators is minimized. The operator has to merely feed the program of instructions in the computer, load the required tools in the machine, and rest of the work is done by the computer automatically. The computer directs the machine tool to perform various machining operations as per the program of instructions fed by the operator.

The CNC technology can be applied to wide variety of operations like drafting, assembly, inspection, sheet metal working, etc. But it is more prominently used for various metal machining processes like turning, drilling, milling, shaping, etc. Due to the CNC, all the machining operations can be performed at the fast rate resulting in bulk manufacturing becoming quite cheaper.



How It Works

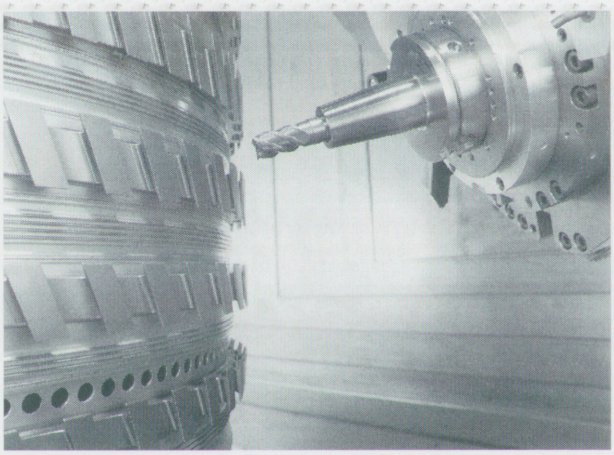
The CNC machine comprises of the computer in which the program is fed for cutting of the metal of the job as per the requirements. All the cutting processes that are to be carried out and all the final dimensions are fed into the computer via the program. The computer thus knows what exactly is to be done and carries out all the cutting processes. CNC machine works like the Robot, which has to be fed with the program and it follows all your instructions.

You don't have to worry about the accuracy of the job; all the CNC machines are designed to meet very close accuracies. In fact, these days for most of the precision jobs CNC machine is compulsory. When your job is finished, you don't even have to remove it, the machine does that for you and it picks up the next job on its own. This way your machine can keep on doing the fabrication works all the 24 hours of the day without the need of much monitoring, of course you will have to feed it with the program initially and supply the required raw material.

Since the earliest days of production manufacturing, ways have been sought to increase dimensional accuracy as well as speed of production. Simply put, numerical control is a method of automatically operating a manufacturing machine based on a code of letter, numbers, and special characters. As they developed, application of digital computers control of manufacturing equipment was realized. Computers were soon used to provide direct control of machine tools. The integrated circuit led to small computers used to control individual machines, and the computer numerical control (CNC) era was born. This Computer Numerical Control era has become so sophisticated it is the preferred method of almost every phase of precision manufacturing, particularly machining. Precision dimensional requirements, mainstay of the machining processes, are ideal candidates for use of computer control systems. Computer numerical control now appears in many other types of manufacturing processes. A distinct advantage of computer control of machine tools is rapid, high-precision positioning of work piece and cutting tools.

Today, manual machine tools have been largely replaced by Computer numerical Control (CNC) machine tools. The machine tool are controlled electronically rather than by hand. CNC machine tools can produce the same

part over and over again with very little variation. Modern CNC machines can position cutting tools and work pieces at traverse feed rates of several hundred inches per minute, to an accuracy of .0001". Once programming is complete and tooling is set up, they can run day or night, week after week, without getting tried, with only routine service and cutting tool maintenance. These are obvious advantage over manual machine tools, which need a great deal of human interaction in order to do anything. Cutting feed rates and spindle speeds may be optimized through program instructions. Modern CNC machine tools have turret or belt tool holders and some can hold more than 150 tools. Tool change take less than 15 seconds.



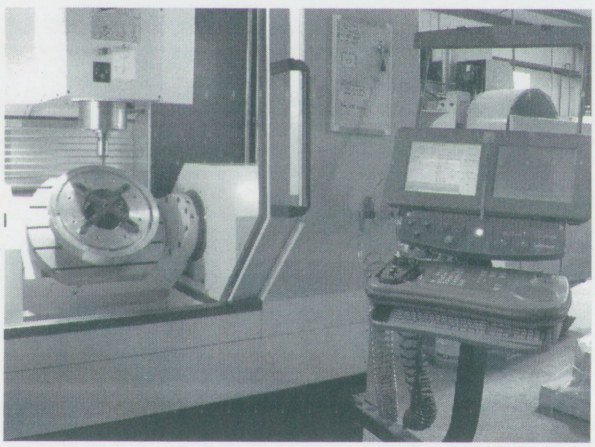
Computer Numerical Control machine are highly productive. They are also expensive to purchase, set up, and maintain. However, the productivity advantage can easily offset this cost if their use is properly managed. A most important advantage of CNC is ability to program the machine to do different jobs. Tool selection and changing under program control is extremely productive, with little time wasted applying a tool to the job.

A program developed to accomplish a given task may be used for a short production run of one, or a few parts. The machine may then be set up for a new job and used for long production runs of hundreds or thousands of production units. It can be interrupted, used for the original job or another new job, and quickly returned to the long production run. This makes the CNC machine tool extremely versatile and productive. Computer-aided design (CAD), has become the preferred method of product design & development. The connection between CAD & CNC was logical. A computer part design can go directly to program used to develop CNC machine control information. A CNC manufacturing machine can then make the part. The computer is extremely useful for assisting the CNC programmer in developing a program to manufacture a specific part. Computer-aided manufacturing, or CAM, systems are now the industry standard for programming. When CAD, CAM & CNC are blended, the greatest capability emerges, producing parts extremely difficult or impossible to make by manual methods.

CNC motion is based on the Cartesian coordinate system. A CNC machine cannot be successfully operated without an understanding of the how coordinate systems are defined in CNC machine and how the systems work together.

To fully understand numerical control programming you must understand axes and coordinates. Think of a part that you would have make. You could describe it to someone else by its geometry. For example, the part you have make is a 5 inch by 8 inch rectangle. All parts can be described in this fashion. Any point on the machined part, such as a pocket to be cut or a hole to be drilled, can be described in term of its position. The system that allows us to do this, called the Cartesian coordinate or **rectangular coordinate system**.

Cartesian coordinate system is a coordinate system that specifies each point uniquely in a plane by a pair of numerical coordinates, which are the signed distances to the point from two fixed perpendicular directed lines, measured in the same unit of length.

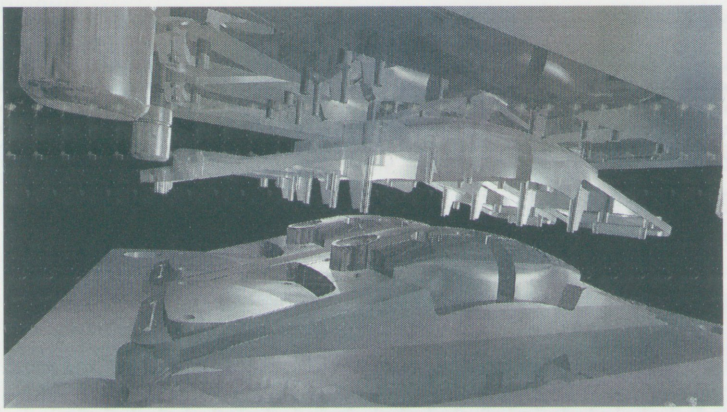


6.2 COMPUTER AIDED MANUFACTURING

In a world full of physical stuff – whether that's products, parts, or places – Computer Aided Manufacturing (CAM) makes it all possible. We're the ones that give the power of flight to airplanes, or the rumble of horsepower to automobiles. When you need something made, not just designed, CAM is your answer. What happens behind the scenes? Keep reading and you'll find out.

Computer Aided Manufacturing (CAM) is the use of software and computer-controlled machinery to automate a manufacturing process.

Computer Aided Manufacturing (CAM) refers to an automation process that accurately converts product design and drawing of an object into a code format, readable by the machine to manufacture the product. The system allows professionals who have completed Computer Aided Design courses to control machinery in a highly automated environment to manufacture various items and pieces. CAM is also used in all computer-aided operations in a manufacturing plant, such as planning, management, transpiration, and storage.



Based on that definition, you need three components for a CAM system to function:

- **Software** that tells a machine how to make a product by generating toolpaths.
- **Machinery** that can turn raw material into a finished product.
- **Post Processing** that converts toolpaths into a language machines can understand.

These three components are glued together with tons of human labor and skill. As an industry we've spent years building and refining the best manufacturing machinery around. Today, there's no design too tough for any capable machinist shop to handle.

6.2.1 History

CAM evolved from the technology utilized in the Computer Numerical Control machines that were used in the early 1950s, which involved the use of coded instructions on a punched paper tape and could control simple manufacturing functions. Computer Aided Manufacturing is a logical extension of that idea, as it allows for a whole set of manufacturing functions to be controlled simultaneously.

The system's primary purpose is to speed up the production process of different components with more precise dimensions and material consistency. In some cases, Computer Aided Manufacturing uses only the required amount of raw material, thus minimizing waste and reducing energy consumption.

Practical Applications

The CAM system controls manufacturing operations performed by robotic welding machines and other industrial tools. A professional with Process Piping Training oversees how the system moves the raw material to different machines after the completion of each step. Finished products are also moved within the system to complete other manufacturing tasks such as synthesizing, quality control, packaging and final checks.

Some of the major applications of the system are woodturning, **metalworking**, glass working, spinning and graphical optimization of the entire manufacturing procedure. Production of surfaces and screw threads, or aspheric optical elements made from glass, crystals, and other metals, can also be done through Computer-Aided Manufacturing. Since CAM can manufacture three-dimensional solids using ornamental lathes with great intricacy and detail, its practical applications are nearly endless.

Metalworking is the process of working with metals to create individual parts, assemblies, or large-scale structures.

The system can construct products like:

- candlestick holders
- table legs
- bowls
- baseball bats
- crankshafts
- camshafts

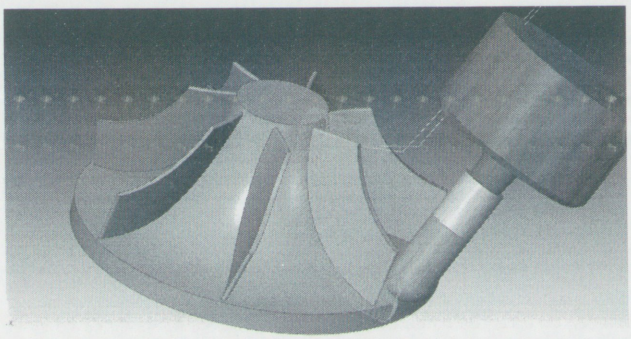
6.2.2 Benefits of CAM

Computer Aided Manufacturing makes it easier for professionals with Engineering Training to measure a plant's output and production as a whole as well as to optimize the assembly process. CAM systems can maximize utilization of a full range of production equipment, such as high speed, 5-axis turning machine, and electrical discharge machines, and can help to implement advanced productivity tools like simulation and optimization to leverage specific professional skills.

In fact, one of the key areas of development is the simulation of performance. Among the most common types of simulation are testing a piece or item for response to stress. In stress tests, model surfaces distort as the part

comes under simulated physical or thermal stress. The ease with which a part's specifications can be changed facilitates the development.

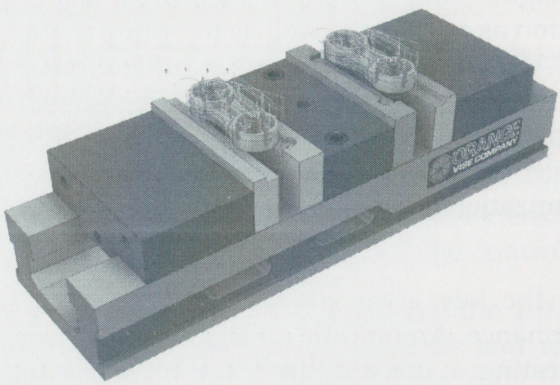
CAM can be applied to the fields of mechanical, electrical, industrial and aerospace engineering. Other applications such as thermodynamics, fluid dynamics, electromagnetism, and kinematics are also compatible with Computer-Aided Manufacturing, leveraging the value of skilled professionals that have received excellent training.



6.2.3 CAD to CAM Process

Without CAM, there is no CAD. CAD focuses on the design of a product or part. How it looks, how it functions. CAM focuses on how to make it. You can design the most elegant part in your CAD tool, but if you can't efficiently make it with a CAM system then you're better off kicking rocks.

The start of every engineering process begins in the world of CAD. Engineers will make either a 2D or 3D drawing, whether that's a crankshaft for an automobile, the inner skeleton of a kitchen faucet, or the hidden electronics in a circuit board. In the world of CAD, any design is called a **model** and contains a set of physical properties that will be used by a CAM system.



When a design is complete in CAD, it can then be loaded into CAM. This is traditionally done by exporting a CAD file and then importing it into CAM software. If you're using a tool like Fusion 360, both CAD and CAM exist in the same world, so there's no import/export required.

Once your CAD model is imported into CAM, the software starts preparing the model for **machining**. Machining is the controlled process of transforming raw material into a defined shape through actions like cutting, drilling, or boring.

CAM software prepares a model for machining by working through several actions, including:

- Checking if the model has any geometry errors that will impact the manufacturing process.
- Creating a **toolpath** for the model, which is a set of coordinates the machine will follow during the machining process.
- Setting any required machine parameters including cutting speed, voltage, cut/pierce height, etc...
- Configuring **nesting** where the CAM system will decide the best orientation for a part to maximize machining efficiency.



Running a Contour toolpath in Fusion 360.

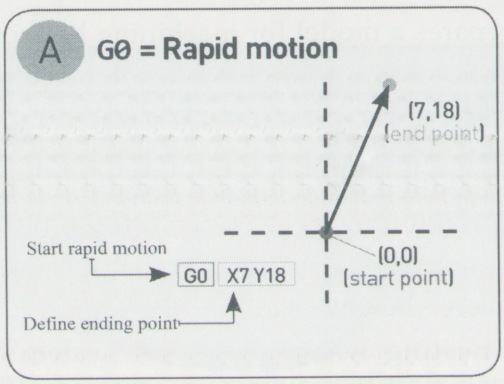
Once the model is prepared for machining, all of that information gets sent to a machine to physically produce the part. However, we can't just give a machine a bunch of instructions in English, we need to speak the machine's language. To do this we convert all of our machining information to a language called **G-code**. This is the set of instructions that controls a machine's actions including speed, feed rate, coolants, etc.

G-code is easy to read once you understand the format. An example looks like this:

G01 X1 Y1 F20 T01 S500

This breaks down from left to right as:

- **G01** indicates a linear move, based on coordinates **X1** and **Y1**.
- **F20** sets a feed rate, which is the distance the machine travels in one spindle revolution.
- **T01** tells the machine to use Tool 1, and **S500** sets the spindle speed.



A more visual way to understand G-code coordinates.

Once the G-code is loaded into the machine and an operator hits start, our job is done. Now it's time to let the machine do the job of executing G-code to transform a raw material block into a finished product.

6.2.4 CNC Machines at a Glance

Up until this point we've talked about the machinery in a CAM system as simply machines, but that really doesn't do them justice. Watching a Haas milling machine slide through a block of metal like it's butter puts a smile on my face every time. Without these machines, my job would be impossible.



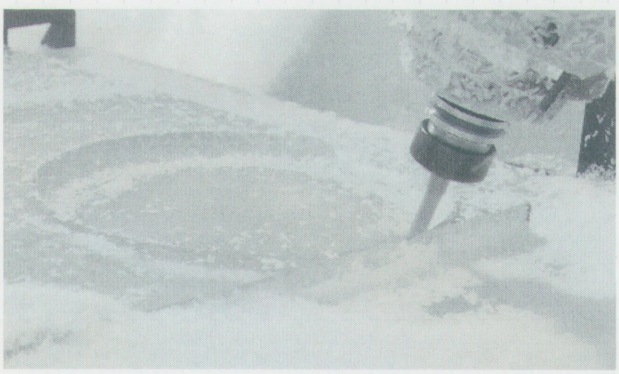
All modern manufacturing centers will be running a variety of Computer Numerical Control (CNC) machines to produce engineered parts. The process of programming a CNC machine to perform specific actions is called CNC machining.

Before CNC machines came to be, manufacturing centers were operated manually by Machinist veterans. Of course, like all things that computers touch, **automation** soon followed. These days the only human intervention required for running a CNC machine is loading a program, inserting raw material, and then unloading a finished product.

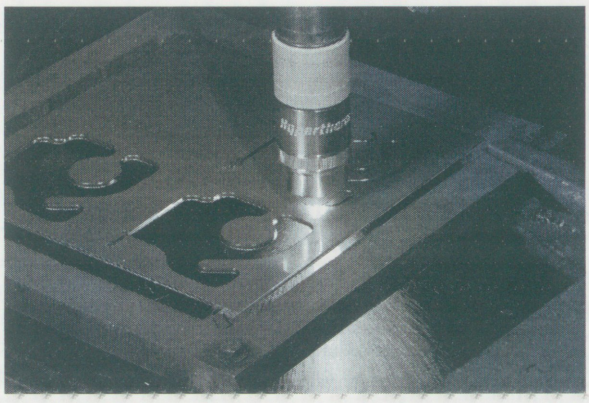
Automation is the creation of technology and its application in order to control and monitor the production and delivery of various goods and services.

Over at the Autodesk Pier 9 workshop we have a decent sample of CNC machines, including:

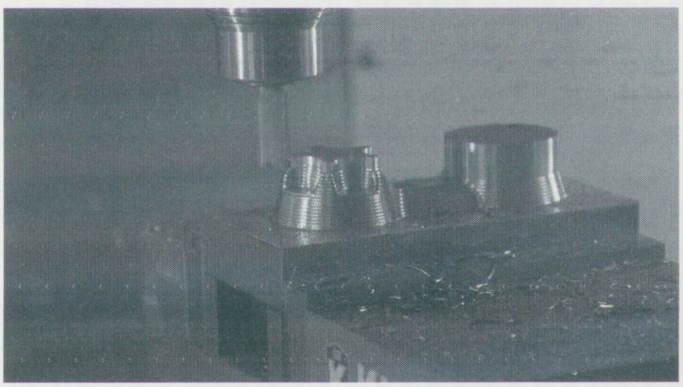
CNC Routers: These machines cut parts and carve out a variety of shapes with high speed spinning components. For example, a CNC router used for woodworking can make easy work of cutting plywood into cabinet parts. It can also easily tackle complex decorative engraving on a door panel. CNC routers have 3-axis cutting capabilities, which allows them to move along the X, Y, and Z axes.



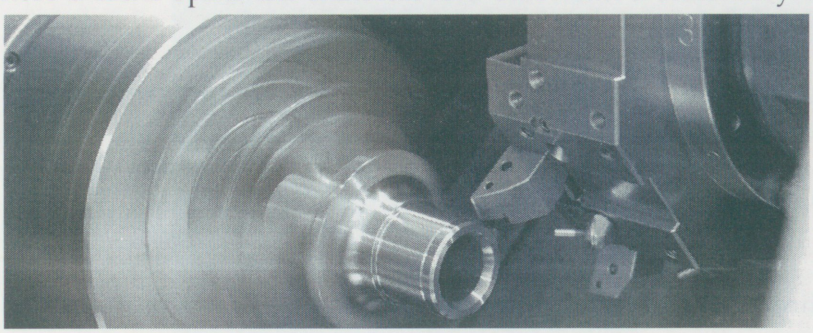
Water, Plasma & Laser Cutters: These machines use precise lasers, high pressure water, or a plasma torch to perform a controlled cut or engraved finished. Manual engraving techniques can take months to complete by hand, but one of these machines can complete the same work in hours or days. Plasma cutters are especially useful for cutting through electrically conductive materials like metals.



Milling Machines: These machines chip away at a variety of materials like metal, wood, composites, etc. Milling machines have enormous versatility with a variety of tools that can accomplish specific material and shape requirements. The overall goal of a milling machine is to remove mass from a raw block of material as efficiently as possible.

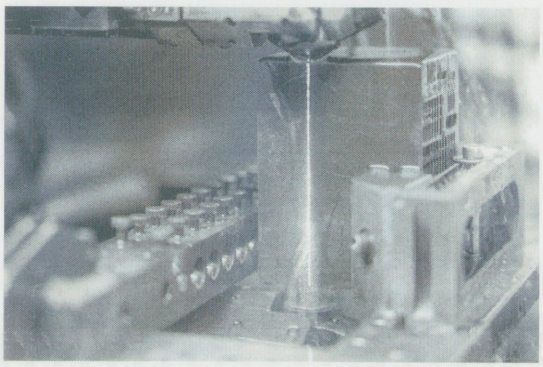


Lathes: These machines also chip away at raw materials like a milling machine, they just do it differently. A milling machine has a spinning tool and stationary material, where a lathe spins the material and cuts with a stationary tool.



Electrical Discharge Machines (EDM): These machines cut a desired shape out of raw material through an electrical discharge. An electrical spark is created between an electrode and raw material, with the spark's temperature reaching

8,000 to 12,000 degrees Celsius. This allows an EDM to melt through nearly anything in a controlled and ultra-precise process.



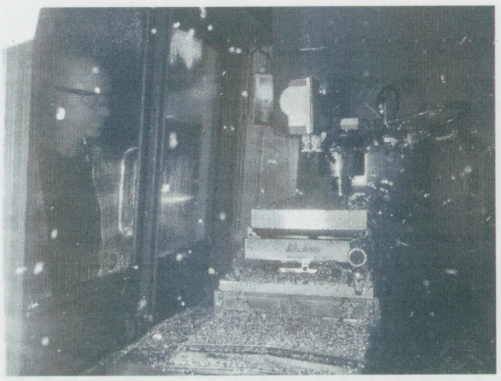
6.2.5 The Human Element of CAM

The human element has always been a touchy subject since CAM arrived on scene in the 1990s. Back in the 1950s when CNC machining was first introduced by John T. Parsons, skillfully operating machines required an enormous amount of training and practice. The video below from NYC CNC shows a great example of how different manual machines are from today's CNC machines:

In the days of manual machining, being a Machinist was a badge of honor that took years of training to perfect. A Machinist had to do it all – read blueprints, know which tools to use, define feeds and speeds for specific materials, and carefully cut a part by hand. It wasn't just about precise manual dexterity. Being a Machinist was, and still is, both an art and a science.



These days, the Modern Machinist is alive and well as man, machine, and software combine to move our industry forward. Skills that used to take 40 years to master can now be conquered in a fraction of the time.

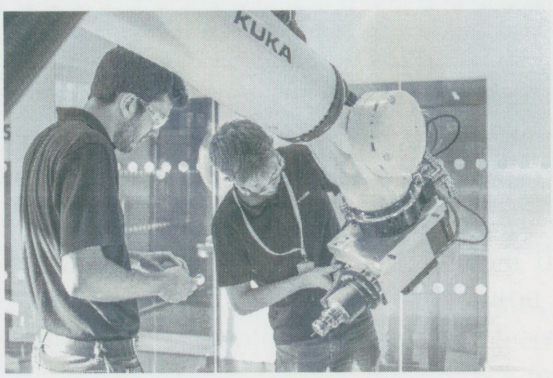


What does all this mean for the human element of manufacturing? The role of a Traditional Machinist is shifting. Today we're seeing an environment of Modern Machinists played out with three typical roles:

- **The Operator**. This individual loads raw materials into a CNC machine and run completed parts through the final packaging process.
- **The Setup Operator**. This individual performs the initial configuration for a CNC machine, which includes loading a G-code program and setting up tools.
- **The Programmer**. This individual takes the drawing for a CAD model and decides how to make it with their available CNC machines. Their job is to define the toolpaths, tools, speeds, and feeds in the G-code to get the job done.

In a typical workflow the Programmer will hand off his program to the Setup Operator, who will then load the G-code into the machine. Once the machine is ready to roll, the Operator will then make the part. In some shops these roles might combine and overlap into the responsibilities of one or two people.

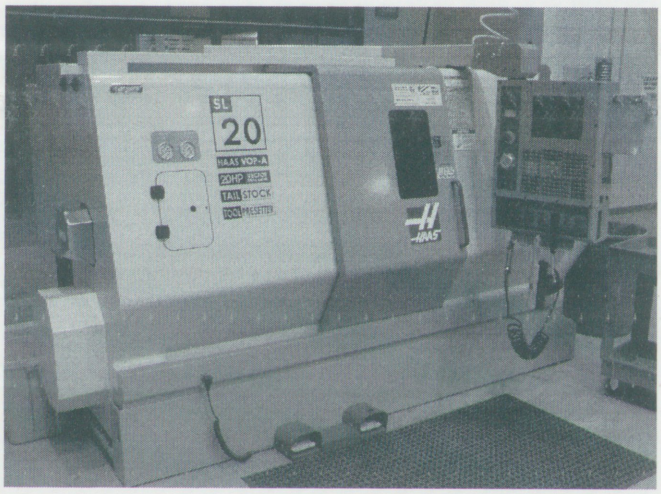
Outside of day-to-day machine operations, there is also the Manufacturing Engineer on staff. In a new shop setup, this individual typically establishes systems and determines an ideal manufacturing process. For existing setups, a Manufacturing Engineer will monitor equipment and product quality while handling other managerial tasks.



6.2.6 The Impact of CAM

We have John T. Parsons to thank for introducing a punch card method to program and automate machinery. In 1949 the United States Air Force funded Parsons to build an automated machine that could outperform manual **NC machines**. With some help from MIT, Parsons was able to develop the first NC prototype.

Numerical control machines is defined as the form of programmable automation, in which the process is controlled by the number, letters, and symbols. In case of the machine tools this programmable automation is used for the operation of the machines.



From there the world of CNC machining started to take off. In the 1950s the United States Army bought NC machine and loaned them out to manufacturers. The idea was to incentive companies to adopt the new technology into their manufacturing process. During this time we also saw MIT develop the first universal programming language for CNC machines: G-code.

Code	Group	Description	Modal	Page
GOO	1	Rapid Move	Y	10
GO1	1	Linear Feed Move	Y	10
G02	1	Clockwise Arc Feed Move	Y	11
G03	1	Counter Clockwise Arc Feed Move	Y	11
G04	0	Dwell	N	14
G09	0	Exact stop	N	14
G10	0	Fixture and Tool Offset Setting	N	15
G12	1	Clockwise Circle	Y	18
G13	1	Counter Clockwise Circle	Y	18
G15	11	Polar Coordinate Cancel	Y	18

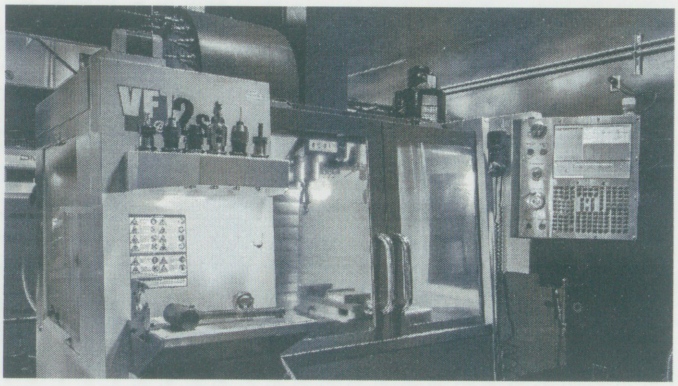
G16	11	Polar Coordinate	Y	18
G17	2	XY Plane Select	Y	20
G18	2	ZX Plane Select	Y	20
G19	2	YZ Plane Select	Y	20
G20	6	Inch	Y	20
G21	6	Millimeter	Y	20
G28	0	Zero Return	N	21
G30	0	2"^{0}, 3rd, eZero Return	N	22
G31	1	Probe function	N	22
G32	1	Threading*	N	23
G40	7	Cutter Compensation Cancel	Y	23
G41	7	Cutter Compensation Left	Y	25
G42	7	Cutter Compensation Right	Y	25
G43	8	Tool Length Offset + Enable	Y	25
G44	8	Tool Length Offset - Enable	Y	25
G49	8	Tool Length Offset Cancel	Y	25
G50	9	Cancel Scaling	Y	25
G51	9	Scale Axes	Y	25
G52	0	Local Coordinate System Shift	Y	26

The 1990s brought the introduction of CAD and CAM on the PC, and has completely revolutionized how we approach manufacturing today. The earliest CAD and CAM jobs were reserved for expensive automotive and aerospace applications, but today software like Fusion 360 is available for manufacturing shops of any shape and size.

Since its inception, CAM has delivered a ton of improvements to the manufacturing process, including:

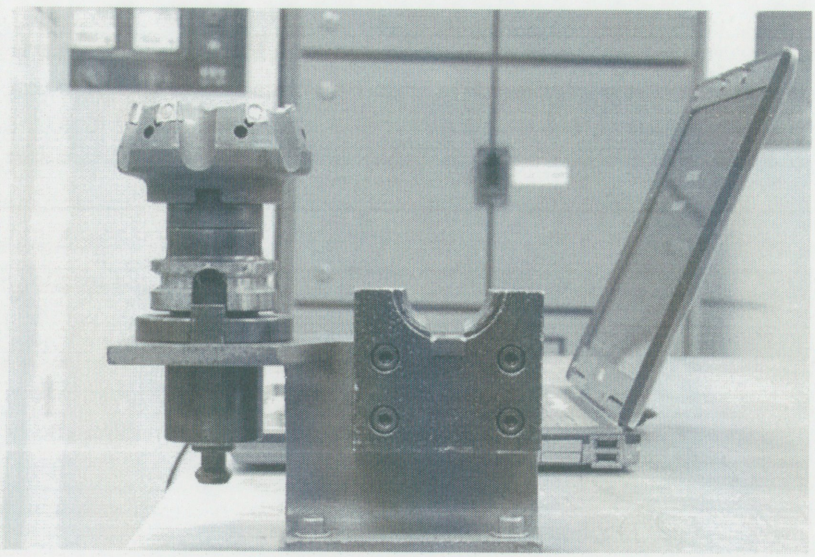
- **Improved machine capabilities**. CAM systems can take advantage of advanced 5-axis machinery to deliver more sophisticated and higher quality parts.
- **Improved machine efficiency**. Today's CAM software provides high-speed machine tool paths that help us manufacture parts faster than ever.
- **Improved material usage**. With additive machinery and CAM systems, we're able to produce complex geometries with minimal waste which means lower costs.

Of course, these benefits have some trade-offs. CAM systems and machinery require a massive upfront cost. For example, a Haas VF-1 costs about $45k out the door; now imagine an entire shop floor of those. There's also the problem of turnover. With machine operation becoming less of a skilled trade, it's incredibly hard to attract and retain good talent.



6.3 APPLICATIONS OF COMPUTER AIDED MANUFACTURING

Computer-aided manufacturing, also known as CAM, uses geometrical design data to control automated machinery. These systems differ from older forms of numerical control, in that geometrical data are encoded mechanically. Using CAM, it's possible to simulate in three dimensions the movement of a part through a production process. This process can simulate feed rates, angles and speeds of machine tools as well as other constraints limiting the operations of a machine. The ability to simulate various manufacturing processes is one of the key selling points of CAM, allowing the system to gain widespread acceptance in the industry. The CAM system also facilitates communication among those involved in the design process, which can be important when one firm contracts another to design or produce a component.



"The CAM system controls manufacturing operations performed by robotic welding machines and other industrial tools. A professional oversees how the system moves the raw material to different machines after the completion of each step. Finished products are also moved within the system to complete other manufacturing tasks such as synthesizing, **quality control**, packaging and final checks. Some of the major applications of the system are woodturning, metalworking, glass working, spinning and graphical optimization of the entire manufacturing procedure. Production of surfaces and screw threads, or aspheric optical elements made from glass, crystals, and other metals, can also be done through Computer-Aided Manufacturing."

Quality control, or QC for short, is a process by which entities review the quality of all factors involved in production. I

6.3.1 The Origins of CAD/CAM

CAD had its origins in three separate sources, which also serve to highlight the basic operations that CAD systems provide. The first source of CAD resulted from attempts to automate the drafting process. These developments were pioneered by the General Motors Research Laboratories in the early 1960s. One of the important time-saving advantages of computer modeling over traditional drafting methods is that the former can be quickly corrected or manipulated by changing a model's parameters. The second source of CAD was in the testing of designs by simulation. The use of computer modeling to test products was pioneered by high-tech industries like aerospace and semiconductors. The third source of CAD development resulted from efforts to facilitate the flow from the design process to the manufacturing process using numerical control (NC) technologies, which enjoyed widespread use in many applications by the mid-1960s. It was this source that resulted in the linkage between CAD and CAM. One of the most important trends in CAD/CAM technologies is the ever-tighter integration between the design and manufacturing stages of CAD/CAM-based production processes.



The development of CAD and CAM and particularly the linkage between the two overcame traditional NC shortcomings in expense, ease of use, and speed by enabling the design and manufacture of a part to be undertaken using the same system of encoding geometrical data. This innovation greatly shortened the period between design and manufacture and greatly expanded the scope of production processes for which automated machinery could be economically used. Just as important, CAD/CAM gave the designer much more direct control over the production process, creating the possibility of completely integrated design and manufacturing processes.

The rapid growth in the use of CAD/CAM technologies after the early 1970s was made possible by the development of mass-produced silicon chips and the microprocessor, resulting in more readily affordable computers. As the price of computers continued to decline and their processing power improved, the use of CAD/CAM broadened from large firms using large-scale mass production techniques to firms of all sizes. The scope of operations to which CAD/CAM was applied broadened as well. In addition to parts-shaping by traditional machine tool processes such as stamping, drilling, milling, and grinding, CAD/CAM has come to be used by firms involved in producing consumer electronics, electronic components, molded plastics, and a host of other products. Computers are also used to control a number of manufacturing processes (such as chemical processing) that are not strictly defined as CAM because the control data are not based on geometrical parameters.

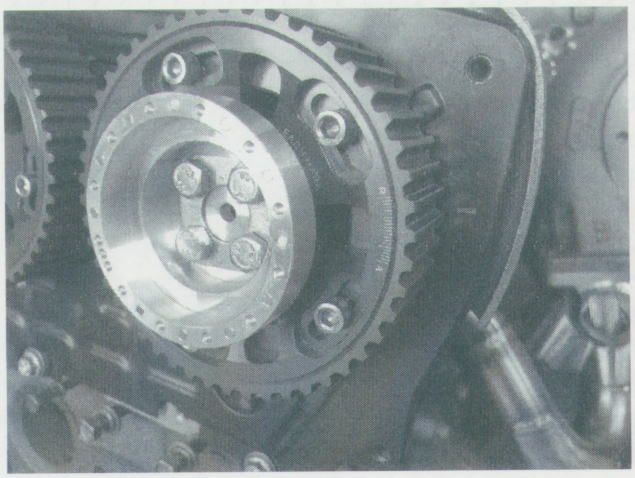
Using CAD, it is possible to simulate in three dimensions the movement of a part through a production process. This process can simulate feed rates, angles and speeds of machine tools, the position of part-holding clamps, as well as range and other constraints limiting the operations of a machine. The continuing development of the simulation of various manufacturing processes is one of the key means by which CAD and CAM systems are becoming increasingly integrated. CAD/CAM systems also facilitate communication among those involved in design, manufacturing, and other processes. This is of particular importance when one firm contracts another to either design or produce a component.

6.3.2 The Case for CAS and CAS/CAM

A conceptually and functionally parallel development to CAD/CAM is CAS or CASE, computer-aided software engineering. As defined by SearchSMB.com in its article on "CASE," "CASE '¦ is the use of a computer-assisted method to organize and control the development of software, especially on large, complex projects involving many software components and people." CASE dates back to the 1970s when computer companies began to apply concepts from the CAD/CAM experience to introduce more discipline into the software development process.

Computer-Aided Selling: The term sales support involves using computer-based tools and methods to optimize sales processes and in doing so increase sales.

Another abbreviation inspired by the ubiquitous presence of CAD/CAM in the manufacturing sector is CAS/CAM. This phrase stands for **Computer-Aided Selling**/Computer-Aided Marketing software. In the case of CASE as well as CAS/CAM, the core of such technologies is integration of work flows and application of proven rules to a repeating process.



Difference between CAD and CAM

CAD (Computer Aided Drawing/Drafting) and CAM (Computer Aided Manufacturing) are computer technologies used for mainly product designing and manufacturing purposes where former is used in designing of the product through some designing software while latter involves software for controlling the machines in the industries such as CNC machines.

CAD and CAM are the steps included in the manufacturing of a product. Let us understand the difference between CAD and CAM through the given comparison chart.

Comparison Chart

BASIS FOR COMPARISON	CAD	CAM
Basic	CAD is the implementation of digital computers in engineering design and production.	CAM is the implementation of computers in transforming engineering designs into end products.
Involved processes	Definition of a geometric model, definition translator, geometric model, interface algorithm, design and analysis algorithms, drafting and detailing, documentation.	Geometric model, process planning, interface algorithm, NC programs, inspection, assembly and packaging.
Requires	Design conceptualization and analysis.	Control and coordination of the necessary physical processes, equipment, materials, and labour.
Softwares	AutoCAD, Autodesk Inventor, CATIA, SolidWorks	Siemens NX, Power MILL, WorkNC, SolidCAM

CAD (Computer Aided Design) system generate accurately, scaled mathematical models based on user input. Individual models are then integrated as components of an assembly to create the final product through which exact fit of the parts can be checked. Fully furnished 3D models of parts and whole assemblies for designs can be build using 3-Dimensional CAD software. Even the created designs can be examined virtually from any angle before manufacturing the product.

Computer + Designing Software = CAD

CAM (Computer Aided Manufacturing) is evolving as a central element in many productions. It includes a broad range of process to be carried out automatically such as cutting, turning, milling, routing, heat cutting, engraving and even printing of solid materials. After designing and analysing a product, it is manufactured where computers are involved in manufacturing like to checking whether the product can be made or made by which process, and how much time it is going take

Manufacturing Tools + Computer = CAM

In simple words computer system used in planning, managing and controlling the operation of manufacturing plant is called CAM. It actually conserves the material to some extent by careful placing of the components.

Key Differences between CAD and CAM

- Computer-aided design (CAD) involves the use of computers for transforming the elementary idea of product into a detailed engineering design. The evolution includes the creation of product's geometric models, which can further be manipulated, analyzed and refined. On the other hand, Computer-aided manufacturing (CAM) involves the use of computers for assisting managers, manufacturing engineers, and production workers by automating production tasks and it also controls machines and systems.
- CAD comprise of processes such as defining the geometric model and translating the definition, interface, design, and analysis algorithm, drafting, detailing and at last documentation. As against, CAM involves processes such as geometric modelling, numerical control programs, interface algorithms, inspection, process planning, assembly and packaging.
- The CAM system requires control and coordination of the physical process, equipment, material, and labour whereas CAD requires product design conceptualization and analysis.
- There is numerous CAD software, for example, AutoCAD, Autodesk Inventor, CATIA etcetera. In contrast, Siemens NX, Power MILL, WorkNC, SolidCAM are some the examples for CAM software.

Advantages of CAD

- Minimizes the requirement for huge numbers of an expensive draftsman in designing of a product.
- It can be used directly in order to generate cutting data for CNC machines.
- Scaling, re-scaling modification in drawings and models is easier and automatic and accurate.
- Storage and retrieval of models is easier.
- Design data can be shared in computerized manufacturing management systems.
- Precise 3D models can be examined before making expensive materials.
- It increases the speed of production and requires less labor.

- Multiple copies can be stored, printed and shared electronically, which eliminates the need for storing large paper drawings.

Advantages of CAM

- Manufacturing requires minimum supervision and can be accomplished during unsocial work hours.
- Manufacture is less labor intensive and saves labor cost.
- Machines are accurate, and manufacturing can be repeated consistently with large batches.
- Error occurrence is negligible, and machines can run continuously.
- Prototype models can be prepared very speedily for elaborated inspection before finalizing designs for manufacture.
- Virtual machining can be used to evaluate machining routines and outcomes on the screen.

Disadvantages of CAD

- Power cuts and viruses can be problematic for the computerized system.
- Industrial versions of the software could be very expensive to buy especially for the startup costs.
- Traditional drafting skills will be lost as they become unnecessary.
- Expensive training would be required to use the software, which can be time-consuming and costly.

Disadvantages of CAM

- It requires high initial investment and start-up cost.
- Machine maintenance is also costly.
- May result in loss of a workforce with high-level manual skill.
- To assure proper tooling and set up procedures it needs highly trained operatives and technicians.

6.4 CAD-CAM IN THE CNC MANUFACTURING PROCESS

Clearwater, FL – CAD-CAM software is used by thousands of CNC Machine shops around the world for its advantages in CNC metalworking. Here are 10 of the top advantages to adding CAD-CAM software to your CNC toolkit.

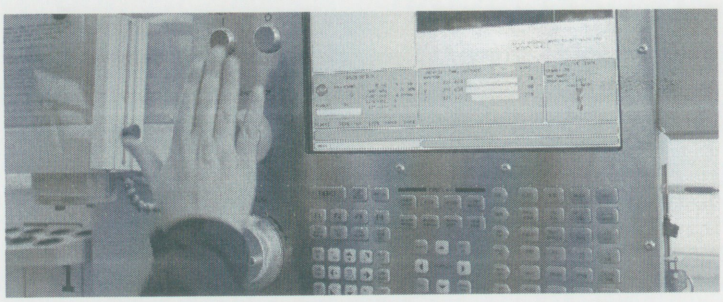
6.4.1 Increase Programming Potential

By adding CAD-CAM software to your CNC toolkit, you can open up possibilities for your business that may not have been there before. An example of this is gaining the ability to take on harder, more complex 3 Axis machining jobs. CAD-CAM can help a shop manage and create tool path and NC programs for complex machining projects such as mold work. These types of jobs are next to impossible to calculate by hand or even through using machine canned cycles. A CAD-CAM system completely automates the process.



6.4.2 Makes You More Accessible by Clients

By having a CAD-CAM software product in your shop, you can receive CAD models from clients faster and easier than ever before. You will be able to open CAD files easily, setup the toolpath for machining and perform simulations that provide valuable information for you in the quoting process such as the calculation of cycle times. Manufacturing can deliver products to market faster and more affordable than ever before. This has a lot to do with technological advancements in CNC machining and in CAD-CAM software. The software allows users to design faster, manage projects, test and simulate as well as machine faster than ever.



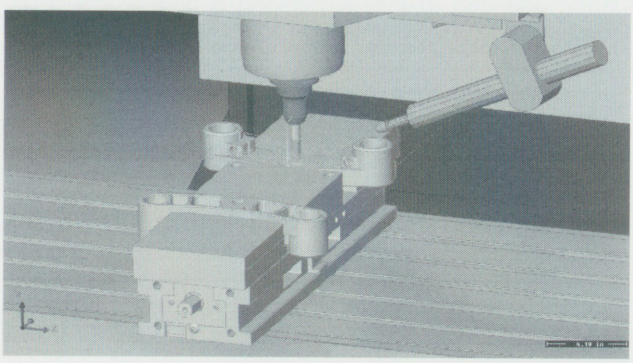
6.4.3 Improved Control over Job Programming

Modern CAD-CAM functionality includes a CAM Tree Manager that allows you to track the job from beginning to end. You have full control over post processing, stock, work coordinates, material and tooling as well as access to machining operations that determine how the part will be machined as well as the output of the NC Program. The CAM Tree has many built-in benefits such as saving and loading machining templates, copying and pasting machining operations, reordering how the job is sequenced, toolpath associativity so that if a CAD edit is made to the part, all of the toolpaths are updated and much more. Higher control capabilities lead to perfectly finished parts being completed faster.



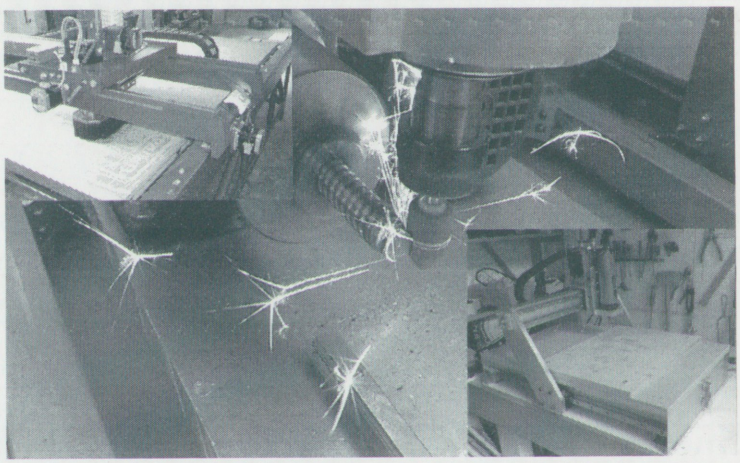
6.4.4 Machining Wizards Remove the Guesswork

CAD-CAM provides the automation required to maximize programming efficiency. Machining wizards remove the guesswork from programming as they step the operator through the process of setting cutting depths, selecting tools, choosing tool path styles, managing cutter lead-ins and lead-outs, choosing compensation settings as well as many other important parameters that have to do with creating machine tool path. Wizards allow new programmers to be successful faster while still providing advanced programmers with the utilities and confidence to program error free parts regardless of their complexity.



6.4.5 Getting the Most Out of Your CNC Machine Tool

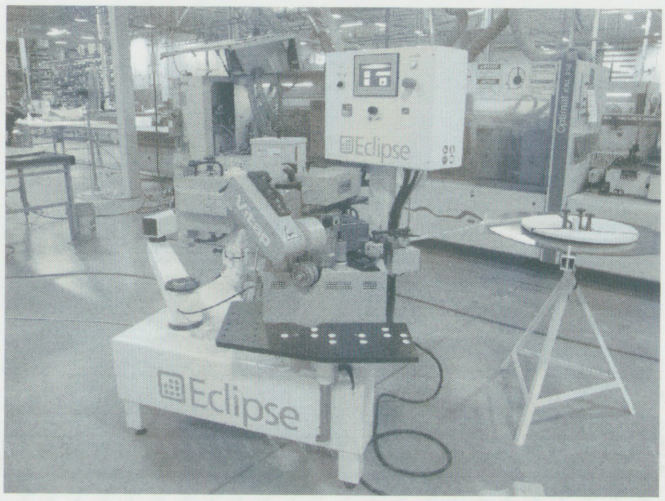
CAD-CAM software provides high-speed machine toolpaths that deliver a host of benefits that all equal up to reduced cycle times, less tool wear and a reduction in machine wear and tear over the long term. High-speed toolpaths allow you to improve the quality of cutting by eliminating the stop and go actions that traditional offset toolpath creates. The rounded more circular cutting motions at higher speeds allow a constant tool engagement with the material, deeper cuts and the ability to use more of the cutting tool itself. High speed machining can improve CNC machine productivity by as much as 50%.



6.4.6 Eliminate Costly Mistakes & Waste

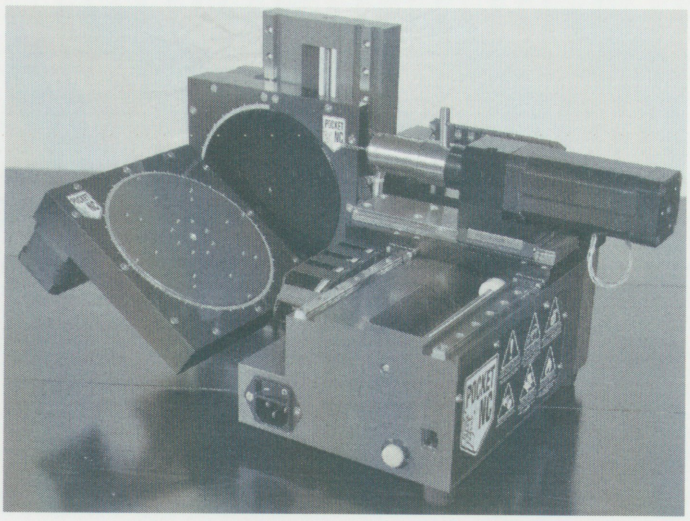
CAD-CAM software provides powerful simulation features. Simulation allows you to visually inspect the machining process, catch costly tool gouges and collisions before they reach the CNC machine. This alone makes adding a CAD-CAM product to the shop a good decision. Simulation also provides detailed information about the toolpath, cycle times, part deviation analysis, the ability to create simulation presentations and much more. Higher levels of simulation will allow you to use your machines kinematics to simulate machining with the actual machine tool visually.

Work holding can also be modeled and added to simulation to complete the visual inspection of the part being machined as well as everything else involved.



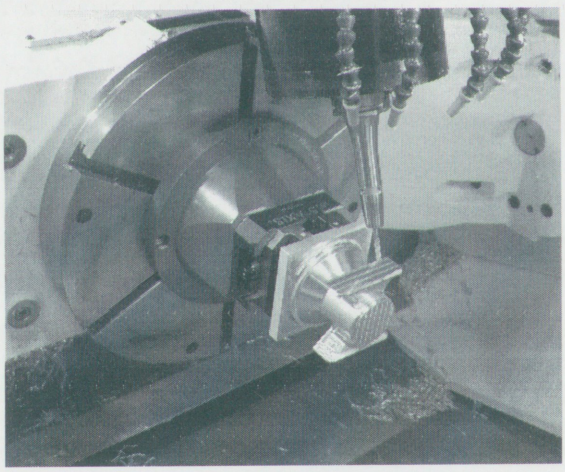
6.4.7 Powerful 3 Axis CNC Programming Operations

CAD-CAM software provides the ability create complex 3 Axis machine toolpath quickly and efficiently. Without CAD-CAM, programming complex parts is practically impossible as often time there are multiple toolpaths required from advanced roughing, semi-finishing and then multiple finishing toolpath strategies. In addition, the latest releases of BobCAD-CAM provide Dynamic Machining Strategies™ allowing the programmer to apply multiple roughing and finishing operations to a single CAD feature.



6.4.8 Multiaxis CAM Technology Makes Complex Machining Simple and Cost Effective

Simultaneous 4 and 5 Axis CNC machining can be the most difficult to create NC programs for. CAD-CAM software provides the solutions to make these types of CNC jobs much easier than ever before. This starts with 4th Axis indexing and rotary machining jobs that require toolpath and special post processing that only a CAM system can offer. Posting can even be customized by the operator with a little training for a wide variety of 4 and 5 Axis machines. Full 5 axis toolpaths include surface-based machining operations that accommodate port milling, SWARF and undercutting type toolpath strategies as well as 3+2 programming. Without a CAD-CAM system this level of CNC programming is nearly impossible. CAM systems can also provide full 4 & 5 Axis simulation, which is critical when programming these types of parts to visually inspect the machining process before an NC program ever reaches the machine.

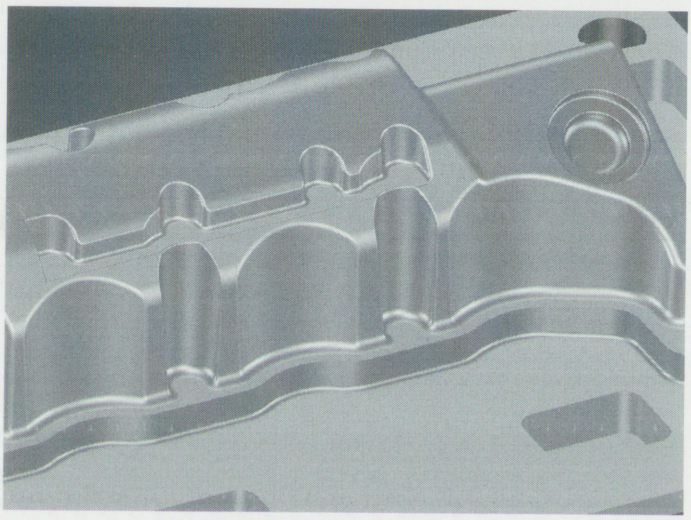


6.4.9 Turn Art into CNC Programs & Finished Parts Easily

Artistic CAD-CAM technology has evolved to support a wide range of custom applications. Two of these specialized industries would be the custom woodworking and jewelry making industry. These types' applications require the ability to turn a picture into a 3D relief model that can be machined in a variety of ways. This also includes the ability to turn a picture into 2D profiles that can

be used for engraving, pocket milling and profile milling. These industries have to then be able to create these programs to me machined on a CNC Mill or Router in 2, 3 and 4 Axis. Some even require 5 Axis CNC programming capabilities.

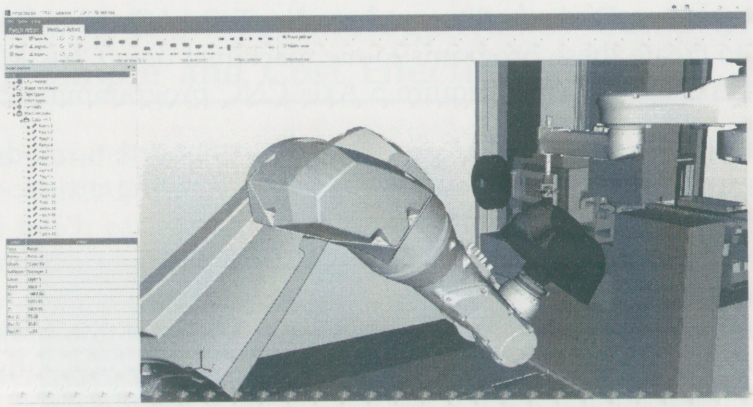
Whatever the case, CAD-CAM providers now offer artistic modules that can be added on to a machining product for creating amazing artistic CNC parts.



6.4.10 Seamless Integration with Popular CAD Design Products

Some CAD-CAM providers have teamed up with highly popular CAD vendors such as SolidWorks® to create powerful CAM machining modules that integrate into the CAD software as a plug-in. This allows existing CAD users to create the necessary machining for the part, simulate everything and create the NC programs for them. This is highly beneficial, as the CAD users do not have to completely re-learn a new CAD-CAM system; they only need to learn the machining side. By going this way, a CAD Designer can acquire more value and seek more clients for being a full service design and programming facility. Typically CAM products that plug-in to CAD systems can be easier to learn and use after some training.

These 10 advantages are key contributors that help determine the success of a CNC machine shop when it comes to using a CAD-CAM system to stay competitive, productive and profitable. While CAM technology continues to advance and become faster, smarter and easier to use, BobCAD-CAM remains a world leader in providing powerful and affordable CAD-CAM products as well as Gold partner CAM add-ons to SolidWorks.



CAD Manufacturing Benefits

CAD Manufacturing Benefits: Computer Aided Manufacturing (CAM)

- 3D CAD files can quickly be imported to drive Computer Aided Manufacturing (CAM) production software. In turn, CAM drives machine tools and other capital equipment through computer-numerical-control (CNC). CNC manufacturing processes included multi-axis milling, turning, sheet metal work (such as brake presses and punches) and high speed machining.
- **CAD/CAM software enables you to check tool paths before any material is cut**. The ability to run a simulation and so verify the complete machining process in a virtual environment is critical for keeping waste and scrap to a minimum. This may be crucial on some jobs, such as those using expensive alloys, large material-intensive components, or for those with complex geometry. Other verification advantages that result from less scrap include less energy consumption and reduced tool wear.
- CAD/CAM simulations also enable you to identify how long the production run time will take. Clearly this is useful for scheduling, as well as the planning of throughput, material supply and delivery.
- As the CAD model is the source of the manufacturing data, the design intent is preserved and the **dimensional accuracy** is retained. In contrast, converting data into 2D drawings and then back into machining code, inherently introduces the risk of making mistakes.

CAD Manufacturing Benefits: Tooling

- **Tooling and die suppliers** can accurately and relatively quickly prepare with CAD data for moulded, casted or pressed parts.
- Tooling, die, mould and component suppliers can be simultaneously sent CAD data from anywhere in the world, both for quotes and for the production of parts.

- 3D CAD equips the manufacturing engineer with the means to relatively quickly design **tooling, jigs, fixtures, custom gauges** and components for work holding.

CAD Manufacturing Benefits: Outsourcing

- For some often lucrative contracts, the ability to handle 3D CAD data is a prerequisite. Prime manufacturers and their tier 1 suppliers sometimes mandate this for smaller manufacturers further down the supply chain.
- 3D CAD enables the **automatic generation of bills of materials**, giving the option of quotations for outsourcing.
- If you are that way inclined, production can be outsourced to lower cost parts of the world, with the potential to overcome language barriers, as the data is digital.
- 3D CAD software interfaces with prototyping and manufacturing processes by exporting data files in standard formats. These include STL, IGES and STEP.
- Others in the **supply chain** (or indeed other development process stakeholders) can view, manipulate and add notes to 3D CAD models without having to purchase the software. Instead low cost or free CAD viewers make it possible to communicate and offer feedback on CAD models.

CAD Manufacturing Benefits: Inspection and Additive Manufacture

- **Inspection** can be enhanced by checking physical parts against CAD models.
- **Coordinate Measuring Machines (CMM)** can check accuracy, based on the CAD data generated at the design development stage.
- 3D printing (additive manufacturing) can be produced directly from CAD data. Different 3D printing technologies can be used to produce final production parts in a wide variety of materials (polymers, metals and even ceramics), depending on your requirements.

SUMMARY

- CNC (Computer Numerical Control) Machining is a process used in the manufacturing sector that involves the use of computers to control machine tools. Tools that can be controlled in this manner include lathes, mills, routers and grinders.
- CNC is the automation of machine tools that are operated by precisely programmed commands encoded and played by a computer as opposed to controlled manually via hand wheels or levers.
- The CNC technology can be applied to wide variety of operations like drafting, assembly, inspection, sheet metal working, etc. But it is more prominently used for various metal machining processes like turning, drilling, milling, shaping, etc.
- Computer Numerical Control machine are highly productive. They are also expensive to purchase, set up, and maintain. However, the productivity advantage can easily offset this cost if their use is properly managed.
- CNC motion is based on the Cartesian coordinate system. A CNC machine cannot be successfully operated without an understanding of the how coordinate systems are defined in CNC machine and how the systems work together.
- Computer Aided Manufacturing (CAM) is the use of software and computer-controlled machinery to automate a manufacturing process.
- The CAM system controls manufacturing operations performed by robotic welding machines and other industrial tools. A professional with Process Piping Training oversees how the system moves the raw material to different machines after the completion of each step.
- Computer Aided Manufacturing makes it easier for professionals with Engineering Training to measure a plant's output and production as a whole as well as to optimize the assembly process.
- Computer-aided manufacturing, also known as CAM, uses geometrical design data to control automated machinery.
- Production of surfaces and screw threads, or aspheric optical elements made from glass, crystals, and other metals, can also be done through Computer-Aided Manufacturing."
- The continuing development of the simulation of various manufacturing processes is one of the key means by which CAD and CAM systems are becoming increasingly integrated.
- CAD (Computer Aided Drawing/Drafting) and CAM (Computer Aided Manufacturing) are computer technologies used for mainly product designing and manufacturing purposes where former is used in designing of the product through some designing software while latter involves

software for controlling the machines in the industries such as CNC machines.

- CAD-CAM software provides high-speed machine toolpaths that deliver a host of benefits that all equal up to reduced cycle times, less tool wear and a reduction in machine wear and tear over the long term.
- CAD-CAM software provides powerful simulation features. Simulation allows you to visually inspect the machining process, catch costly tool gouges and collisions before they reach the CNC machine. This alone makes adding a CAD-CAM product to the shop a good decision
- Artistic CAD-CAM technology has evolved to support a wide range of custom applications. Two of these specialized industries would be the custom woodworking and jewelry making industry.

REFERENCES

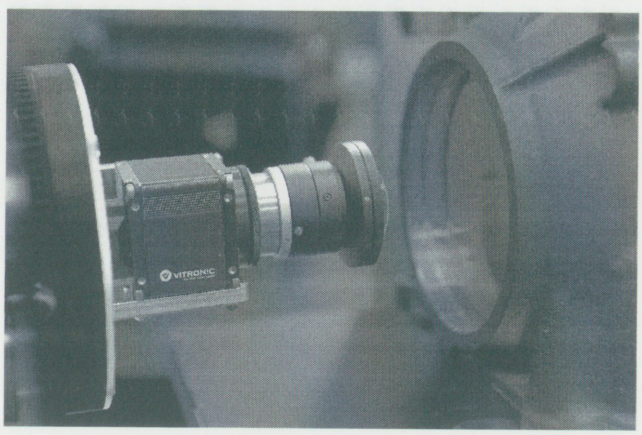
1. http://schools-training.com/articles/applications-computer-aided-manufacturing.html
2. http://www.alliedacademies.org/articles/application-of-computer-aided-design-and-fused-deposition-modeling-technology-in-the-digital-manufacture-of-orthodontic-study-mode.html
3. http://www.industrial-electronics.com/engineering-industrial/1_Applications_Computer_Aided_Manufacturing.html
4. https://bobcad.com/10-top-advantages-to-using-cad-cam-in-the-cnc-manufacturing-process/
5. https://openoregon.pressbooks.pub/manufacturingprocesses45/chapter/chapter-8-cnc/
6. https://techdifferences.com/difference-between-cad-and-cam.html
7. https://www.autodesk.com/products/fusion-360/blog/computer-aided-manufacturing-beginners/
8. https://www.inc.com/encyclopedia/computer-aided-design-cad-and-computer-aided-cam.html
9. https://www.techopedia.com/definition/4698/computer-aided-manufacturing-cam
10. https://www.techopedia.com/definition/6305/computer-aided-designcomputer-aided-manufacturing-cadcam

CHAPTER 7

MEASUREMENT, INSPECTION AND QUALITY CONTROL

INTRODUCTION

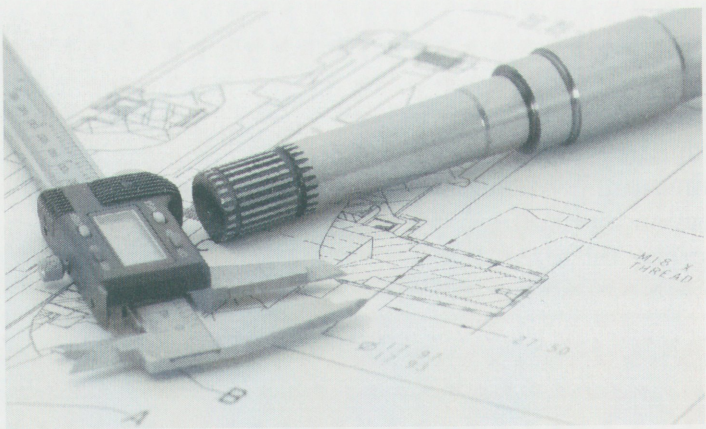
The inspection and measurement of things is indispensable to manufacturing activities in order to guarantee that products are manufactured as designed. An inspection and measurement technology platform consists of four core technologies: (1) visual inspection and metrology, (2) nondestructive inspection, (3) chemical measurement and probe imaging, and (4) optical 3D shape measurement.



The integration of quality into management of advanced manufacturing systems has not typically included automated approaches. With the advent of automated inspection and quality tools such as coordinate measuring machines and other dimensional measuring equipment, the linkage with integrated manufacturing systems seems natural.

7.1 BASICS OF METROLOGY AND QUALITY IN MANUFACTURING

Inspection and measurement have undergone much change. Now they are handled in the manufacturing area instead of the quality department in many companies. No longer "standalone" in nature, inspection and measurement are being addressed and planned up-front by product development teams. They are also now orchestrated and widely integrated into production processes, enhancing process control efforts. Results so far have been impressive, with many gains made. The future looks even more promising with manufacturing professionals directly involved.

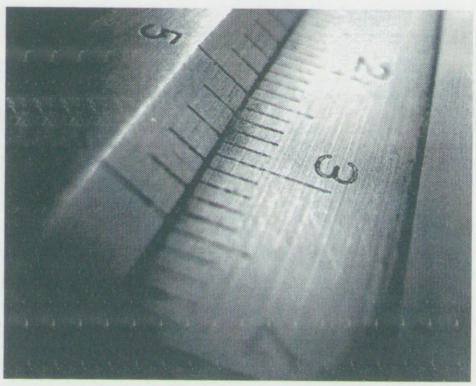


Quality assurance (QA) is a way of preventing mistakes and defects in manufactured products and avoiding problems when delivering solutions or services to customers

This involves **quality assurance**, quality control and metrology. We use quality assurance to gain confidence that quality requirements will be fulfilled. Quality control is used to check that requirements have been fulfilled. This is a subtle difference and in practice the terms are sometimes used interchangeably. Metrology is the science of measurement. It is how we ensure that we can confidently compare the results of measurements made all over the world.

7.1.1 Origins of Measurement

The Egyptians used standards of measurement, with regular calibrations, to ensure stones would fit together in their great construction projects. But modern quality systems really began during the industrial revolution. Before then, mechanical goods were built by craftsmen who would fettle each part individually to fit into an assembly. This meant each machine, and every part in it, was unique. If a part needed to be replaced then a craftsman would need to fit a new part.



In the late 18th Century, French arms manufacturers started to make muskets with standard parts. This meant the army could carry spare parts and quickly exchange them for broken ones. These *interchangeable parts* were still fettled to fit into the assembly but instead of fitting each part to the individual gun it was fit to a *master part*.

A few years later, American gun makers started using this method but adapted it to suit their untrained workers. They filed gauges to fit to the master part, workers would set jigs and production machines using the gauges, and also use the gauges to check the parts. This enabled a row of machines, each carrying out a single operation with an unskilled operator, to produce accurate parts. The parts could then be quickly assembled into complex machines.

The foundation for modern manufacturing had thus been laid, over 100 years before Ford would apply these ideas to a moving production line.

7.1.2 Calibration, True Value and Measurement Error

A system of master parts, gauges and single-use machines worked when an entire product was produced in a single factory. Modern global supply chains need a different system.

Instead of having a physical master part, we have a drawing or a digital CAD model. Specified tolerances ensure the parts will fit together and perform as intended. Rather than every manufacturer coming to a single master part to

set their gauges, they have their measurement instruments calibrated. The instruments are then used to set the production machines and to check the parts produced.



All quality depends on this calibration process.

The most important concept to understand is that all measurements have uncertainty. If it is asked to estimate the height of this text you might say, *'it's about 4 mm'*. Using the word 'about' implies that there is some uncertainty in your estimate.

Uncertainty is a situation which involves imperfect or unknown information. It applies to predictions of future events, to physical measurements that are already made, or to the unknown.

In fact, we can never know the exact *true value* of anything, all measurements are actually estimates, and have some uncertainty. The difference between a measurement result and the true value is the *measurement error*. Since we can't know the true value, we also can't know the error: these are unknowable quantities.

All we can quantify about the world around us is the results of measurements and these always have some uncertainty, even if this **uncertainty** is very small.

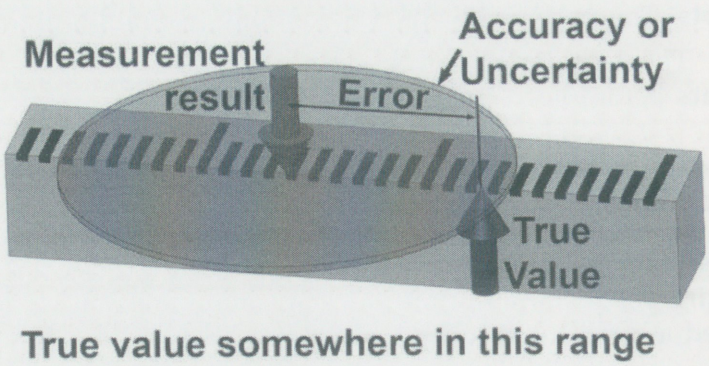


Figure 1: Accuracy and Uncertainty.

If you were to estimate the height of this text as *'about 4 mm, give or take 1 mm'* then you have now assigned some limits to your uncertainty. But you still can't be 100 percent sure that it's true.

You might have some level of confidence, say 95 percent, that it is true. If you were to increase the limits, to say *give or take 2 mm*, then your confidence would increase, perhaps to 99 percent. So the uncertainty gives some bounds within which we have a level of confidence that the true value lies.

7.1.3 Uncertainty and Quality

Once we have determined the uncertainty (or 'accuracy') of a measurement we can then apply this to decide whether a part conforms to a specified tolerance. For example, let's say that a part is specified to be 100 mm +/- 1 mm. We measure it and get a result of 100.87 mm.

Is the part in specification?

The simple answer is: "We don't know, maybe it is, but maybe there was an error in our measurement and actually the part is more than 101 mm. Maybe there was an even bigger error and the parts is actually less than 99 mm!"



Unless we know what the uncertainty of the measurement is, we have no idea how confident we can be that the part is within specification. Let's suppose that the uncertainty of the measurement was given so that the measurement result is 100.87 mm +/- 0.1 mm at 95 percent confidence. Now we can say with better than 95 percent confidence that the part is within specification.

So understanding and quantifying the uncertainty of measurements is critical to maintaining quality.

Now, let's consider calibration and the associated concept of traceability. This is a fundamental aspect of uncertainty. A calibration is a comparison with a reference, and the uncertainty of this comparison must always be included, for reasons explained below.

A traceable measurement is one which has an unbroken chain of calibrations going all the way back to the primary standard. In the case of length measurements, the primary standard is the definition of the meter; the distance travelled by light in a vacuum in 1/299,792,458 seconds, as realized by the International Bureau of Weights and Measures (BIPM) in Paris.

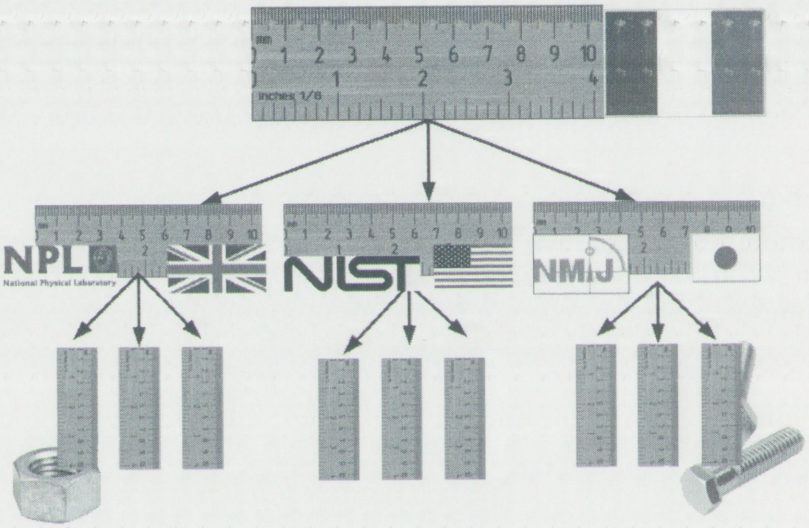


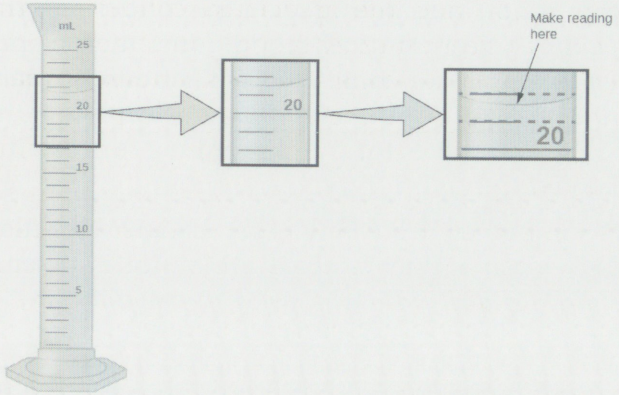
Figure 2: A measurement is traceable if there is an unbroken chain of calibrations back to the primary standard.

Since the 1930s, the inch has been defined as 25.4 mm and is therefore also traceable to the same meter standard. All measurements must be traceable back to the same standard to ensure that parts manufactured in different countries will fit together.

7.1.4 Uncertainty and Error

The uncertainty of measurements arises from different sources. Some of these will lead to a consistent error, or bias, in the result.

For example, the unknown error present when an instrument was calibrated will lead to a consistent error whenever it is used. This type of effect is known as a *systematic uncertainty* leading to a *systematic error*. Other sources will lead to errors which change randomly each time a measurement is made.



Perturbation is a small change in the movement, quality, or behavior of something, especially an unusual change.

For example, turbulence in the air may cause small, randomly changing **perturbations** of laser measurements, mechanical play and alignment may cause randomly changing error in mechanical measurements. This type of effect is known as a *random uncertainty* leading to a *random error*.

It is conventional to divide random uncertainty into *repeatability*, the random uncertainty of results under the same conditions, and *reproducibility*, the random uncertainty under changed conditions.

Of course, the conditions can never be exactly the same or completely different so the distinction is somewhat vague. The types of conditions which might be changed are making the measurement at a different time, with a different operator, a different instrument, using a different calibration and in a different environment.

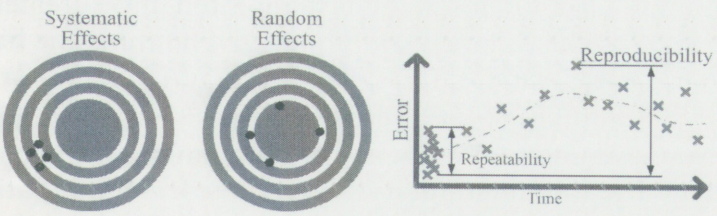


Figure 3: Systematic vs Random Effects.

There are two widely used methods to quantify the uncertainty of a measurement. Calibration laboratories and scientific institutions normally carry out *Uncertainty Evaluation* according to the *Guide to the Expression of Uncertainty in Measurement (GUM)*.

The GUM method involves first considering all of the influences which might affect the measurement result. A mathematical model must then be determined giving the measurement result as a function of these influence quantities. By considering the uncertainty in each input quantity and applying the *'Law of Propagation of Uncertainty'* an estimate for the combined uncertainty of the measurement can be calculated.

The GUM approach is sometimes described as *bottom-up*, since it starts with a consideration of each individual influence. Each influence is normally listed in a table called an *uncertainty budget* which is used to calculate the combined uncertainty.

Source of Uncertainty	Value a_i	Units	Probability Distribution	Divisor	Sensitivity Coefficient c_i	Standard Uncertainty $U_i(y)$ (mm)
Calibration Uncertainty	0.01	mm	Normal (k=2)	2	1	0.005
Resolution	0.005	mm	Rectangular	√3	1	0.003
Cosine error	3	deg	Rectangular	√3	0.046 mm/deg	0.080
Temperature	2	C	Rectangular	√3	0.0023 mm/c	0.003
Repeatability	0.02	mm	Normal (k=1)	1	1	0.020
					Combined Standard Uncertainty $u_c(y)$	**0.082**
					Expanded Uncertainty (k=2, 95% confidence) U	**0.165**

Figure 4: Example uncertainty budget.

Industrial measurement processes are typically evaluated using a *Measurement Systems Analysis (MSA)* approach, as recommended within the *Six-Sigma* methodology, and usually following the guidelines of the *Automotive Industry Action Group (AIAG) MSA Reference Manual.*

MSA involves performing *Gage Studies* in which repeated measurements are compared with a reference under different conditions to determine the bias, repeatability and sometimes reproducibility.

A *Type-1 Gage Study* is the quick check normally carried out to initially understand the variation in a gage. It involves a single operator measuring a single calibrated reference part 25 or more times and then considers the variation and bias in the results. This type of test is often called a repeatability study outside of MSA.

A *Gage Repeatability and Reproducibility (Gage R&R)* study is used to get a more detailed understanding of a measurement process. Typically 10 parts are each measured twice by at least three different operators. A statistical technique called ANOVA is then used to determine how much variation is caused by the instrument ('gage') and how much is caused by the operator. This considers the change of operator and subsequent changes in time and environment to be a full representation of reproducibility conditions.

MSA is sometimes referred to as *top-down* since it largely treats the measurement process as a black-box and experimentally determines systematic and random uncertainties. Two important concepts in MSA are *accuracy*, used as the equivalent of uncertainty; and *precision*, used as the equivalent of random uncertainty.

The advantage of uncertainty evaluation is that it is capable of considering all sources of uncertainty and, if done properly, gives the most accurate estimate of uncertainty. Problems with this approach include the fact that it requires a metrologist capable of producing the mathematical model and the risk of human error leading to significant influences being omitted or incorrectly estimated.

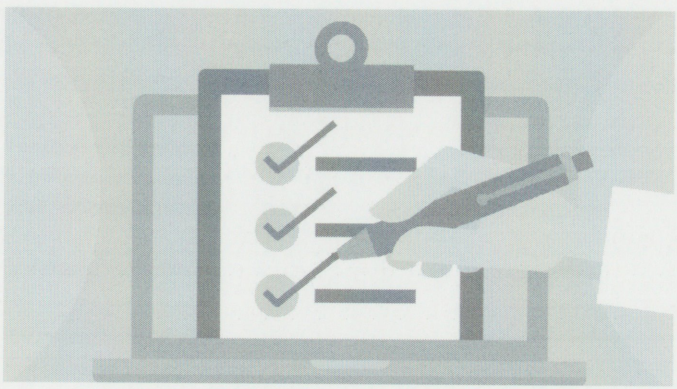
The GUM method is also only valid for an individual measurement which has been carried out with values known for any corrections applied. It is therefore difficult to correctly apply uncertainty evaluation to predict the uncertainty of an industrial measurement process.

MSA can be much more easily applied and is intended to provide a prediction for the accuracy of an industrial measurement process. The problem with this approach is that certain systematic effects are ignored and reproducibility conditions may not be fully represented, leading to an underestimate of uncertainty.

An example of the omission of systematic effects is that when determining the bias, a comparison is made with a reference which is treated as the true value—in reality the reference also has uncertainty, which should be included. This method relies on all reproducibility conditions being varied so that their effects can be seen in the variation of results when making repeated measurements. It is likely that the way in which these conditions are varied will not fully reflect the variation seen during the life of the actual measurement process.

7.1.5 Measurement and Quality Assurance

So far, we have focused on quality control, i.e. how measurements can prove that parts are conforming to specifications after they have been produced. Now, let's briefly consider quality assurance, the way we ensure that the process produces good parts in the first place.



This aspect of quality is largely addressed by *Statistical Process Control (SPC)*. A process may be evaluated by making several parts and measuring them to determine the variation and bias in the manufacturing process. Rather than giving these results directly, it is normal to divide the part tolerance by the process precision to give the *Machine Tool Capability* (C_P) or by the process accuracy to give the ***Process Capability*** (C_{PK}).

Process capability is the repeatability and consistency of a manufacturing process relative to the customer requirements in terms of specification limits of a product parameter.

SPC is in many ways equivalent to MSA. It takes a top-down approach to understand random and systematic effects. However, instead of evaluating measurements, it is used to evaluate process outputs. It generally has the same advantages and disadvantages as MSA, and a bottom-up uncertainty evaluation approach can be used if these are a concern.

It may initially appear that there are fundamental differences between MSA and SPC due to the very different terminology within SPC. However, *common cause variation* (or *chance cause variation* in older literature) is the equivalent of precision; *short-term variability* is the equivalent of repeatability; *long-term variability* is the equivalent of reproducibility; and *special cause variation* (or *assignable cause variation* in older literature) is the equivalent of bias.

SPC also places a much greater emphasis on ensuring that a process is in '*statistical control*'. In broad terms, this means that effects are random and normally distributed with any significant systematic effects corrected for. This is a strong point of SPC and is sometimes overlooked in both uncertainty evaluation and MSA.

The main tool used in SPC to check for an 'in-control' process is the *control chart*. This gives a simple graphical view of a process where it can be easily spotted when a process is drifting or producing errors which cannot be explained by normal random variations. For example, if several points are all increasing or decreasing then this would indicate the process is drifting.

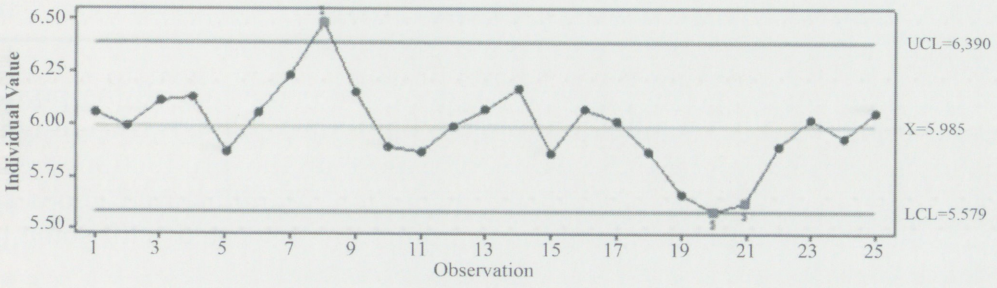
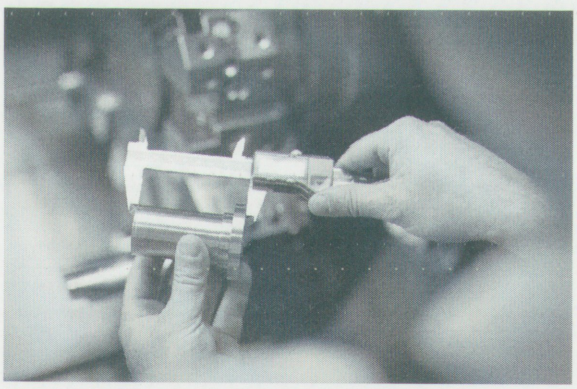


Figure 5: Example control chart.

7.2 QUALITY CONTROL IN MANUFACTURING

In manufacturing, quality control is a process that ensures customers receive products free from defects and meet their needs. When done the wrong way, it can put consumers at risk. For example, the recent defect found in Takata airbags resulted in the biggest automotive recall in history. The recall includes almost 69 million airbag inflators and may cost billions of dollars. The recall will last until the end of 2019 and take until 2020 to resolve.



Major recalls like these can be prevented through effective quality control in manufacturing. Some common tools used to support quality control include:

- Statistical process control (SPC) monitors and controls quality by tracking production metrics. It helps quality managers identify and solve problems before products leave the facility.
- Six Sigma uses five key principles to ensure products meet customers' needs and have zero defects.

When supported by lean tools like Total Productive Maintenance (TPM), 5S, and Kaizen, most if not all defects can be eliminated.

7.2.1 Quality Control Inspection Tools

Quality control inspectors use a variety of tools to ensure that all the products manufactured by the company are within the limits designated by the designers. A quality control inspector checks every aspect of the production process, using a different tool to accomplish the inspection. Manufactured goods such as textiles, clothing, machine parts or electronics are inspected with some type of tool or tools.



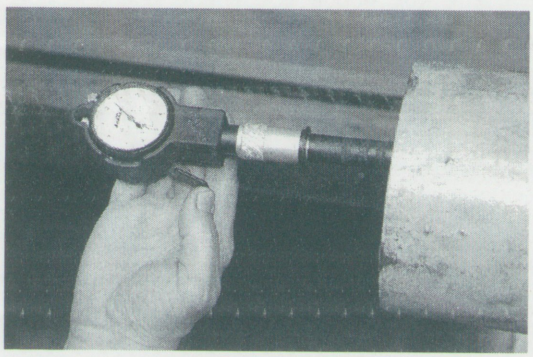
Air Gages

An air gage is a tool used by the quality control inspector to determine several aspects of a part or product. The air gage can determine the inside or outside diameter or dimensions of a part, find any leaks in a product, determine the taper requirements, and even check the depth or thickness of steel. Air gages come in different types such as hand held air gages, assembly line air gages that automatically check the part, bench type air gages in which the inspector places the part into the air gage, and some air gages are automatic but need to have the part placed into it before it checks or inspects the part.



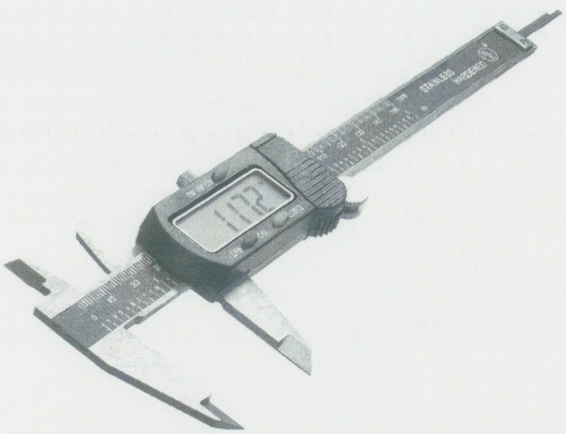
Bore Gages

Quality control inspectors use bore gages to measure the dimensions of a part, any grooves inside the part, degrees of taper or any steps located inside the part. The bore gage comes in many styles and types. Quality inspectors use a mechanical gage that has moving parts to measure the inside of a part. Electronic bore gages use electrical current to test and read the inside dimensions of a component part. Air bore gages are similar to air gages, but only test the inside of a part.



Calipers

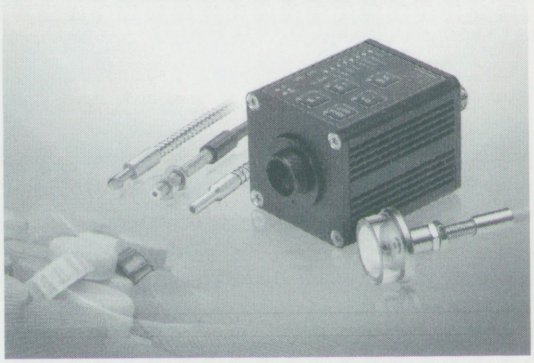
The quality control inspector uses different size calipers to measure every part of the product; it does not matter if the part is square, round, oval or any other shape. The calipers are a slide-measuring device that quality control inspectors read and record the information on an inspection list to ensure the part is within tolerances. Calipers are in the English measurement or in metric depending on the **tolerances** original design.



Color Sensors

Tolerance is a specification for how much variation from ideal measurements you can tolerate for your parts.

Quality inspectors use a color sensor device to determine the proper color mixture of clothing, textile or painted part. The correct color mixture is essential with every color change, and the inspector uses the color sensor to ensure every product piece is the same color. This sensor generally uses only three basic color models: red, blue or green. These three colors can create most colors, and the color sensor checks how much of each color is in the product to ensure a consistent color scheme.



Although dimensional inspection hand tools are frequently a simple and elegant solution, they still must be treated with the same care as a machine that uses more advanced technology. Some devices must be calibrated or regularly cleaned to ensure that they provide consistent, accurate results. It is also important that the operator is appropriately trained to prevent human error.

7.2.2 Types of Quality Control

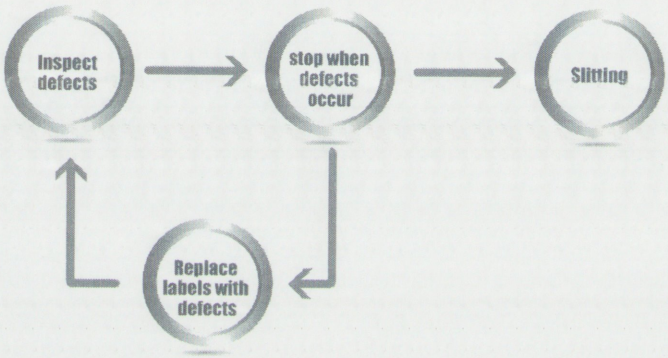
QC is not a function of any single department or a person. It is the primary responsibility of any supervisor to turn out work of acceptable quality. Quality control can be divided into three main sub-areas, those are:

- Off-line quality control,
- Statistical process control and
- Acceptance sampling plans.

Off-line Quality Control

Its procedure deal with measures to select and choose controllable product and process parameters in such a way that the deviation between the product or process output and the standard will be minimized. Much of this task is accomplished through product and process design.

Example: Taguchi method, principles of experimental design etc.



Statistical Process Control

SPC involves comparing the output of a process or a service with a standard and taking remedial actions in case of a discrepancy between the two. It also involves determining whether a process can produce a product that meets desired specification or requirements. On-line SPC means that information is gathered about the product, process, or service while it is functional. The corrective action is taken in that operational phase. This is real-time basis.

Acceptance Sampling Plans

A plan that determines the number of items to sample and the acceptance criteria of the lot, based on meeting certain stipulated conditions (such as the risk of rejecting a good lot or accepting a bad lot) is known as an acceptance sampling plan.

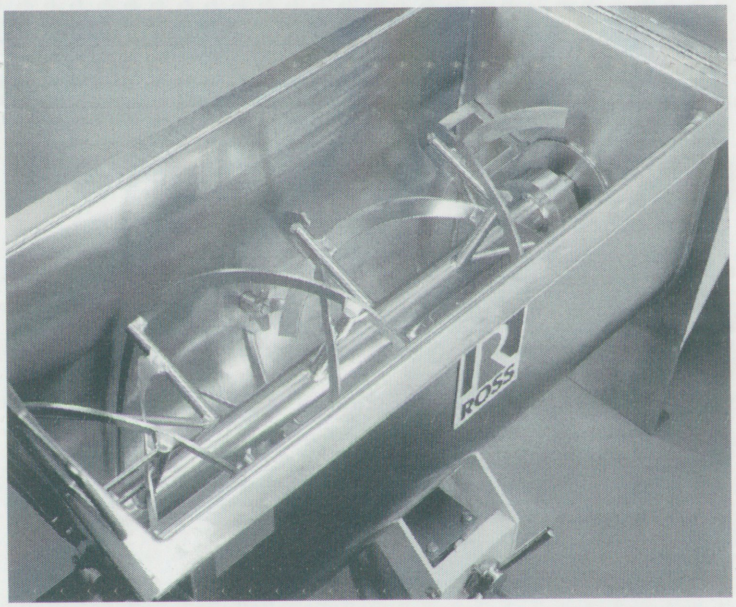
7.2.3 Benefits of Using Quality Control in Manufacturing

Customers expect and demand high-quality products. When customers receive quality products you will:

- Increase customer loyalty
- Gain repeat business

- Gain new customers from referrals
- Maintain or improve your position in the market
- Improve safety
- Reduce liability risks
- Contribute to overall positive branding of your product

Manufacturers with quality control procedures in place are far less likely to face product recalls or place customers at risk from poorly made products.



Manufacturers worldwide stress over the issue of quality control as it pertains to their industry – considering numerous avenues for improving their company's own standards and practices without introducing preposterous price spikes or impossible workflow barriers to their creation processes.

There is no doubt that quality control is of immense importance and contributes directly to a manufacturer's reputation and bottom line. However, micromanaging one's manufacturing process can become tedious work; especially with all other aspects of business management to consider as well.

Software can help and should definitely be utilized in such situations to keep intensive management to a definite minimum, but it helps to know what areas of quality control are important enough to warrant the use of software in the manufacturing industry in the first place. Here, we will discuss the main reasons for quality control to be taken seriously by manufacturers regardless of their specific sectors or end products.

Cost Cuts

Boosting profits can be tricky business when it comes to manufacturing as slight changes in materials used or personnel employed create drastic differences in final products and consumer satisfaction. Thus, making even basic alterations to your company's production process on any level should be avoided whenever possible. However, through the magic of proper quality control costs are often cut by massive amounts every quarter.

Through efficient quality control, costs can be cut transparently. This is due mostly to the fact that multiple stops in the product creation line to assess relative quality and standards help to ward off major errors that would have an item recalled, repaired or rebuilt entirely.

Improved Products

The more intensive and stringent the quality control environment is, the better the end results of the crafted products in question will be. Improving the final product that your business creates tends to come down to effective control throughout the process – ensuring each step is up to the standards you have established.



Strengthened Market Stance

It is no surprise that certain manufacturing brands stand out above the rest – they boast of top tier quality control throughout their production processes and this lands them with final products worthy of acclaim. It is no exaggeration to say that consumers notice and often prefer higher quality products – electing to get them when they can afford the appropriately higher price points. Better products translate to a far more immovable market position.

Effective Compliance

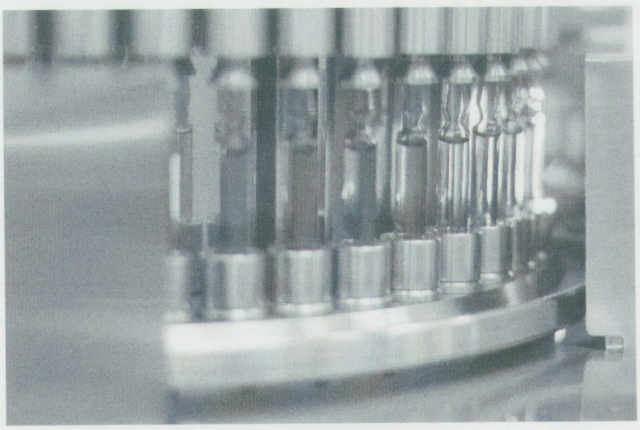
Compliance with regulatory conditions and standards can create unnecessary bottlenecks in production when checked near the end of the assembly line. Effective quality control spreads this load out evenly across the entire process, with multiple checkpoints along the way. This makes for less bottlenecks, less surprises and far less financial losses overall.

Consistency

Consistency with your market offerings ties back into your business's overall reputation. Consistency also allows for more stability in your quarterly pricing as there are far less dynamic fluctuations in productions costs. Naturally, quality control plays a huge part in building consistency throughout the assembly process by eliminating redundant processes and scrapped materials.

Resource Conservation

Conserving resources is important for manufacturers as it makes for less upfront material expenses whilst simultaneously improving the company's reputation with consumers. Less assembly foul-ups means greater throughput and higher gains are a given. Quality control is essential to making this a reality and, therefore, should definitely be taken into account if this is your goal.



Risk Reduction

Minimizing risks goes beyond the proper implementation of safety gear on the factory floor. There are plenty of **financial risks** to consider once your products leave the building. Recalls are costly endeavors and their negative influence on customer and retail perceptions of your company could tarnish your name indefinitely. Obviously, this is a less than favorable occurrence to consider as

it makes for a difficult set of odds to overcome. Quality control helps you to ascertain that all of your products are on the same level when they are finished and can be delivered to retailers/customers without the risk of failure.

Financial risk is the type of specific risk that encompasses the many types of risks related to a company's capital structure, financing and the finance industry.

As can be seen above, quality control is an incredibly important aspect of the manufacturing process – not only ensuring the continued use of your company's products, but also allowing for proper adherence to regulatory standards. Keeping track of the quality control process can be tough, but the right software helps to significantly improve on the process through intuitive optimizations and effective shortcuts. Hopefully, you now have a clearer picture of the areas in which quality control can truly influence your business and you can target these areas as you seek out software for managing such your entire production process more efficiently.

7.2.4 Incorrect Implementation of Quality Control in Manufacturing

Quality control in manufacturing can be a little tricky. Often, it is done at the end of the production process, only catching defects after the fact.

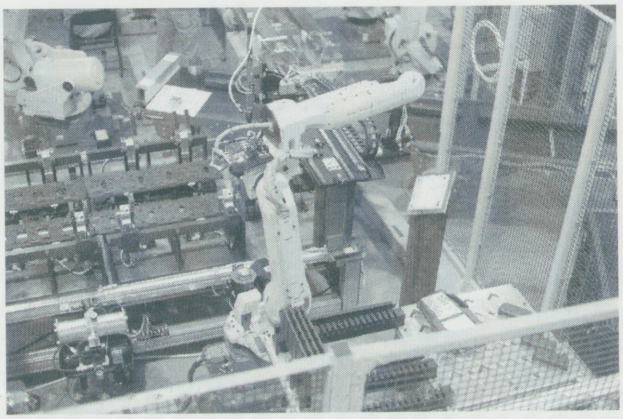
Effective quality control is more involved and should include two levels:

- Operators monitor the manufacturing process and ensure that there is little variation.
- Engineers routinely monitor the product design for issues. When a problem is found, it is immediately fixed.

By monitoring products at the end of production as well as reviewing the products' design, companies can solve problems more efficiently, saving time and money.

7.2.5 Using Quality Assurance with Quality Control in Manufacturing

Quality assurance streamlines production and helps to ensure that the final products meet the company's quality criteria. It ensures that the processes used to design, test, and produce products will be done correctly.



In manufacturing, quality assurance approaches, like ISO 9001, help manage and improve many processes, including:

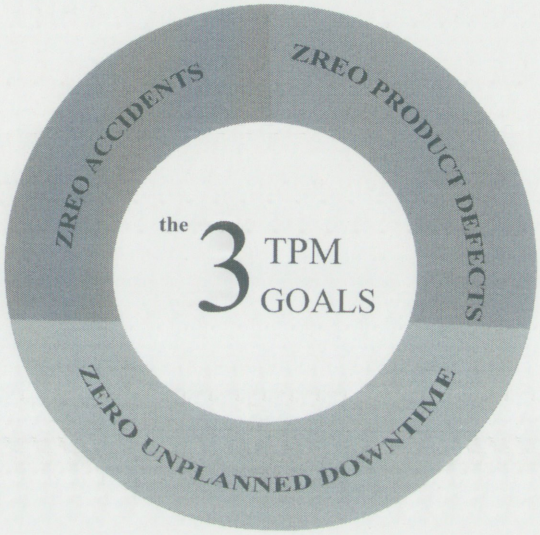
- Acquiring raw materials
- Purchasing third-party components and sub-assemblies
- Designing and using inspection procedures
- Complying with production processes
- Responding to defects

For every business, quality assurance is different. However, ISO 9001 works for businesses both large and small and can be adapted for most any need. It provides the means for creating a lasting quality assurance program, ensuring that everything, from raw materials to inspection procedures are of the highest quality. Issues and defects from poor quality materials or third-party components are all but eliminated.

7.2.6 Quality Control, Quality Assurance and Lean Manufacturing

Lean manufacturing tools can bolster your company's quality program. Lean revolves around improving quality and safety, while increasing efficiency and profits. Some powerful lean manufacturing tools that can bolster your quality system include:

- TPM improves product quality by eliminating downtime, defects, and accidents. TPM accomplishes this through comprehensive maintenance programs and operator training.
- Kaizen helps eliminate problems at their source by empowering workers to find and solve problems on a daily basis.
- 5S helps organize and standardize the workplace. Improve procedures and eliminate errors in your facility.



While every facility has different needs and may require a different lean tool, using lean to support quality control is essential. Procedures will be simplified, and the number of errors will be reduced.

7.2.7 How to Implement Quality Control in Manufacturing

To implement an effective quality control program, first create and document your approach to quality control. This includes:

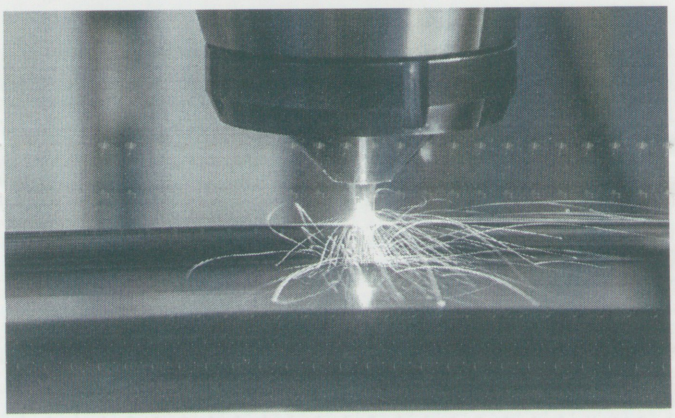
- Defining the quality standards for each product
- Selecting the quality control method
- Defining the number of products/batch that will be tested
- Creating and training employees for quality control
- Creating a communication system for reporting defects or potential issues.

Next, you will need to create procedures for handling defects. Consider the following:

- Will batches be rejected if defected items are found?
- Will there be further testing and potential repair work involved?
- Will production be halted to ensure that there are no more defective products created?
- How will new product versions be handled?

7.3 ADDITIVE MANUFACTURING AND INSPECTION DIFFICULTIES

Traditional nondestructive inspections are performed much the same for additive parts, but there are some new limitations introduced by the AM methods.



Additive manufacturing (AM) is one of the important and most revolutionary processes to come along in many years. The thought of popping a design into a machine and having a functional part come out the other side was science fiction a generation ago. We are nowhere near the Star Trek replicators, but we are closing that gap.

Plastics, infused plastics, ceramics, inks, precious metals, and exotic alloys are manufactured daily across a variety of industries and for a plethora of applications and uses. The range of applications is amazing. Everything from toys to human organs are being printed. Here we will focus on the aviation and power generation side of AM where many are hard at work designing and creating innovative solutions.

In these areas, components being manufactured using AM have become more complex and are being accepted and used in increasingly more critical applications. These applications are just the beginning of where industry wants to go with AM. In the near future, AM powders and alloys will reach new levels of component and design capabilities.

Perhaps though, it is time to take into consideration the actual inspect-ability of the unique and highly optimized shapes that AM is producing. Inspect-ability and metallurgical validation must be an integral part of the AM design and process parameters. There is a real need to discuss the current state of inspection, where it is today, and where it may need to go in the future.

Before focusing on AM inspection, let us first give you a little information on additive manufacturing of metallic complex components.

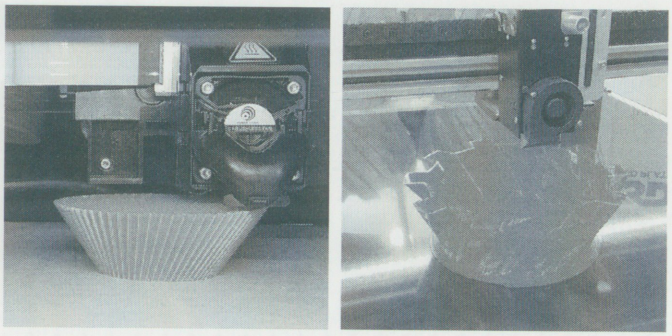


Figure 6: Nonmetallic additive manufacturing images.

First off, AM is not just a single technology, but instead is a group of technologies. AM (commonly known as 3D printing) technologies are broken into two main groups: Powder Bed Fusion (PBF) and Direct Energy Deposition (DED).

Each of the two groups have multiple methods within them.

PBF:

- Direct Metal Laser Sintering (DMLS)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Electron Beam Melting

DED:

- Gas Tungsten Arc (GTA)
- Plasma Arc (PA)
- Gas Metal Arc (GMA)
- Plasma Transferred Arc (PTA)
- Laser Beam (LB)
- Electron Beam Freeform (EBF)

Without getting too deep into any of these methods in particular, let me explain the difference between PBF and DED.

In PBF, a uniform powder layer is fed onto a deposition plane where an electron beam or laser is directed. The energy of the beam or laser melts and fuses at all the designated locations in the plane. When that plane is completed, the system indexes to the next plane and the process repeats. This continues until the components are fully built. In PBF, the deposition plane is fixed in the x and y axis and only moves in the z axis once the current build plane is completely fused.

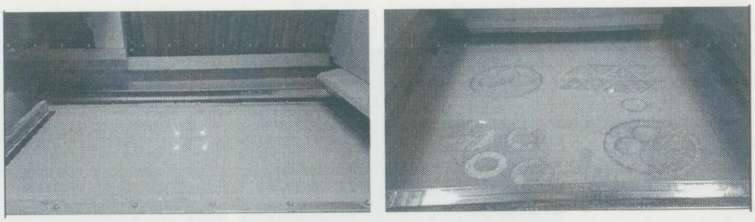


Figure 7: Metallic Powder Bed Fusion additive manufacturing images.

Synchronization is the coordination of events to operate a system in unison.

In DED, a powder or wire material is supplied to a melt pool in **synchronization** with an energy source which is again an electron beam or laser. Just as with PBF, the energy from the beam or laser will melt and fuse the material, but unlike PBF, the deposition spot is not fixed in X and Y. This means that either the surface being built and/or the energy source will be moving in relationship to the build design. DED is also different in that the building of the part layers can be in nearly any direction. This is a drastic difference between the two different AM approaches.

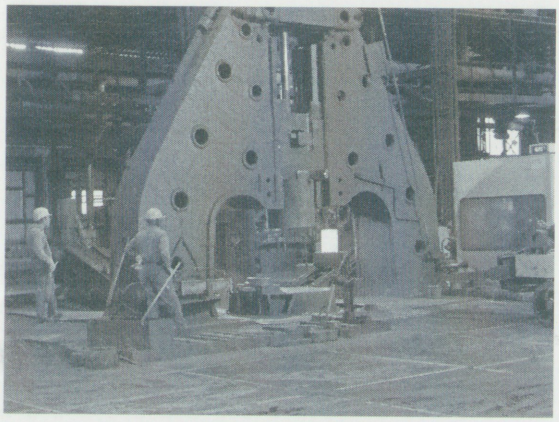
So, both PBF and DED are methods of melting and fusing materials into designed shapes and both can create complex shapes. The difference is the how the material is introduced and how each layer is indexed.

Hopefully this has given you an overview of metallic AM and of the two main AM groups.

Now that we know how AM works, you can probably imagine many advantages over casting and forging methods. A few of these advantages are building parts without molds, in many directions, with very complex shapes, building several parts of different designs at the same time, and even multipart consolidations. This manufacturing technique is nearly boundless, so we need to be sure we also consider the inspect-ability of the produced components.

While current AM inspections are in many ways no different than those for castings and forgings, where parts are subjected to visual, dimensional, external and internal testing, and also surface roughness tests, they can also be quite different, as many of the components are consolidated and redesigned. The consolidated parts (where multiple parts are reduced into one part) are of particular interest as they incorporate several part geometries into a single new design. As AM is more broadly accepted, the inspection

community needs to keep up and ensure that the integrity of the product is maintained at the highest level of quality possible.



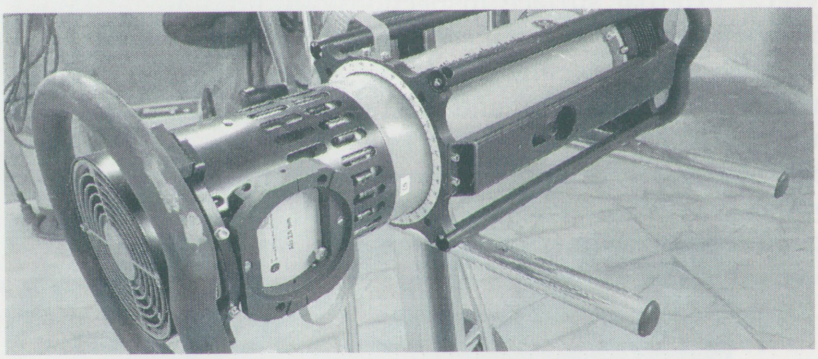
The typical external surface inspections are: fluorescent liquid penetrant (PT), visual (VT, typically enhanced up to 10x), surface roughness, and a dimensional check. Dimensional can be accomplished using gages, coordinate measurement machines (CMM), and white/red/blue light scanners. The typical internal inspections are radiography (RT), electromagnetic (ET), ultrasonic (UT) and in rarer cases even computed tomography (CT).



Each of the inspections serve the same purpose regardless of the method of manufacturing, but the differences in the new manufacturing methods is stark. Castings and forgings are full body methods of manufacturing, meaning that the entire component is formed at one time. AM products are built in layers, typically from .001" to .003" thick depending on the system and the material. This difference is why there must also be a renewed and most likely different focus on inspection.

Traditional nondestructive inspections are performed much the same for the AM parts, but there are some new limitations introduced by the AM methods. The limitations are driven mainly by surface roughness and thin layer build. Some AM parts have excessive surface roughness, at least in some areas, that make PT, VT, ET, and UT nearly impossible. The roughness makes interpretation of the visual methods very difficult and subjective. It also makes the use of contact probes unmanageable.

Knowing the limitations of these particular inspection methods, most AM manufacturers have turned to radiographic internal inspections to validate their parts. RT, especially digital RT (DR), and CT are currently the go-to inspections for many AM manufacturers. The inspections are used both to detect gross defects and to confirm internal geometry. These are decent inspections for these purposes, with CT being much more capable for geometry validation and DR being better at gross defect detection. Unfortunately, neither is as sensitive as required to confirm if defects are present or not at the single layer level.



The building/growing/printing of an AM part in layers can introduce discontinuities that do not form in castings and forgings. Each individual layer is prone to having possible defects and with each layer being so thin, inspection sensitivity or resolution can be critical. DR and CT sensitivity and techniques may be suitable for the larger defects produced by AM, but with the build layers being about 1/3 as thick as the best X-ray resolution levels, the X-ray is capturing three layers of the component at a time. Layer-level defects, a realistic problem with AM processes, are nearly invisible to CT. On top of the resolution issue, geometrical and density challenges limit both of these inspection methods and can make the DR and CT interpretation very subjective and unreliable. Thicker walls, internal cavities, radii, and just plain accessibility are all limiting factors with conventional NDT methods.

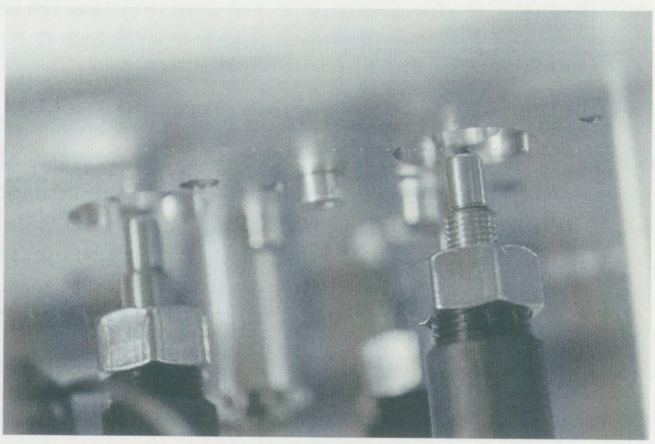
All the external inspections are hampered by surface roughness and the internal radiographic inspections are very limited due to poor resolution, so the assessment of where we are today is basically that we are trading the benefits of additive manufacturing for the significant reduction in inspection confidence from the traditional nondestructive inspections. Most companies are validating each build with a destructively tested metallurgical sample. These samples are

built on the same build plate as the products, under the same conditions, so the thought is that if the sample tests within metallurgical limits, then the products built under the same conditions should be acceptable as well. So, are all the parts representative of the tensile sample? Is one part next to another the same?

We now know what most of the industry is facing with the current and standard technologies. What is needed now is an inspection method that is capable of measuring and assessing each AM-produced component quantitatively, a method that is driven by the part's structural integrity. There are not many choices of inspection that can provide this, but one worth discussing is Process Compensated Resonance Testing or PCRT.

Porosity is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100%.

PCRT is a method that is showing great promise in AM research. PCRT is a whole-body inspection method that uses part resonances, also called natural frequencies, which are sensitive to the material/integrity/dimensional condition of the whole part. PCRT identifies parts that are structurally different in ways that will adversely affect the performance or material properties of the part. PCRT does not identify cosmetic indications. It is a whole-body, structural inspection using statistical processing and pattern recognition tools to segregate parts that are non-conforming. It is both an internal and external inspection all in one.



PCRT data can be used to monitor each part after build to ensure compliance with a given acceptance range or tolerance, or it can be taught to detect printed samples with specific defect types or even carefully modeled defects. PCRT analyses learn by example. Acceptable part variation, and unacceptable defective conditions like **porosity** and

lack of fusion, can be taught with physical samples, or can be modeled for predictive responses and then those modeled responses can be programmed into an algorithm for detectability. This allows for very quick detection of known structural issues.

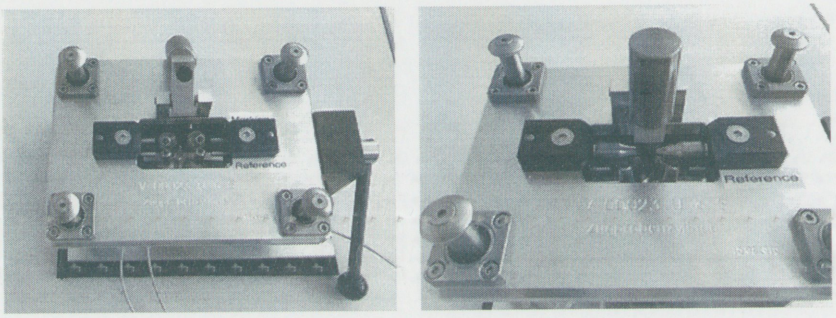


Figure 8: Process Compensated Resonance Testing fixture with additive manufacturing dogbone.

PCRT cannot generally be used yet to locate, size or characterize defects, although PCRT measures will report which samples are most different from the nominal reference set. PCRT can be used to segregate parts within the same build plate that may have single layer defects that are currently undetectable using DR and CT. In sample population AM studies, PCRT has been used to detect unacceptable levels of porosity, cracking, lack of fusion, and even sub-optimal heat treatment in AM components. This is also a relatively fast process. Measurements take from 30 seconds to three minutes per part, so it can be used as a 100% inspection method. It requires no chemicals and produces no waste. PCRT should be performed on individual components, removed from the build plate.

PCRT inspections are already in use in commercial aerospace applications on complex geometries, improving component reliability while reducing inspection and part replacement costs, and may represent the future of AM component inspection. The current suite of inspections is not providing the individual part validation that is needed and the industry is currently relying on an assumed representative tensile sample to confirm material conformance of batches of parts. PCRT meets both of these needs, providing a production-ready, 100% inspection option that quantifies inspection results, supporting process monitoring, quality assurance, and continuous improvement.

7.3.1 Industrial CT for Use in Additive Manufacturing Inspection

New part designs that would be impossible with traditional machining methods require new measurement tools.



Figure 9: Wall thickness analysis of tubes designed to carry fluid and inspect channels for blockages.

Every day additively manufactured (AM) parts are being used in new applications as the industry rapidly matures. As additive parts become more economical for small productions runs and move beyond use solely in tooling and prototyping, the need to nondestructively inspect parts for quality increases as well.

Industrial CT is an excellent inspection method for additive parts and components from the automotive, medical implant and aerospace industries where quality and a high degree of reliability are critical. Computed tomography (CT) has some advantages over other nondestructive inspection methods for additive manufacturing. With CT the entire 3D build volume of a part may be inspected and features uncovered within complex internal geometries.

7.3.2 Challenges Currently Facing the Additive Manufacturing Industry

Are there any defects in your additively manufactured part? CT is used for identifying un-fused powder, missed print layers or foreign object debris or other factors that may weaken the part and cause premature failure over the part's lifetime, or cause contamination once the part is integrated into a final assembly.

Are your parts being produced as intended? CT scan results, combined with design data such as the CAD model, can reveal deviations internally on a point by point basis. Part-to-CAD, part-to-part and nominal-to-actual analysis measures multi-axis accuracy. Shrinkage and the dimensions and orientation of critical features within additive parts can be determined.

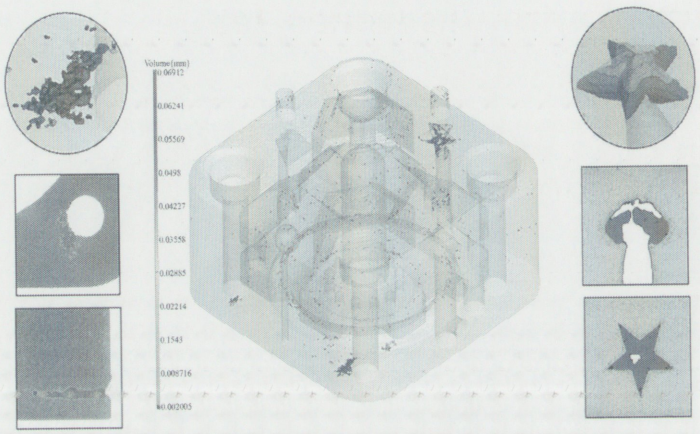


Figure 10: An industrial CT scan of an additively manufactured aluminum block with advanced analysis techniques. Purple represents porosity and a missed print layer. Red represents trapped un-fused powder within the star shaped feature.

Can industrial CT shrink your AM part product development time and increase production yields? Some complex metal parts have build times of anywhere from 24 hours to upwards of over a week to complete. It is inevitable that there will be a learning curve as new part types are developed. "Fail fast forward" is a commonly used term today among product development and hardware engineers building new products for the first time. While engineering is based on the hard laws of physics, there is a delicate dance of getting equipment to perform as expected and for new designs of parts to be printed as designed. Getting key data from the actual internal structures rather than just the as-designed models is imperative.

The costs and benefits of shrinking inspection and part qualification times. The nature of building a product up layer-by-layer allows the opportunity of introducing unique features within additive parts that don't exist in subtractive or machined parts. The primary defects most commonly found in AM parts are un-fused powder within a solid structure, excess powder within an internal channel that is not fully removed or successfully cleaned at the completion of a part build, missing sections of a print layer (porosity), foreign material within a print build (FOD or high density inclusions) or an internal feature not adequately supported during the print process.

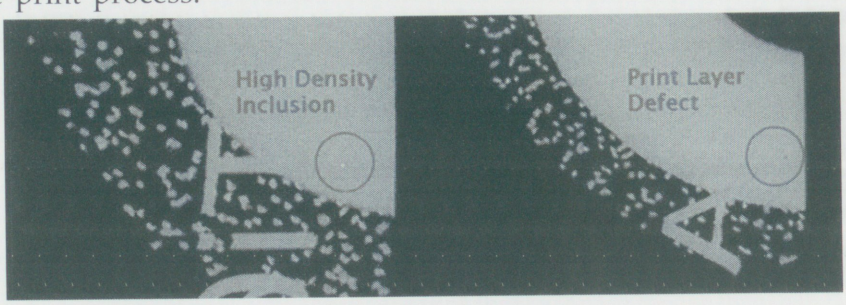


Figure 11: Print layer defects.

7.3.3 Quality Control Inspection for Additive Manufactured Parts

Measurement is key to maintaining quality control. New part designs that would be impossible with traditional machining methods require new measurement tools. As quality requirements evolve inside of a disruptive industry like additive manufacturing, finding tools and innovative approaches to using those tools to advance nondestructive testing methodology is critical.

7.3.4 Visual Inspection of Internal Features

A simple but effective form of quality control is a quick visual inspection of a part for obvious defects. For parts with hidden interior features, this was not practical prior to CT scanning. CT data allows inspectors to slice the part in any X, Y, and Z planes at all critical locations. The X-ray penetration for each image is mapped to a grayscale histogram, which illuminates material/density differences similar to a standard X-ray image. If there is un-fused powder left in an interior feature, it will typically show as muted grey compared to the fused material, while high density **inclusions** will appear as a brighter white. If a print layer shift is visibly observed on the exterior of the part, a CT scan may show if there is internal porosity that could weaken the part. Conversely, CT scanning can also show that bonds are strong across particular layers, all powder is fused properly, and the part is viable for use in production.

Inclusion is any material that is trapped inside a mineral during its formation.

The ability to see the internals of our as printed parts nondestructively at the microscopic level is a game changer. A micro CT scanner is a three-dimensional microscope which allows us to ensure the quality of parts. There is simply no other way to do this.

For parts with critical interior channels such as heat exchangers, water cooled molds or fuel lines, a CT scan can reveal trapped powder, unwanted overhangs or blockages.

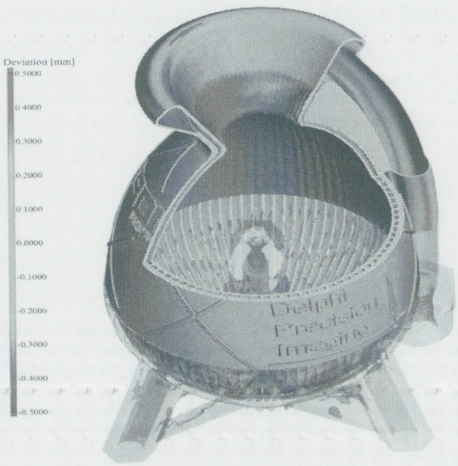


Figure 12: Rocker chamber.

Porosity analysis after the completion of a CT scan quantifies the amount of porosity in a part or within a region of interest. Detailed porosity reports provide the percentage and volumes of porosities or inclusions in an entire part or a designated area of interest such as near thread tapping locations, inside of thin walls or at critical stress points.

7.3.5 Part-to-CAD and Internal Part Inspection

Measurement is key to maintaining quality control. New part designs that would be impossible with traditional machining methods also require new measurement tools. CT scanning of DMLM metal parts has incredible benefits for our clients in aerospace and defense where quality is critical. CT scan and analysis provides tangible and transmittable material data, helping DMLM build high quality standards inside of intensely requiring industries.

Part-to-CAD analysis compares the dimensions of the printed part to the part as designed in the CAD file. Advanced analysis of CT data can provide detailed reports on total area within tolerance, and total porosity for the entire part of a critical area of interest. While laser scanning is usually faster and less expensive than industrial CT, it cannot see within the part.

Creating unique geometries unattainable by conventional manufacturing is one of the main advantages of metal additive manufacturing. "Due to their complex design, many of these geometries can be difficult—or even impossible—to evaluate via conventional inspection methods like CMM or gaging. Even more

advanced techniques like light and laser scanning have limitations. Advances in CT scanning capabilities make it a unique complementary technology for metal additive manufacturing. Industrial CT scanning allows for high resolution inspection of these geometries and features, while also providing information about the metallurgical integrity of the printed part."

In addition to part-to-CAD analysis, CT data can be converted to mesh data (.stl) for part-to-part comparisons. One of the most powerful uses of industrial CT that Delphi Precision Imaging has done was an analysis of a legacy flow valve. We compared a traditional, out of manufacture, cast and machined part, versus an additive manufactured replacement valve. The customer had conveyed that the flow rate on the new valve did not match the flow rate on the old valve. After scanning of both parts, overlayed the .STL files of both parts, and it was instantly obvious that the CMM data used to create the original part missed a critical interior chamfer.

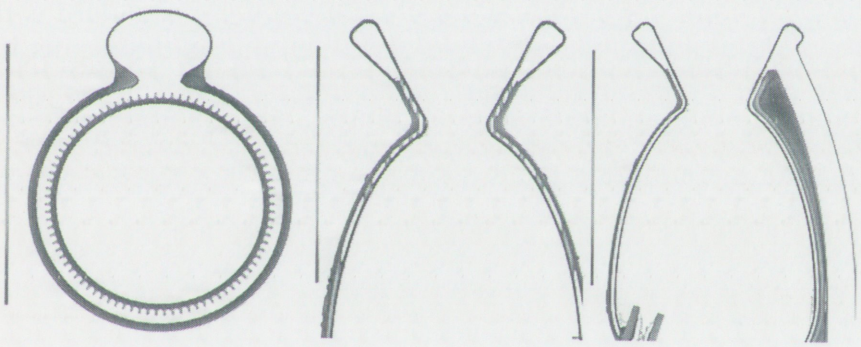


Figure 13: A cross section of a rocket chamber, cooling channels and propellant paths a seen from the X, Y and Z planes.

7.3.6 Digital Radiography and Industrial CT Industry Standards

Currently there are established standards that are being utilized industry wide for digital radiography or 2D imaging. Most of these standards were adopted from similar principles in film radiography. More specifically ASTM 2737, which is intended to be a system longevity check, to ensure the major imaging components are performing as expected. ASTM 2597 is used to identify and correct defective pixels in the detector array.



There are no current CT standards that are recognized industry wide, like the ASTM standards for radiography. Commonly what is being seen is that certain customers are generating their own internal standards.

The problem with not having an established, industry standard is that each customer has its own specific set of criteria which makes the results in testing inconsistent.

SUMMARY

- The inspection and measurement of things is indispensable to manufacturing activities in order to guarantee that products are manufactured as designed.
- Inspection and measurement have undergone much change. Now they are handled in the manufacturing area instead of the quality department in many companies.
- The Egyptians used standards of measurement, with regular calibrations, to ensure stones would fit together in their great construction projects. But modern quality systems really began during the industrial revolution. Before then, mechanical goods were built by craftsmen who would fettle each part individually to fit into an assembly. This meant each machine, and every part in it, was unique. If a part needed to be replaced then a craftsman would need to fit a new part.
- A system of master parts, gauges and single-use machines worked when an entire product was produced in a single factory.
- The most important concept to understand is that all measurements have uncertainty. If it is asked to estimate the height of this text you might say, *'it's about 4 mm'*. Using the word 'about' implies that there is some uncertainty in your estimate.
- A traceable measurement is one which has an unbroken chain of calibrations going all the way back to the primary standard.
- The uncertainty of measurements arises from different sources. Some of these will lead to a consistent error, or bias, in the result.
- The advantage of uncertainty evaluation is that it is capable of considering all sources of uncertainty and, if done properly, gives the most accurate estimate of uncertainty.
- In manufacturing, quality control is a process that ensures customers receive products free from defects and meet their needs.
- Quality control inspectors use a variety of tools to ensure that all the products manufactured by the company are within the limits designated by the designers. A quality control inspector checks every aspect of the production process, using a different tool to accomplish the inspection. Manufactured goods such as textiles, clothing, machine parts or electronics are inspected with some type of tool or tools.
- QC is not a function of any single department or a person. It is the primary responsibility of any supervisor to turn out work of acceptable quality.
- Quality assurance streamlines production and helps to ensure that the final products meet the company's quality criteria. It ensures that the processes used to design, test, and produce products will be done correctly.

- Lean manufacturing tools can bolster your company's quality program. Lean revolves around improving quality and safety, while increasing efficiency and profits.
- Measurement is key to maintaining quality control. New part designs that would be impossible with traditional machining methods require new measurement tools.

REFERENCES

1. Akao, Y. *Quality Function Deployment: Integrating Customer Requirements into Product Design.* Cambridge, MA, Productivity press, 1990.
2. American Society for Quality Statistics Division. *Glossary & Tables for Statistical Quality Control* 4e, ASQ Quality Press, Milwaukee, WI, 2005.
3. Amrine, H., J. Ritchey, C. Moodie, & J. Kmec. *Manufacturing Organization and Management* 6e, Prentice Hall, Englewood Cliffs, NJ, 1993.
4. ANSI/ASQ Z1.4-2003 Sampling Procedures and Tables for Inspection by Attributes.
5. ANSI/ASQ Z1.9-2003 Sampling Procedures and Tables for Inspection by Variables for Percent Nonconforming.
6. ANSI/ASQC Q1-1986, American National Standard Generic Guidelines for Auditing of Quality Systems.
7. ANSI/ASQC Q9000-1-1994, American National Standard Quality Management and Quality Assurance Standards--Guidelines for Selection and Use.
8. ANSI/ISO/ASQ Q9004-2000, American National Standard Quality Management Systems—Guidelines for performance Improvements.
9. ANSI/ISO/ASQC Q10011-1994 Series: Guidelines for Auditing Quality Systems - E-Standards
10. Dessler, G. *Human Resource Management,* 10th ed. Prentice Hall, Upper Saddle River, NJ, 2005.
11. Dodge, H.F., & H.G. Romig. *Sampling Inspection Tables, Single and Double Sampling,* 2nd edition, Wiley, New York, 1959.
12. Duncan, A. J. *Quality Control and Industrial Statistics* 5e, Irwin, Homewood, IL, 1986.
13. Evans, J. *Creative Thinking in the Decision and Management Sciences,* Southwestern, Cincinnati, OH, 1990.
14. Farago, F.T. *Handbook of Dimensional Measurement,* 3rd edition, Industrial Press, New York, 1994.
15. Feigenbaum, A.V. *Total Quality Control,* 3rd edition, McGraw-Hill, New York, 1983.
16. Feigenbaum, A.V. "Total Quality Control." *Harvard Business Review* 34:6 (1956): 93-101. Reprinted in Sower, V., J. Motwani, & M. Savoie. *Classic Readings in Operations Management.* Ft. Worth, TX, 1995, pp. 307-321.
17. Fiorentino, R., and M. Perigord. "Going From an Investigative to a Formative Auditor." *Quality Progress,* vol. 27, no. 10, October 1994, pp. 61-65.
18. Galloway, D. *Mapping Work Processes,* ASQ Quality Press, Milwaukee, 1994.

19. Garvin, D.G. "Competing on the Eight Dimensions of Quality." *Harvard Business Review* 65:6 (1987): 101-109. Reprinted in Sower, V.E., J. Motwani, & M.J. Savoie. *Classic Readings in Operations Management*, Ft. Worth, TX: Dryden, 1995, pp. 323-339.

20. Giakatis, G., T. Enkawa, & K. Washitani. "Hidden Quality Costs and the Distinction Between Quality Cost and Quality Loss." *Total Quality Management* 12(2), March 2001, 179-190.

21. https://bizfluent.com/list-6825704-quality-control-inspection-tools.html

22. https://www.engineering.com/AdvancedManufacturing/ArticleID/14896/An-Introduction-to-Metrology-and-Quality-in-Manufacturing.aspx

23. https://www.featuredcustomers.com/blog/importance-quality-control-manufacturing

24. https://www.graphicproducts.com/articles/quality-control-in-manufacturing/

25. https://www.qualitymag.com/articles/94838-additive-manufacturing-and-inspection-difficulties

26. https://www.qualitymag.com/articles/94884-industrial-ct-for-use-in-additive-manufacturing-inspection

INDEX

A

Abrasive Jet Machining (AJM) 48, 50, 51, 78
Abrasive Water Jet Machining 48, 50
Additive manufacturing (AM) 270
Advanced Manufacturing Technologies (AMTs) 2
air gage 260
alloys 270
Assembly machine 147, 156, 165
Automated assembly 147
automated inspection and testing systems (AITS) 39
Automated material handling systems (AMHS) 39
automation 6, 7, 16, 31, 34, 35, 37, 39, 43
Automotive industry 152

B

bore gage 261

C

CAD-CAM technology 242
calibrations 251, 254, 283
calipers 261
Casting 17, 18, 20
Cellular manufacturing (CM) 12
cellular manufacturing system (CMS) 12
Cemented carbide 103, 111
chemical vapor deposition 84
CNC (Computer Numerical Control) 215
CNC machines 143
color sensor device 262
Computed tomography (CT) 277
Computer-Aided Design (CAD) 215, 216 219, 220, 244
Computer-Aided Manufacturing (CAM) 216
computer-aided manufacturing system (CAM) 33
computer integrated manufacturing (CIM) 32

computerized numerical control machine (CNC) 34

Computer memory 152, 155
Computer numerical control (CNC) 142, 217
Computer program 152
Consistency 266
continuous process 11
control chart 258, 259
Conventional machining 48, 49, 51, 73
coordinate measurement machines (CMM) 273
craftsman 251, 283
Cubic boron nitride (CBN) 83, 92, 97
cutting processes 81, 103
CVD diamonds 84

D

DC brush motors 132
DC linear actuator 124, 125
deposition plane 271
Diamond 82, 84, 85, 88, 89, 92, 93, 95, 96, 97, 110, 112, 113
difficult-to-cut (DTC) materials 102, 111
dimensional measuring equipment 250
Direct Energy Deposition (DED) 271
Direct Metal Laser Sintering (DMLS) 271
Drilling 50, 61, 62, 78
Dynamic Machining Strategies 241

E

Electrical Discharge Machines (EDM) 226
Electro Jet Drilling (EJD) 50
Electron Beam Freeform (EBF) 271
Electron Beam Machining (EBM) 50
Electron Beam Melting 271

F

Flexible manufacturing proposes 170, 212
Flexible manufacturing system (FMS) 159
flow shops 9

G

Gas Metal Arc (GMA) 271
Gas Tungsten Arc (GTA) 271
gauges 251, 252, 283
Grinding 50, 51, 67, 68, 78
Grinding wheels 95, 97

I

Inches per tooth (IPT) 59
industrial measurement process 257
industrial revolution 251, 283
Industrial robot 142, 165
information communication technology (ICT) 33
Inspection 249, 250, 260, 276, 279, 280, 283, 285
integrative and managerial systems (IMS) 38

J

Job shop 8
Just-in-time (JIT) 36

K

Kaizen 259, 268

L

Laser Beam (LB) 271
Laser Jet Machining (LJM) 50
Lean manufacturing 170, 171, 172, 173, 174, 175, 176, 178, 179, 209, 212
Lean manufacturing tools 268, 284
Linear induction motor 116, 165
Linear motor 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 133, 136, 137, 165
Lorentz-type actuator 116

M

Machine Tool Capability 258
Manufacturing 1, 2, 3, 4, 5, 6, 7, 12, 15, 16, 17, 18, 22, 23, 28, 31, 32, 36, 37, 38, 39, 43, 45
Manufacturing equipment 145
Manufacturing line 172, 173, 185
Manufacturing system 169, 170, 171, 175, 178, 179, 180, 181, 184, 185, 186, 188, 189, 202, 203, 211, 212

measurement 249, 250, 251, 252, 253, 254, 255, 256, 257, 261, 273, 276, 279, 280, 283, 284
measurement error 252
Measurement Systems Analysis (MSA) 256
Metal forming 19
Metrology 250, 286
Milling 48, 63, 64, 65, 66, 67, 69, 79
Modern tooling systems 81

N

nanodiamond 84
Non Traditional Machining (NTM) 48, 49
Numerical control (NC) 232

P

perturbations 255
Photochemical Milling (PCM) 50
Plasma Arc (PA) 271
Plasma Transferred Arc (PTA) 271
polycrystalline cubic boron nitride (PCBN) 96, 99
Polycrystalline diamond (PCD) tools 101, 111
porosity 275, 276, 278, 279, 280
Powder Bed Fusion (PBF) 271
Process Capability 258
Production line 171, 172, 173, 174, 181, 189, 190, 199, 200, 202, 204, 205, 206, 208, 212, 213
project shop 10

Q

Quality assurance 267, 283
Quality control 250, 260, 261, 262, 266, 267, 283

R

repeatability 255, 256, 258
reproducibility 255, 256, 257, 258
RVG-D (Resin, Vitrified. Grinding—Dry) 88
RVG-W (Resin, Vitrified. Grinding—Wet) 88

S

Selective Laser Melting (SLM) 271
short-term variability 258
Single-phase induction motor 133
Statistical Process Control (SPC 258
Superabrasive cutting tools 82, 110
Surface feet per minute (SFM) 60
systems, devices and stations (SDS) 38

T

tantalum carbide (TaC) 103
tolerances 251, 261
Total Productive Maintenance (TPM) 259
Total Quality Management (TQM) 171
true value 252, 253, 257
tungsten carbide (WC) 103
Turning 57, 58, 78

U

Ultrasonic Machining (USM) 48, 50
uncertainty 252, 253, 254, 255, 256, 257, 258, 283
uncertainty budget 256

V

Variable reluctance (VR) 130
Voice coil actuators 126, 127, 128

W

work- in-progress (WIP) 12

3GE COLLECTION ON ENGINEERING

Advanced Manufacturing

The market place of the twenty-first century is evolving into one of merging national markets, fragmented consumer markets, and rapidly changing product technologies. These changes are driving firms to compete, simultaneously, along several different dimensions: design, manufacturing, distribution, communication, sales and others. Although manufacturing has not been utilized as a competitive weapon historically, the market place of the twenty first century will demand that manufacturing assume a crucial role in the new competitive arena.

This book "Advanced Manufacturing" summarizes the trends we observe in technology research and development that relate to the current and future state of advanced manufacturing. The book explains how manufacturing has traditionally been defined and how the processes in a production plant have been viewed as a mainly step-wise linear transformation of inputs towards finished goods.

The goal of this book is to find how innovation in manufacturing processes and associated product design impacts the prospects for manufacturing in the early 21st century. Innovations in manufacturing are often reported one-at-a-time and it is not immediately clear how these innovations fit together and how they collectively impact the practice and economics of manufacturing. This book is intended to present advanced manufacturing technology innovations in a larger context.

Innovation involves important feed-forward and feedback mechanisms in the real economy. The invention of new products and processes, as well as the improvement of existing processes, leads to higher productivity and expansion of product portfolios and associated service offerings. Progress in human society has been accomplished by the creation of new technologies. The last few years have witnessed unparalleled changes throughout the world. Rapid changes in the markets demand drastically shortened product life cycles and high-quality products at competitive prices. Customers now prefer a large variety of products. This phenomenon has inspired manufacturing firms to look for progressive computerized automation in various processes. Thus mass production is being replaced by low-volume, high-variety production. Manufacturing firms have recognized the importance of flexibility in the manufacturing system to meet the challenges posed by the pluralistic market. The concept of flexibility in manufacturing systems has attained significant importance in meeting the challenges for a variety of products of shorter lead-times, together with higher productivity and quality.

This book provides an overview of the processes in discrete-event manufacturing systems, and emphasizes concepts relating to the interconnection of the wide range of activities involved. This book provides a broad vision of the future of manufacturing, analysed from a system-management viewpoint and with a special focus on ICT-related matters.

ISBN 978-1-98462-354-6



3G E-LEARNING
www.3ge-learning.com
email: info@3ge-learning.com