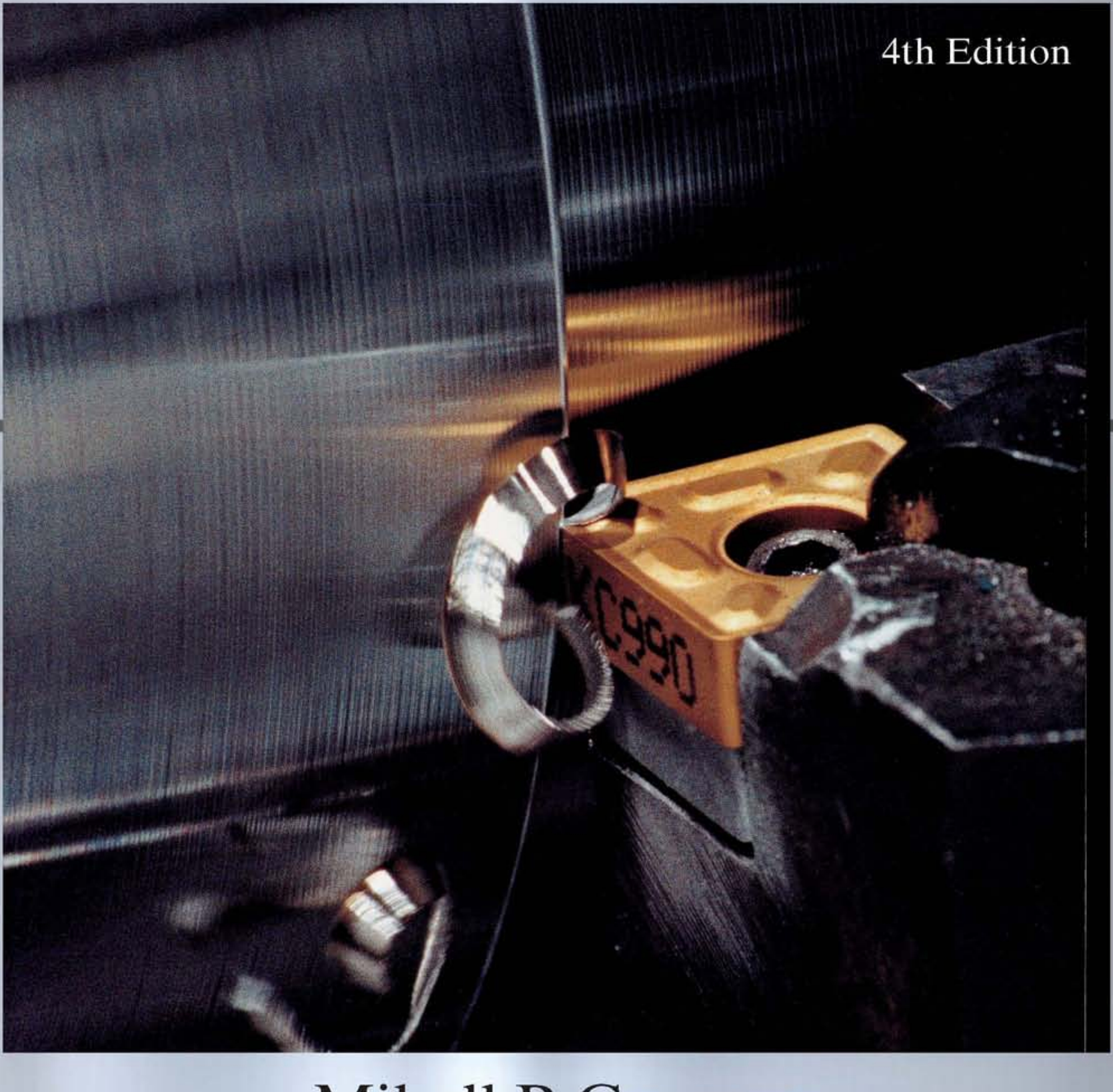
Fundamentals of Modern Manufacturing

Materials, Processes, and Systems


4th Edition

Mikell P. Groover

FUNDAMENTALS OF MODERN MANUFACTURING

Materials, Processes, and Systems

Fourth Edition

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Systems Engineering
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The author and publisher gratefully acknowledge the contributions of Dr. Gregory L. Tonkay, Associate Professor of Industrial and Systems Engineering, Lehigh University.

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PREFACE

Fundamentals of Modern Manufacturing: Materials, Processes, and Systems is designed for a first course or two-course sequence in manufacturing at the junior level in mechanical, industrial, and manufacturing engineering curricula. Given its coverage of engineering materials, it is also suitable for materials science and engineering courses that emphasize materials processing. Finally, it may be appropriate for technology programs related to the preceding engineering disciplines. Most of the book's content is concerned with manufacturing processes (about 65% of the text), but it also provides significant coverage of engineering materials and production systems. Materials, processes, and systems are the basic building blocks of modern manufacturing and the three broad subject areas covered in the book.

APPROACH

The author's objective in this edition and its predecessors is to provide a treatment of manufacturing that is ***modern*** and ***quantitative***. Its claim to be "modern" is based on (1) its balanced coverage of the basic engineering materials (metals, ceramics, polymers, and composite materials), (2) its inclusion of recently developed manufacturing processes in addition to the traditional processes that have been used and refined over many years, and (3) its comprehensive coverage of electronics manufacturing technologies. Competing textbooks tend to emphasize metals and their processing at the expense of the other engineering materials, whose applications and methods of processing have grown significantly in the last several decades. Also, most competing books provide minimum coverage of electronics manufacturing. Yet the commercial importance of electronics products and their associated industries have increased substantially during recent decades.

The book's claim to be more "quantitative" is based on its emphasis on manufacturing science and its greater use of mathematical models and quantitative (end-of-chapter) problems than other manufacturing textbooks. In the case of some processes, it was the first manufacturing processes book to ever provide a quantitative engineering coverage of the topic.

NEW TO THIS EDITION

This fourth edition is an updated version of the third edition. The publisher's instructions to the author were to increase content but reduce page count. As this preface is being written, it is too early to tell whether the page count is reduced, but the content has definitely been increased. Additions and changes in the fourth edition include the following:

- The chapter count has been reduced from 45 to 42 through consolidation of several chapters.
- Selected end-of-chapter problems have been revised to make use of PC spread sheet calculations.
- A new section on trends in manufacturing has been added in Chapter 1.

- Chapter 5 on dimensions, tolerances, and surfaces has been modified to include measuring and gauging techniques used for these part features.
- A new section on specialty steels has been added to Chapter 8 on metals.
- Sections on polymer recycling and biodegradable plastics have been added in Chapter 8 on polymers.
- Several new casting processes are discussed in Chapter 11.
- Sections on thread cutting and gear cutting have been added in Chapter 22 on machining operations and machine tools.
- Several additional hole-making tools have been included in Chapter 23 on cutting tool technology.
- Former Chapters 28 and 29 on industrial cleaning and coating processes have been consolidated into a single chapter.
- A new section on friction-stir welding has been added to Chapter 30 on welding processes.
- Chapter 37 on nanotechnology has been reorganized with several new topics and processes added.
- The three previous Chapters 39, 40, and 41on manufacturing systems have been consolidated into two chapters: Chapter 38 titled Automation for Manufacturing Systems and Chapter 39 on Integrated Manufacturing Systems. New topics covered in these chapters include automation components and material handling technologies.
- Former Chapters 44 on Quality Control and 45 on Measurement and Inspection have been consolidated into a single chapter, Chapter 42 titled Quality Control and Inspection. New sections have been added on Total Quality Management, Six Sigma, and ISO 9000. The text on conventional measuring techniques has been moved to Chapter 5.

OTHER KEY FEATURES

Additional features of the book continued from the third edition include the following:

- A DVD showing action videos of many of the manufacturing processes is included with the book.
- A large number of end-of-chapter problems, review questions, and multiple choice questions are available to instructors to use for homework exercises and quizzes.
- Sections on ***Guide to Processing*** are included in each of the chapters on engineering materials.
- Sections on ***Product Design Considerations*** are provided in many of the manufacturing process chapters.
- ***Historical Notes*** on many of the technologies are included throughout the book.
- The principal engineering units are System International (metric), but both metric and U.S. Customary Units are used throughout the text.

SUPPORT MATERIAL FOR INSTRUCTORS

For instructors who adopt the book for their courses, the following support materials are available:

- A ***Solutions Manual*** (in digital format) covering all problems, review questions, and multiple-choice quizzes.
- A complete set of PowerPoint slides for all chapters.

These support materials may be found at the website www.wiley.com/college/groover. Evidence that the book has been adopted as the main textbook for the course must be verified. Individual questions or comments may be directed to the author personally at Mikell.Groover@Lehigh.edu.

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For their advice on this fourth edition, I would like to thank the following people: Barbara Mizdail (The Pennsylvania State University – Berks campus) and Jack Feng (formerly of Bradley University and now at Caterpillar, Inc.) for conveying questions and feedback from their students, Larry Smith (St. Clair College, Windsor, Ontario) for his advice on using the ASME standards for hole drilling, Richard Budihas (Voltaic LLC) for his contributed research on nanotechnology and integrated circuit processing, and colleague Marvin White at Lehigh for his insights on integrated circuit technology.

In addition, it seems appropriate to acknowledge my colleagues at Wiley, Senior Acquisition Editor Michael McDonald and Production Editor Anna Melhorn. Last but certainly not least, I appreciate the kind efforts of editor Sumit Shridhar of Thomson Digital.

ABOUT THE AUTHOR

Mikell P. Groover is Professor of Industrial and Systems Engineering at Lehigh University, where he also serves as faculty member in the Manufacturing Systems Engineering Program. He received his B.A. in Arts and Science (1961), B.S. in Mechanical Engineering (1962), M.S. in Industrial Engineering (1966), and Ph.D. (1969), all from Lehigh. He is a Registered Professional Engineer in Pennsylvania. His industrial experience includes several years as a manufacturing engineer with Eastman Kodak Company. Since joining Lehigh, he has done consulting, research, and project work for a number of industrial companies.

His teaching and research areas include manufacturing processes, production systems, automation, material handling, facilities planning, and work systems. He has received a number of teaching awards at Lehigh University, as well as the ***Albert G. Holzman Outstanding Educator Award*** from the Institute of Industrial Engineers (1995) and the ***SME Education Award*** from the Society of Manufacturing Engineers (2001). His publications include over 75 technical articles and ten books (listed below). His books are used throughout the world and have been translated into French, German, Spanish, Portuguese, Russian, Japanese, Korean, and Chinese. The first edition of the current book ***Fundamentals of Modern Manufacturing*** received the ***IIE Joint Publishers Award*** (1996) and the ***M. Eugene Merchant Manufacturing Textbook Award*** from the Society of Manufacturing Engineers (1996).

Dr. Groover is a member of the Institute of Industrial Engineers, American Society of Mechanical Engineers (ASME), the Society of Manufacturing Engineers (SME), the North American Manufacturing Research Institute (NAMRI), and ASM International. He is a Fellow of IIE (1987) and SME (1996).

PREVIOUS BOOKS BY THE AUTHOR

Automation, Production Systems, and Computer-Aided Manufacturing, Prentice Hall, 1980.

CAD/CAM: Computer-Aided Design and Manufacturing, Prentice Hall, 1984 (co-authored with E. W. Zimmers, Jr.).

Industrial Robotics: Technology, Programming, and Applications, McGraw-Hill Book Company, 1986 (co-authored with M. Weiss, R. Nagel, and N. Odrey).

Automation, Production Systems, and Computer Integrated Manufacturing, Prentice Hall, 1987.

Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, originally published by Prentice Hall in 1996, and subsequently published by John Wiley & Sons, Inc., 1999.

Automation, Production Systems, and Computer Integrated Manufacturing, Second Edition, Prentice Hall, 2001.

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Automation, Production Systems, and Computer Integrated Manufacturing, Third Edition, Pearson Prentice Hall, 2008.

CONTENTS

1

INTRODUCTION AND OVERVIEW OF MANUFACTURING

Chapter Contents

Making things has been an essential activity of human civilizations since before recorded history. Today, the term ***manufacturing*** is used for this activity. For technological and economic reasons, manufacturing is important to the welfare of the United States and most other developed and developing nations. ***Technology*** can be defined as the application of science to provide society and its members with those things that are needed or desired. Technology affects our daily lives, directly and indirectly, in many ways. Consider the list of products in Table 1.1. They represent various technologies that help society and its members to live better. What do all these products have in common? They are all manufactured. These technological wonders would not be available to society if they could not be manufactured. Manufacturing is the critical factor that makes technology possible.

Economically, manufacturing is an important means by which a nation creates material wealth. In the United States, the manufacturing industries account for about 15% of gross domestic product (GDP). A country's natural resources, such as agricultural lands, mineral deposits, and oil reserves, also create wealth. In the U.S., agriculture, mining, and similar industries account for less than 5% of GDP (agriculture alone is only about 1%). Construction and public utilities make up around 5%. The rest is service industries, which include retail, transportation, banking, communication, education, and government. The service sector accounts for more than 75% of U.S. GDP. Government alone accounts for about as much of GDP as the manufacturing sector; however, government services do not create wealth. In the modern global economy, a nation must have a strong manufacturing base (or it must have significant natural resources) if it is to provide a strong economy and a high standard of living for its people.

In this opening chapter, we consider some general topics about manufacturing. What is manufacturing? How is it organized in industry? What are the materials, processes, and systems by which it is accomplished?

TABLE 1.1 Products representing various technologies, most of which affect nearly everyone.

Athletic shoes
Automatic teller machine
Automatic dishwasher
Ballpoint pen
Cell phone
Compact disc (CD)
Compact disc player
Compact fluorescent light bulb
Contact lenses
Digital camera
Digital video disc (DVD)
Digital video disc player
Fax machine
Flat-screen high-definition television
Hand-held electronic calculator
High density PC diskette
Home security system
Hybrid gas-electric automobile
Industrial robot
Ink-jet color printer
Integrated circuit
Magnetic resonance imaging (MRI) machine for medical diagnosis
Microwave oven
One-piece molded plastic patio chair
Optical scanner
Personal computer (PC)
Photocopying machine
Pull-tab beverage cans
Quartz crystal wrist watch
Self-propelled mulching lawnmower
Supersonic aircraft
Tennis racket of composite materials
Video games
Washing machine and dryer

1.1 WHAT IS MANUFACTURING?

The word ***manufacture*** is derived from two Latin words, ***manus*** (hand) and ***factus*** (make); the combination means made by hand. The English word ***manufacture*** is several centuries old, and "made by hand" accurately described the manual methods used when the word was first coined.[1] Most modern manufacturing is accomplished by automated and computer-controlled machinery (Historical Note 1.1).

Historical Note 1.1 *History of manufacturing*

The history of manufacturing can be separated into two subjects: (1) human's discovery and invention of materials and processes to make things, and (2) development of the systems of production. The materials and processes to make things predate the systems by several millennia. Some of the processes—casting, hammering (forging), and grinding—date back 6000 years or more. The early fabrication of implements and weapons was accomplished more as crafts and trades than manufacturing as it is known today. The ancient Romans had what might be called factories to produce weapons, scrolls, pottery and glassware, and other products of the time, but the procedures were largely based on handicraft.

The systems aspects of manufacturing are examined here, and the materials and processes are postponed until Historical Note 1.2. ***Systems of manufacturing*** refer to the ways of organizing people and equipment so that production can be performed more efficiently. Several historical events and discoveries stand out as having had a major impact on the development of modern manufacturing systems.

Certainly one significant discovery was the principle of ***division of labor***—dividing the total work into tasks and having individual workers each become a specialist at performing only one task. This principle had been practiced for centuries, but the economist Adam Smith (1723–1790) is credited with first explaining its economic significance in ***The Wealth of Nations.***

The ***Industrial Revolution*** (circa 1760–1830) had a major impact on production in several ways. It marked the change from an economy based on agriculture and handicraft to one based on industry and manufacturing. The change began in England, where a series of machines were invented and steam power replaced water, wind, and animal power. These advances gave British industry significant advantages over other nations, and England attempted to restrict export of the new technologies. However, the revolution eventually spread to other European countries and the United States.

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[1] As a noun, the word ***manufacture*** first appeared in English around 1567 AD. As a verb, it first appeared around 1683 AD.

Several inventions of the Industrial Revolution greatly contributed to the development of manufacturing: (1) ***Watt's steam engine,*** a new power-generating technology for industry; (2) ***machine tools,*** starting with John Wilkinson's boring machine around 1775 (Historical Note 22.1); (3) the ***spinning jenny, power loom,*** and other machinery for the textile industry that permitted significant increases in productivity; and (4) the ***factory system,*** a new way of organizing large numbers of production workers based on division of labor.

While England was leading the industrial revolution, an important concept was being introduced in the United States: ***interchangeable parts*** manufacture. Much credit for this concept is given to Eli Whitney (1765–1825), although its importance had been recognized by others [9]. In 1797, Whitney negotiated a contract to produce 10,000 muskets for the U.S. government. The traditional way of making guns at the time was to custom fabricate each part for a particular gun and then hand-fit the parts together by filing. Each musket was unique, and the time to make it was considerable. Whitney believed that the components could be made accurately enough to permit parts assembly without fitting. After several years of development in his Connecticut factory, he traveled to Washington in 1801 to demonstrate the principle. He laid out components for 10 muskets before government officials, including Thomas Jefferson, and proceeded to select parts randomly to assemble the guns. No special filing or fitting was required, and all of the guns worked perfectly. The secret behind his achievement was the collection of special machines, fixtures, and gages that he had developed in his factory. Interchangeable parts manufacture required many years of development before becoming a practical reality, but it revolutionized methods of manufacturing. It is a prerequisite for mass production. Because its origins were in the United States, interchangeable parts production came to be known as the ***American System*** of manufacture.

The mid- and late 1800s witnessed the expansion of railroads, steam-powered ships, and other machines that created a growing need for iron and steel. New steel production methods were developed to meet this demand (Historical Note 6.1). Also during this period, several consumer products were developed, including the sewing machine, bicycle, and automobile. To meet the mass demand for these products, more efficient production methods were required. Some historians identify developments during this period as the ***Second Industrial Revolution,*** characterized in terms of its effects on manufacturing systems by: (1) mass production, (2) scientific management movement, (3) assembly lines, and (4) electrification of factories.

In the late 1800s, the ***scientific management*** movement was developing in the United States in response to the need to plan and control the activities of growing numbers of production workers. The movement's leaders included Frederick W. Taylor (1856–1915), Frank Gilbreth (1868–1924), and his wife Lilian (1878–1972). Scientific management included several features [2]: (1) ***motion study,*** aimed at finding the best method to perform a given task; (2) ***time study,*** to establish work standards for a job; (3) extensive use of ***standards*** in industry; (4) the ***piece rate system*** and similar labor incentive plans; and (5) use of data collection, record keeping, and cost accounting in factory operations.

Henry Ford (1863–1947) introduced the ***assembly line*** in 1913 at his Highland Park, MI plant. The assembly line made possible the mass production of complex consumer products. Use of assembly line methods permitted Ford to sell a Model T automobile for as little as $500, thus making ownership of cars feasible for a large segment of the U.S. population.

In 1881, the first electric power generating station had been built in New York City, and soon electric motors were being used as a power source to operate factory machinery. This was a far more convenient power delivery system than steam engines, which required overhead belts to distribute power to the machines. By 1920, electricity had overtaken steam as the principal power source in U.S. factories. The twentieth century was a time of more technological advances than in all other centuries combined. Many of these developments resulted in the ***automation*** of manufacturing.

1.1.1 MANUFACTURING DEFINED

As a field of study in the modern context, manufacturing can be defined two ways, one technologic and the other economic. Technologically, ***manufacturing*** is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labor, as depicted in Figure 1.1(a).

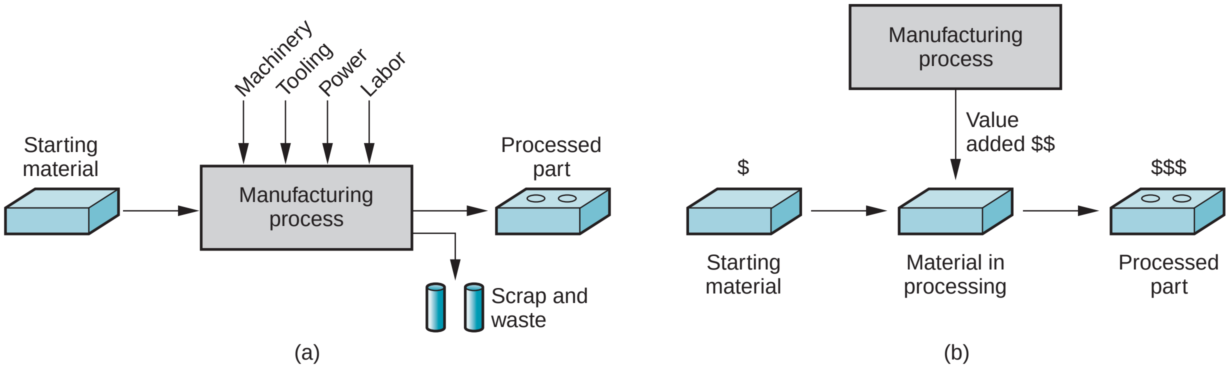

FIGURE 1.1 Two ways to define manufacturing: (a) as a technical process, and (b) as an economic process.

Manufacturing is almost always carried out as a sequence of operations. Each operation brings the material closer to the desired final state.

Economically, ***manufacturing*** is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as depicted in Figure 1.1(b). The key point is that manufacturing ***adds value*** to the material by changing its shape or properties, or by combining it with other materials that have been similarly altered. The material has been made more valuable through the manufacturing operations performed on it. When iron ore is converted into steel, value is added. When sand is transformed into glass, value is added. When petroleum is refined into plastic, value is added. And when plastic is molded into the complex geometry of a patio chair, it is made even more valuable.

The words ***manufacturing*** and ***production*** are often used interchangeably. The author's view is that production has a broader meaning than manufacturing. To illustrate, one might speak of "crude oil production," but the phrase "crude oil manufacturing" seems out of place. Yet when used in the context of products such as metal parts or automobiles, either word seems okay.

1.1.2 MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity performed by companies that sell products to customers. The type of manufacturing done by a company depends on the kind of product it makes. Let us explore this relationship by examining the types of industries in manufacturing and identifying the products they make.

Manufacturing Industries Industry consists of enterprises and organizations that produce or supply goods and services. Industries can be classified as primary, secondary, or tertiary. ***Primary industries*** cultivate and exploit natural resources, such as agriculture and mining. ***Secondary industries*** take the outputs of the primary industries and convert them into consumer and capital goods. Manufacturing is the principal activity in this category, but construction and power utilities are also included. ***Tertiary industries*** constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 1.2.

This book is concerned with the secondary industries in Table 1.2, which include the companies engaged in manufacturing. However, the International Standard Industrial Classification (ISIC) used to compile Table 1.2 includes several industries whose production technologies are not covered in this text; for example, beverages, chemicals, and food processing. In this book, manufacturing means production of ***hardware,*** which ranges from nuts and bolts to digital computers and military weapons. Plastic and ceramic

TABLE 1.2 Specific industries in the primary, secondary, and tertiary categories.

Primary	Secondary		Tertiary (Service)	
Agriculture	Aerospace	Food processing	Banking	Insurance
Forestry	Apparel	Glass, ceramics	Communications	Legal
Fishing	Automotive	Heavy machinery	Education	Real estate
Livestock	Basic metals	Paper	Entertainment	Repair and maintenance
Quarries	Beverages	Petroleum refining	Financial services	Restaurant
Mining	Building materials	Pharmaceuticals	Government	Retail trade
Petroleum	Chemicals	Plastics (shaping)	Health and medical	Tourism
	Computers	Power utilities	Hotel	Transportation
	Construction	Publishing	Information	Wholesale trade
	Consumer appliances	Textiles		
	Electronics	Tire and rubber		
	Equipment	Wood and furniture		
	Fabricated metals			

products are included, but apparel, paper, pharmaceuticals, power utilities, publishing, and wood products are excluded.

Manufactured Products Final products made by the manufacturing industries can be divided into two major classes: consumer goods and capital goods. ***Consumer goods*** are products purchased directly by consumers, such as cars, personal computers, TVs, tires, and tennis rackets. ***Capital goods*** are those purchased by companies to produce goods and/or provide services. Examples of capital goods include aircraft, computers, communication equipment, medical apparatus, trucks and buses, railroad locomotives, machine tools, and construction equipment. Most of these capital goods are purchased by the service industries. It was noted in the Introduction that manufacturing accounts for about 15% of GDP and services about 75% of GDP in the United States. Yet the manufactured capital goods purchased by the service sector are the enablers of that sector. Without the capital goods, the service industries could not function.

In addition to final products, other manufactured items include the ***materials, components,*** and ***supplies*** used by the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings and extrusions, cutting tools, dies, molds, and lubricants. Thus, the manufacturing industries consist of a complex infrastructure with various categories and layers of intermediate suppliers with whom the final consumer never deals.

This book is generally concerned with ***discrete items***—individual parts and assembled products, rather than items produced by ***continuous processes.*** A metal stamping is a discrete item, but the sheet-metal coil from which it is made is continuous (almost). Many discrete parts start out as continuous or semicontinuous products, such as extrusions and electrical wire. Long sections made in almost continuous lengths are cut to the desired size. An oil refinery is a better example of a continuous process.

Production Quantity and Product Variety The quantity of products made by a factory has an important influence on the way its people, facilities, and procedures are organized. Annual production quantities can be classified into three ranges: (1) ***low*** production, quantities in the range 1 to 100 units per year; (2) ***medium*** production, from 100 to 10,000 units annually; and (3) ***high*** production, 10,000 to millions of units. The boundaries

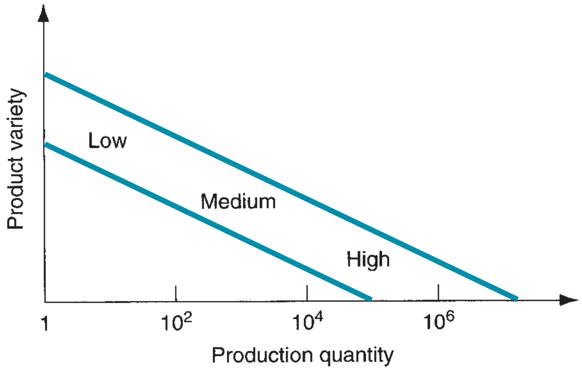

FIGURE 1.2 Relationship between product variety and production quantity in discrete product manufacturing.

between the three ranges are somewhat arbitrary (in the author's judgment). Depending on the kinds of products, these boundaries may shift by an order of magnitude or so.

Production quantity refers to the number of units produced annually of a particular product type. Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. ***Product variety*** refers to different product designs or types that are produced in the plant. Different products have different shapes and sizes; they perform different functions; they are intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. When the number of product types made in the factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. If a factory's product variety is high, then its production quantity is likely to be low; but if production quantity is high, then product variety will be low, as depicted in Figure 1.2. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.2.

Although product variety has been identified as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity, because details on how much the designs differ are not captured simply by the number of different designs. Differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Within each product type, there are differences among specific models.

The extent of the product differences may be small or great, as illustrated in the automotive industry. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are virtually the same. In different plants, the company builds heavy trucks. The terms "soft" and "hard" might be used to describe these differences in product variety. ***Soft product variety*** occurs when there are only small differences among products, such as the differences among car models made on the same production line. In an assembled product, soft variety is characterized by a high proportion of common parts among the models. ***Hard product variety*** occurs when the products differ substantially, and there are few common parts, if any. The difference between a car and a truck exemplifies hard variety.

1.1.3 MANUFACTURING CAPABILITY

A manufacturing plant consists of a set of ***processes*** and ***systems*** (and people, of course) designed to transform a certain limited range of ***materials*** into products of increased value. These three building blocks—materials, processes, and systems—constitute the subject of modern manufacturing. There is a strong interdependence among these factors. A company engaged in manufacturing cannot do everything. It must do only certain things, and it must do those things well. ***Manufacturing capability*** refers to the technical and physical limitations of a manufacturing firm and each of its plants. Several dimensions of this capability can be identified: (1) technological processing capability, (2) physical size and weight of product, and (3) production capacity.

Technological Processing Capability The technological processing capability of a plant (or company) is its available set of manufacturing processes. Certain plants perform machining operations, others roll steel billets into sheet stock, and others build automobiles. A machine shop cannot roll steel, and a rolling mill cannot build cars. The underlying feature that distinguishes these plants is the processes they can perform. Technological processing capability is closely related to material type. Certain manufacturing processes are suited to certain materials, whereas other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in certain material types. Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies must concentrate on the design and manufacture of products that are compatible with their technological processing capability.

Physical Product Limitations A second aspect of manufacturing capability is imposed by the physical product. A plant with a given set of processes is limited in terms of the size and weight of the products that can be accommodated. Large, heavy products are difficult to move. To move these products about, the plant must be equipped with cranes of the required load capacity. Smaller parts and products made in large quantities can be moved by conveyor or other means. The limitation on product size and weight extends to the physical capacity of the manufacturing equipment as well. Production machines come in different sizes. Larger machines must be used to process larger parts. The production and material handling equipment must be planned for products that lie within a certain size and weight range.

Production Capacity A third limitation on a plant's manufacturing capability is the production quantity that can be produced in a given time period (e.g., month or year). This quantity limitation is commonly called ***plant capacity,*** or ***production capacity,*** defined as the maximum rate of production that a plant can achieve under assumed operating conditions. The operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and so on. These factors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?

Plant capacity is usually measured in terms of output units, such as annual tons of steel produced by a steel mill, or number of cars produced by a final assembly plant. In these cases, the outputs are homogeneous. In cases in which the output units are not homogeneous, other factors may be more appropriate measures, such as available labor hours of productive capacity in a machine shop that produces a variety of parts.

Materials, processes, and systems are the basic building blocks of manufacturing and the three broad subject areas of this book. This introductory chapter provides an overview of these three subjects before embarking on detailed coverage in the remaining chapters.

1.2 MATERIALS IN MANUFACTURING

Most engineering materials can be classified into one of three basic categories:(1) metals, (2) ceramics, and (3) polymers.Their chemistries are different, their mechanical and physical properties are different, and these differences affect the manufacturing processes that can be used to produce products from them. In addition to the three basic categories, there are

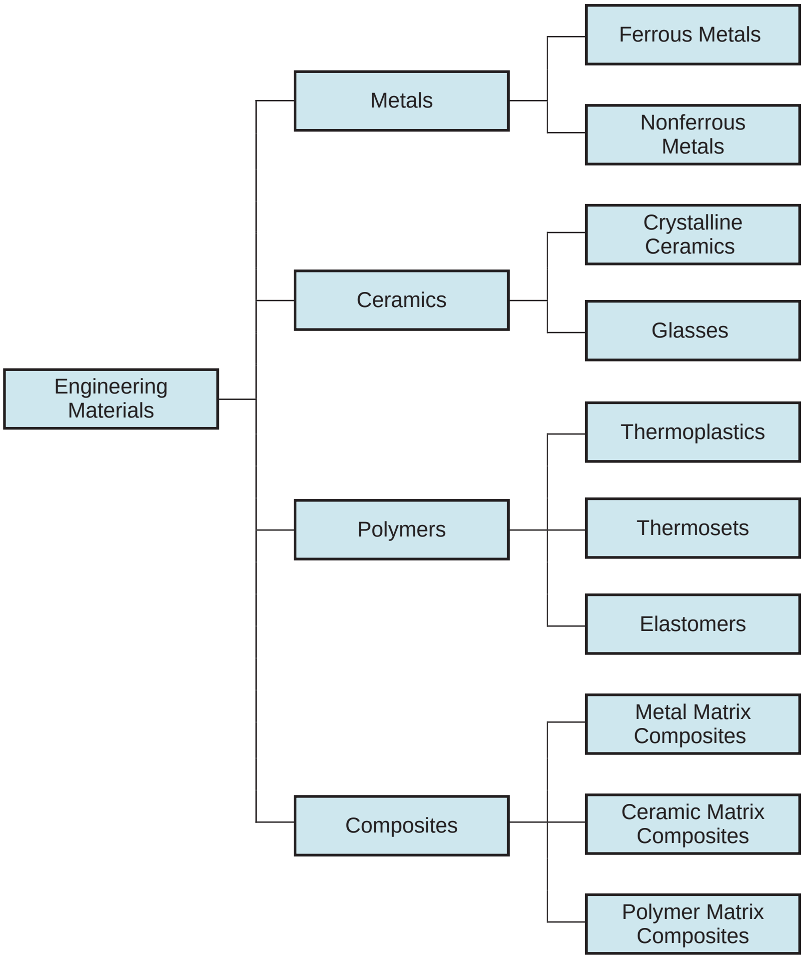

FIGURE 1.3
Classification of the four engineering materials.

(4) ***composites***—nonhomogeneous mixtures of the other three basic types rather than a unique category. The classification of the four groups is pictured in Figure 1.3. This section surveys these materials. Chapters 6 through 9 cover the four material types in more detail.

1.2.1 METALS

Metals used in manufacturing are usually ***alloys,*** which are composed of two or more elements, with at least one being a metallic element. Metals and alloys can be divided into two basic groups: (1) ferrous and (2) nonferrous.

Ferrous Metals Ferrous metals are based on iron; the group includes steel and cast iron. These metals constitute the most important group commercially, more than three fourths of the metal tonnage throughout the world. Pure iron has limited commercial use, but when alloyed with carbon, iron has more uses and greater commercial value than any other metal. Alloys of iron and carbon form steel and cast iron.

Steel can be defined as an iron–carbon alloy containing 0.02% to 2.11% carbon. It is the most important category within the ferrous metal group. Its composition often includes other alloying elements as well, such as manganese, chromium, nickel, and molybdenum, to enhance the properties of the metal. Applications of steel include construction (bridges, I-beams, and nails), transportation (trucks, rails, and rolling stock for railroads), and consumer products (automobiles and appliances).

Cast iron is an alloy of iron and carbon (2% to 4%) used in casting (primarily sand casting). Silicon is also present in the alloy (in amounts from 0.5% to 3%), and other elements are often added also, to obtain desirable properties in the cast part. Cast iron is available in several different forms, of which gray cast iron is the most common; its applications include blocks and heads for internal combustion engines.

Nonferrous Metals Nonferrous metals include the other metallic elements and their alloys. In almost all cases, the alloys are more important commercially than the pure metals. The nonferrous metals include the pure metals and alloys of aluminum, copper, gold, magnesium, nickel, silver, tin, titanium, zinc, and other metals.

1.2.2 CERAMICS

A ***ceramic*** is defined as a compound containing metallic (or semimetallic) and nonmetallic elements. Typical nonmetallic elements are oxygen, nitrogen, and carbon. Ceramics include a variety of traditional and modern materials. Traditional ceramics, some of which have been used for thousands of years, include: ***clay*** (abundantly available, consisting of fine particles of hydrous aluminum silicates and other minerals used in making brick, tile, and pottery); ***silica*** (the basis for nearly all glass products); and ***alumina*** and ***silicon carbide*** (two abrasive materials used in grinding). Modern ceramics include some of the preceding materials, such as alumina, whose properties are enhanced in various ways through modern processing methods. Newer ceramics include: ***carbides***—metal carbides such as tungsten carbide and titanium carbide, which are widely used as cutting tool materials; and ***nitrides***—metal and semimetal nitrides such as titanium nitride and boron nitride, used as cutting tools and grinding abrasives.

For processing purposes, ceramics can be divided into crystalline ceramics and glasses. Different methods of manufacturing are required for the two types. Crystalline ceramics are formed in various ways from powders and then fired (heated to a temperature below the melting point to achieve bonding between the powders). The glass ceramics (namely, glass) can be melted and cast, and then formed in processes such as traditional glass blowing.

1.2.3 POLYMERS

A ***polymer*** is a compound formed of repeating structural units called ***mers,*** whose atoms share electrons to form very large molecules. Polymers usually consist of carbon plus one or more other elements, such as hydrogen, nitrogen, oxygen, and chlorine. Polymers are divided into three categories: (1) thermoplastic polymers, (2) thermosetting polymers, and (3) elastomers.

Thermoplastic polymers can be subjected to multiple heating and cooling cycles without substantially altering the molecular structure of the polymer. Common thermoplastics include polyethylene, polystyrene, polyvinylchloride, and nylon. ***Thermosetting polymers*** chemically transform (cure) into a rigid structure on cooling from a heated plastic condition; hence the name thermosetting. Members of this type include phenolics, amino resins, and epoxies. Although the name thermosetting is used, some of these polymers cure by mechanisms other than heating. ***Elastomers*** are polymers that exhibit significant elastic behavior; hence the name elastomer. They include natural rubber, neoprene, silicone, and polyurethane.

1.2.4 COMPOSITES

Composites do not really constitute a separate category of materials; they are mixtures of the other three types. A ***composite*** is a material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to those of its constituents. The term ***phase*** refers to a homogeneous mass of material, such as an aggregation of grains of identical unit cell structure in a solid metal. The usual structure of a composite consists of particles or fibers of one phase mixed in a second phase, called the ***matrix.***

Composites are found in nature (e.g., wood), and they can be produced synthetically. The synthesized type is of greater interest here, and it includes glass fibers in a polymer matrix, such as fiber-reinforced plastic; polymer fibers of one type in a matrix of a second polymer, such as an epoxy-Kevlar composite; and ceramic in a metal matrix, such as a tungsten carbide in a cobalt binder to form a cemented carbide cutting tool.

Properties of a composite depend on its components, the physical shapes of the components, and the way they are combined to form the final material. Some composites combine high strength with light weight and are suited to applications such as aircraft components, car bodies, boat hulls, tennis rackets, and fishing rods. Other composites are strong, hard, and capable of maintaining these properties at elevated temperatures, for example, cemented carbide cutting tools.

1.3 MANUFACTURING PROCESSES

A ***manufacturing process*** is a designed procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. A manufacturing process is usually carried out as a ***unit operation*** **,** which means that it is a single step in the sequence of steps required to transform the starting material into a final product. Manufacturing operations can be divided into two basic types: (1) processing operations and (2) assembly operations. A ***processing operation*** transforms a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete workparts, but certain processing operations are also applicable to assembled items (e.g., painting a spot-welded car body). An ***assembly operation*** joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process (e.g., a welded assembly is called a ***weldment***). A classification of manufacturing processes is presented in Figure 1.4. Many of the manufacturing processes covered in this text can be viewed on the DVD that comes with this book. Alerts are provided on these video clips throughout the text. Some of the basic processes used in modern manufacturing date from antiquity (Historical Note 1.2).

1.3.1 PROCESSING OPERATIONS

A processing operation uses energy to alter a workpart's shape, physical properties, or appearance to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but the human workers are generally employed to control the machines, oversee the operations, and load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 1.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed workpart exits the process. Most production operations produce waste or scrap, either as a natural aspect of the process (e.g., removing material, as in machining) or in the form of occasional defective pieces. It is an important objective in manufacturing to reduce waste in either of these forms.

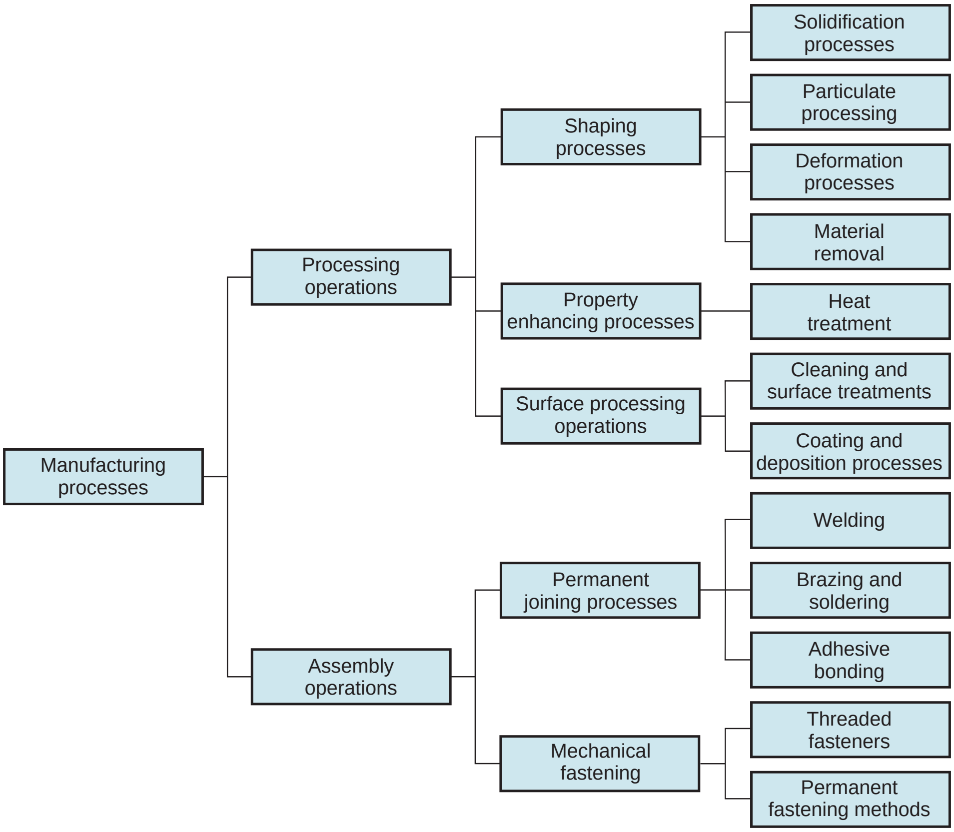

FIGURE 1.4 Classification of manufacturing processes.

Historical Note 1.2 *Manufacturing materials and processes*

Although most of the historical developments that form the modern practice of manufacturing have occurred only during the last few centuries (Historical Note 1.1), several of the basic fabrication processes date as far back as the Neolithic period (circa 8000–3000 BCE.). It was during this period that processes such as the following were developed: carving and other ***woodworking,*** hand forming and ***firing*** of clay pottery, ***grinding*** and ***polishing*** of stone, ***spinning*** and ***weaving*** of textiles, and ***dyeing*** of cloth.

Metallurgy and metalworking also began during the Neolithic period, in Mesopotamia and other areas around the Mediterranean. It either spread to, or developed independently in, regions of Europe and Asia. Gold was found by early humans in relatively pure form in nature; it could be ***hammered*** into shape. Copper was probably the first metal to be extracted from ores, thus requiring ***smelting*** as a processing technique. Copper could not be hammered readily because it strain hardened; instead, it was shaped by ***casting*** (Historical Note 10.1). Other metals used during this period were silver and tin. It was discovered that copper alloyed with tin produced a more workable metal than copper alone (casting and hammering could both be used). This heralded the important period known as the ***Bronze Age*** (circa 3500–1500 BCE.).

Iron was also first smelted during the Bronze Age. Meteorites may have been one source of the metal, but iron ore was also mined. Temperatures required to reduce iron ore to metal are significantly higher than for copper, which made furnace operations more difficult. Other processing methods were also more difficult for the same reason. Early blacksmiths learned that when certain irons (those containing small amounts of carbon) were sufficiently ***heated*** and then ***quenched,*** they became very hard. This permitted grinding a very sharp cutting edge on knives and weapons, but it also made the metal brittle. Toughness could be increased by reheating at a lower temperature, a process known as ***tempering.***

What we have described is, of course, the ***heat treatment*** of steel. The superior properties of steel caused it to succeed bronze in many applications (weaponry, agriculture, and mechanical devices). The period of its use has subsequently been named the ***Iron Age*** (starting around 1000 BCE.). It was not until much later, well into the nineteenth century, that the demand for steel grew significantly and more modern steelmaking techniques were developed (Historical Note 6.1).

The beginnings of machine tool technology occurred during the Industrial Revolution. During the period 1770–1850, machine tools were developed for most of the conventional ***material removal processes,*** such as ***boring, turning, drilling, milling, shaping,*** and ***planing*** (Historical Note 22.1). Many of the individual processes predate the machine tools by centuries; for example, drilling and sawing (of wood) date from ancient times, and turning (of wood) from around the time of Christ.

Assembly methods were used in ancient cultures to make ships, weapons, tools, farm implements, machinery, chariots and carts, furniture, and garments. The earliest processes included ***binding*** with twine and rope, ***riveting*** and ***nailing,*** and ***soldering.*** Around 2000 years ago, ***forge welding*** and ***adhesive bonding*** were developed. Widespread use of screws, bolts, and nuts as fasteners—so common in today's assembly—required the development of machine tools that could accurately cut the required helical shapes (e.g., Maudsley's screw cutting lathe, 1800). It was not until around 1900 that ***fusion welding*** processes started to be developed as assembly techniques (Historical Note 29.1).

Natural rubber was the first polymer to be used in manufacturing (if we overlook wood, which is a polymer composite). The ***vulcanization*** process, discovered by Charles Goodyear in 1839, made rubber a useful engineering material (Historical Note 8.2). Subsequent developments included plastics such as cellulose nitrate in 1870, Bakelite in 1900, polyvinylchloride in 1927, polyethylene in 1932, and nylon in the late 1930s (Historical Note 8.1). Processing requirements for plastics led to the development of ***injection molding*** (based on die casting, one of the metal casting processes) and other polymer-shaping techniques.

Electronics products have imposed unusual demands on manufacturing in terms of miniaturization. The evolution of the technology has been to package more and more devices into smaller and smaller areas—in some cases millions of transistors onto a flat piece of semiconductor material that is only 12 mm (0.50 in.) on a side. The history of electronics processing and packaging dates from only a few decades (Historical Notes 34.1, 35.1, and 35.2).

More than one processing operation is usually required to transform the starting material into final form. The operations are performed in the particular sequence required to achieve the geometry and condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations, (2) property-enhancing operations, and (3) surface processing operations. ***Shaping operations*** alter the geometry of the starting work material by various methods. Common shaping processes include casting, forging, and machining. ***Property-enhancing operations*** add value to the material by improving its physical properties without changing its shape. Heat treatment is the most common example. ***Surface processing operations*** are performed to clean, treat, coat, or deposit material onto the exterior surface of the work. Common examples of coating are plating and painting. Shaping processes are covered in Parts III through VI, corresponding to the four main categories of shaping processes in Figure 1.4. Property-enhancing processes and surface processing operations are covered in Part VII.

Shaping Processes Most shape processing operations apply heat, mechanical force, or a combination of these to effect a change in geometry of the work material. There are various ways to classify the shaping processes. The classification used in this book is based on the state of the starting material, by which we have four categories: (1) ***solidification processes,*** in which the starting material is a heated ***liquid*** or ***semifluid*** that cools and solidifies to form the part geometry; (2) ***particulate processing,*** in which the starting material is a ***powder,*** and the powders are formed and heated into the desired geometry; (3) ***deformation processes,*** in which the starting material is a ***ductile solid*** (commonly metal) that is deformed to shape the part; and (4) ***material removal processes,*** in which

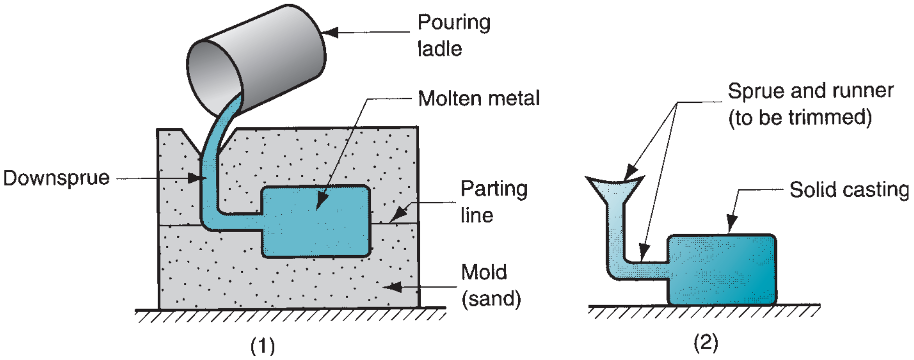

FIGURE 1.5 Casting and molding processes start with a work material heated to a fluid or semifluid state. The process consists of: (1) pouring the fluid into a mold cavity and (2) allowing the fluid to solidify, after which the solid part is removed from the mold.

the starting material is a ***solid*** (ductile or brittle), from which material is removed so that the resulting part has the desired geometry.

In the first category, the starting material is heated sufficiently to transform it into a liquid or highly plastic (semifluid) state. Nearly all materials can be processed in this way. Metals, ceramic glasses, and plastics can all be heated to sufficiently high temperatures to convert them into liquids. With the material in a liquid or semifluid form, it can be poured or otherwise forced to flow into a mold cavity and allowed to solidify, thus taking a solid shape that is the same as the cavity. Most processes that operate this way are called casting or molding. ***Casting*** is the name used for metals, and ***molding*** is the common term used for plastics. This category of shaping process is depicted in Figure 1.5.

In ***particulate processing,*** the starting materials are powders of metals or ceramics. Although these two materials are quite different, the processes to shape them in particulate processing are quite similar. The common technique involves pressing and sintering, illustrated in Figure 1.6, in which the powders are first squeezed into a die cavity under high pressure and then heated to bond the individual particles together.

In ***deformation processes,*** the starting workpart is shaped by the application of forces that exceed the yield strength of the material. For the material to be formed in this way, it must be sufficiently ductile to avoid fracture during deformation. To increase ductility (and for other reasons), the work material is often heated before forming to a temperature below the melting point. Deformation processes are associated most closely with metalworking and include operations such as ***forging*** and ***extrusion,*** shown in Figure 1.7.

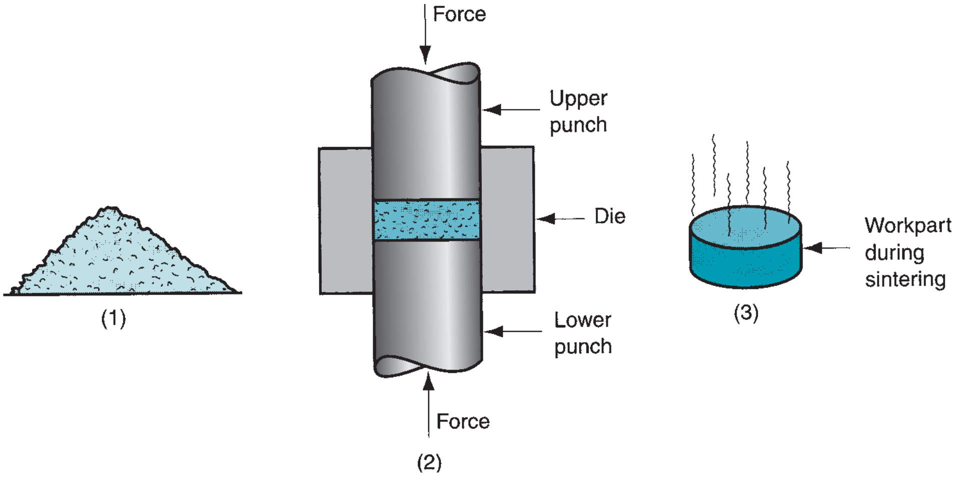

FIGURE 1.6 Particulate processing: (1) the starting material is powder; the usual process consists of (2) pressing and (3) sintering.

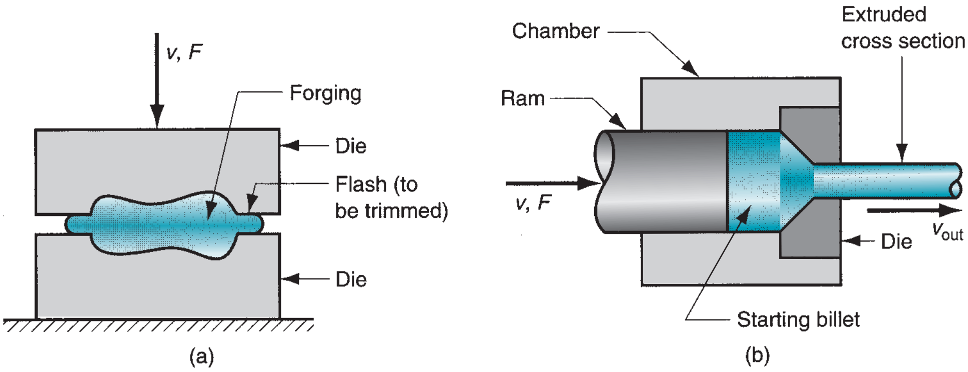

FIGURE 1.7 Some common deformation processes: (a) **forging**, in which two halves of a die squeeze the workpart, causing it to assume the shape of the die cavity; and (b) **extrusion**, in which a billet is forced to flow through a die orifice, thus taking the cross-sectional shape of the orifice.

Material removal processes are operations that remove excess material from the starting workpiece so that the resulting shape is the desired geometry. The most important processes in this category are ***machining*** operations such as ***turning, drilling,*** and ***milling,*** shown in Figure 1.8. These cutting operations are most commonly applied to solid metals, performed using cutting tools that are harder and stronger than the work metal. ***Grinding*** is another common process in this category. Other material removal processes are known as ***nontraditional processes*** because they use lasers, electron beams, chemical erosion, electric discharges, and electrochemical energy to remove material rather than cutting or grinding tools.

It is desirable to minimize waste and scrap in converting a starting workpart into its subsequent geometry. Certain shaping processes are more efficient than others in terms of material conservation. Material removal processes (e.g., machining) tend to be wasteful of material, simply by the way they work. The material removed from the starting shape is waste, at least in terms of the unit operation. Other processes, such as certain casting and molding operations, often convert close to 100% of the starting material into final product. Manufacturing processes that transform nearly all of the starting material into product and require no subsequent machining to achieve final part geometry are called ***net shape processes.*** Other processes require minimum machining to produce the final shape and are called ***near net shape processes.***

Property-Enhancing Processes The second major type of part processing is performed to improve mechanical or physical properties of the work material. These processes do not alter the shape of the part, except unintentionally in some cases. The most important property-enhancing processes involve ***heat treatments,*** which include various annealing

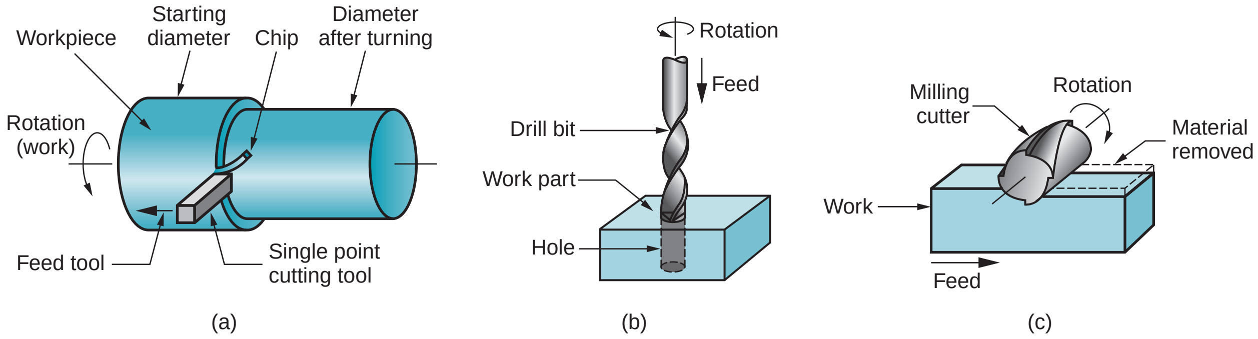

FIGURE 1.8 Common machining operations: (a) ***turning,*** in which a single-point cutting tool removes metal from a rotating workpiece to reduce its diameter; (b) ***drilling,*** in which a rotating drill bit is fed into the work to create a round hole; and (c) ***milling,*** in which a workpart is fed past a rotating cutter with multiple edges.

and strengthening processes for metals and glasses. ***Sintering*** of powdered metals and ceramics is also a heat treatment that strengthens a pressed powder metal workpart.

Surface Processing Surface processing operations include (1) cleaning, (2) surface treatments, and (3) coating and thin film deposition processes. ***Cleaning*** includes both chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface. ***Surface treatments*** include mechanical working such as shot peening and sand blasting, and physical processes such as diffusion and ion implantation. ***Coating*** and ***thin film deposition*** processes apply a coating of material to the exterior surface of the workpart. Common coating processes include ***electroplating, anodizing*** of aluminum, organic ***coating*** (call it ***painting***), and porcelain enameling. Thin film deposition processes include ***physical vapor deposition*** and ***chemical vapor deposition*** to form extremely thin coatings of various substances.

Several surface-processing operations have been adapted to fabricate semiconductor materials into integrated circuits for microelectronics. These processes include chemical vapor deposition, physical vapor deposition, and oxidation. They are applied to very localized areas on the surface of a thin wafer of silicon (or other semiconductor material) to create the microscopic circuit.

1.3.2 ASSEMBLY OPERATIONS

The second basic type of manufacturing operation is ***assembly,*** in which two or more separate parts are joined to form a new entity. Components of the new entity are connected either permanently or semipermanently. Permanent joining processes include ***welding, brazing, soldering,*** and ***adhesive bonding.*** They form a joint between components that cannot be easily disconnected. Certain ***mechanical assembly*** methods are available to fasten two (or more) parts together in a joint that can be conveniently disassembled. The use of screws, bolts, and other ***threaded fasteners*** are important traditional methods in this category. Other mechanical assembly techniques form a more permanent connection; these include ***rivets, press fitting,*** and ***expansion fits.*** Special joining and fastening methods are used in the assembly of electronic products. Some of the methods are identical to or are adaptations of the preceding processes, for example, soldering. Electronics assembly is concerned primarily with the assembly of components such as integrated circuit packages to printed circuit boards to produce the complex circuits used in so many of today's products. Joining and assembly processes are discussed in Part VIII, and the specialized assembly techniques for electronics are described in Part IX.

1.3.3 PRODUCTION MACHINES AND TOOLING

Manufacturing operations are accomplished using machinery and tooling (and people). The extensive use of machinery in manufacturing began with the Industrial Revolution. It was at that time that metal cutting machines started to be developed and widely used. These were called ***machine tools***—power-driven machines used to operate cutting tools previously operated by hand. Modern machine tools are described by the same basic definition, except that the power is electrical rather than water or steam, and the level of precision and automation is much greater today. Machine tools are among the most versatile of all production machines. They are used to make not only parts for consumer products, but also components for other production machines. Both in a historic and a reproductive sense, the machine tool is the mother of all machinery.

Other production machines include ***presses*** for stamping operations, ***forge hammers*** for forging, ***rolling mills*** for rolling sheet metal, ***welding machines*** for welding, and ***insertion machines*** for inserting electronic components into printed circuit boards. The name of the equipment usually follows from the name of the process.

TABLE 1.3 Production equipment and tooling used for various manufacturing processes.

Process	Equipment	Special Tooling (Function)
Casting	[a]	Mold (cavity for molten metal)
Molding	Molding machine	Mold (cavity for hot polymer)
Rolling	Rolling mill	Roll (reduce work thickness)
Forging	Forge hammer or press	Die (squeeze work to shape)
Extrusion	Press	Extrusion die (reduce cross-section)
Stamping	Press	Die (shearing, forming sheet metal)
Machining	Machine tool	Cutting tool (material removal) Fixture (hold workpart) Jig (hold part and guide tool)
Grinding	Grinding machine	Grinding wheel (material removal)
Welding	Welding machine	Electrode (fusion of work metal) Fixture (hold parts during welding)

[a] Various types of casting setups and equipment (Chapter 11).

Production equipment can be general purpose or special purpose. ***General purpose equipment*** is more flexible and adaptable to a variety of jobs. It is commercially available for any manufacturing company to invest in. ***Special purpose equipment*** is usually designed to produce a specific part or product in very large quantities. The economics of mass production justify large investments in special purpose machinery to achieve high efficiencies and short cycle times. This is not the only reason for special purpose equipment, but it is the dominant one. Another reason may be because the process is unique and commercial equipment is not available. Some companies with unique processing requirements develop their own special purpose equipment.

Production machinery usually requires ***tooling*** that customizes the equipment for the particular part or product. In many cases, the tooling must be designed specifically for the part or product configuration. When used with general purpose equipment, it is designed to be exchanged. For each workpart type, the tooling is fastened to the machine and the production run is made. When the run is completed, the tooling is changed for the next workpart type. When used with special purpose machines, the tooling is often designed as an integral part of the machine. Because the special purpose machine is likely being used for mass production, the tooling may never need changing except for replacement of worn components or for repair of worn surfaces.

The type of tooling depends on the type of manufacturing process. Table 1.3 lists examples of special tooling used in various operations. Details are provided in the chapters that discuss these processes.

1.4 PRODUCTION SYSTEMS

To operate effectively, a manufacturing firm must have systems that allow it to efficiently accomplish its type of production. Production systems consist of people, equipment, and procedures designed for the combination of materials and processes that constitute a firm's manufacturing operations. Production systems can be divided into two categories: (1) production facilities and (2) manufacturing support systems, as shown in Figure 1.10. ***Production facilities*** refer to the physical equipment and the arrangement of equipment in the factory. ***Manufacturing support systems*** are the procedures used by the company to manage production and solve the technical and logistics problems encountered in ordering materials, moving work through the factory, and ensuring that products meet quality standards. Both categories include people. People make these systems work. In general, direct labor workers are responsible for operating the manufacturing equipment; and professional staff workers are responsible for manufacturing support.

1.4.1 PRODUCTION FACILITIES

Production facilities consist of the factory and the production, material handling, and other equipment in the factory. The equipment comes in direct physical contact with the parts and/or assemblies as they are being made. The facilities "touch" the product. Facilities also include the way the equipment is arranged in the factory—the ***plant layout.*** The equipment is usually organized into logical groupings; which can be called ***manufacturing systems,*** such as an automated production line, or a machine cell consisting of an industrial robot and two machine tools.

A manufacturing company attempts to design its manufacturing systems and organize its factories to serve the particular mission of each plant in the most efficient way. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given combination of product variety and production quantity, as discussed in Section 1.1.2. Different types of facilities are required for each of the three ranges of annual production quantities.

Low-Quantity Production In the low-quantity range (1–100 units/year), the term ***job shop*** is often used to describe the type of production facility. A job shop makes low quantities of specialized and customized products. The products are typically complex, such as space capsules, prototype aircraft, and special machinery. The equipment in a job shop is general purpose, and the labor force is highly skilled.

A job shop must be designed for maximum flexibility to deal with the wide product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move, it typically remains in a single location during its fabrication or assembly. Workers and processing equipment are brought to the product, rather than moving the product to the equipment. This type of layout is referred to as a ***fixed-position layout,*** shown in Figure 1.9(a). In a pure situation, the product remains in a single location during its entire production. Examples of such products include ships, aircraft, locomotives, and heavy machinery. In actual practice, these items are usually built in large modules at single locations, and then the completed modules are brought together for final assembly using large-capacity cranes.

The individual components of these large products are often made in factories in which the equipment is arranged according to function or type. This arrangement is called a ***process layout.*** The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.9(b). Different parts, each requiring a different operation sequence, are routed through the departments in the particular order needed for their processing, usually in batches. The process layout is noted for its flexibility; it can accommodate a great variety of operation sequences for different part configurations. Its disadvantage is that the machinery and methods to produce a part are not designed for high efficiency.

Medium Quantity Production In the medium-quantity range (100–10,000 units annually), two different types of facility are distinguished, depending on product variety. When product variety is hard, the usual approach is ***batch production,*** in which a batch of one product is made, after which the manufacturing equipment is changed over to produce a batch of the next product, and so on. The production rate of the equipment is greater than the demand rate for any single product type, and so the same equipment can be shared among multiple products. The changeover between production runs takes time—time to change tooling and set up the machinery. This setup time is lost production time, and this is a disadvantage of batch manufacturing. Batch production is commonly used for make-to-stock situations, in which

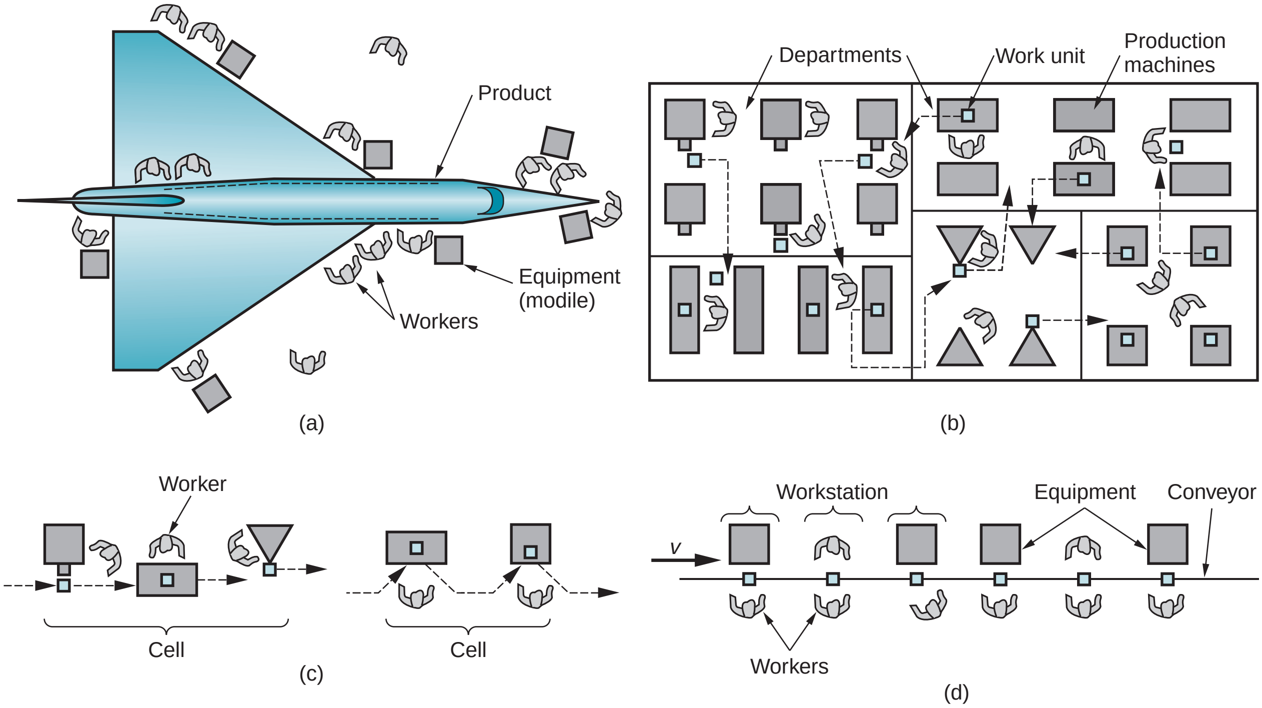

FIGURE 1.9 Various types of plant layout: (a) fixed-position layout, (b) process layout, (c) cellular layout, and (d) product layout.

items are manufactured to replenish inventory that has been gradually depleted by demand. The equipment is usually arranged in a process layout, as in Figure 1.9(b).

An alternative approach to medium-range production is possible if product variety is soft. In this case, extensive changeovers between one product style and the next may not be necessary. It is often possible to configure the manufacturing system so that groups of similar products can be made on the same equipment without significant lost time because of setup. The processing or assembly of different parts or products is accomplished in cells consisting of several workstations or machines. The term ***cellular manufacturing*** is often associated with this type of production. Each cell is designed to produce a limited variety of part configurations; that is, the cell specializes in the production of a given set of similar parts, according to the principles of ***group technology*** (Section 39.5). The layout is called a ***cellular layout***, depicted in Figure 1.9(c).

High Production The high-quantity range (10,000 to millions of units per year) is referred to as ***mass production.*** The situation is characterized by a high demand rate for the product, and the manufacturing system is dedicated to the production of that single item. Two categories of mass production can be distinguished: quantity production and flow line production. ***Quantity production*** involves the mass production of single parts on single pieces of equipment. It typically involves standard machines (e.g., stamping presses) equipped with special tooling (e.g., dies and material handling devices), in effect dedicating the equipment to the production of one part type. Typical layouts used in quantity production are the process layout and cellular layout.

Flow line production involves multiple pieces of equipment or workstations arranged in sequence, and the work units are physically moved through the sequence to complete the product. The workstations and equipment are designed specifically for the product to maximize efficiency. The layout is called a ***product layout,*** and the workstations are arranged into one long line, as in Figure 1.9(d), or into a series of connected line segments. The work is usually moved between stations by mechanized conveyor. At each station, a small amount of the total work is completed on each unit of product.

The most familiar example of flow line production is the assembly line, associated with products such as cars and household appliances. The pure case of flow line production occurs when there is no variation in the products made on the line. Every product is identical, and the line is referred to as a ***single model production line.*** To successfully market a given product, it is often beneficial to introduce feature and model variations so that individual customers can choose the exact merchandise that appeals to them. From a production viewpoint, the feature differences represent a case of soft product variety. The term ***mixed-model production line*** applies to situations in which there is soft variety in the products made on the line. Modern automobile assembly is an example. Cars coming off the assembly line have variations in options and trim representing different models and in many cases different nameplates of the same basic car design.

1.4.2 MANUFACTURING SUPPORT SYSTEMS

To operate its facilities efficiently, a company must organize itself to design the processes and equipment, plan and control the production orders, and satisfy product quality requirements. These functions are accomplished by manufacturing support systems—people and procedures by which a company manages its production operations. Most of these support systems do not directly contact the product, but they plan and control its progress through the factory. Manufacturing support functions are often carried out in the firm by people organized into departments such as the following:

- ***Manufacturing engineering.*** The manufacturing engineering department is responsible for planning the manufacturing processes—deciding what processes should be used to make the parts and assemble the products. This department is also involved in designing and ordering the machine tools and other equipment used by the operating departments to accomplish processing and assembly.
- ***Production planning and control.*** This department is responsible for solving the logistics problem in manufacturing—ordering materials and purchased parts, scheduling production, and making sure that the operating departments have the necessary capacity to meet the production schedules.
- ***Quality control.*** Producing high-quality products should be a top priority of any manufacturing firm in today's competitive environment. It means designing and

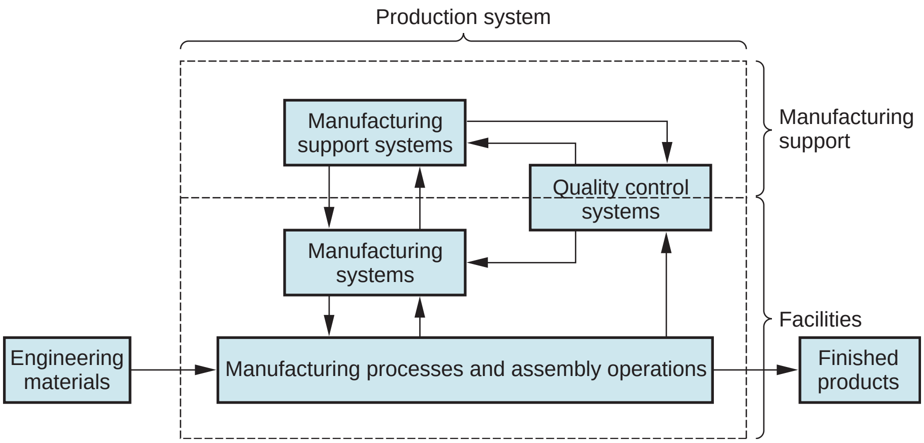

FIGURE 1.10 Overview of major topics covered in the book.

building products that conform to specifications and satisfy or exceed customer expectations. Much of this effort is the responsibility of the QC department.

1.5 TRENDS IN MANUFACTURING

This section considers several trends that are affecting the materials, processes, and systems used in manufacturing. These trends are motivated by technological and economic factors occurring throughout the world. Their effects are not limited to manufacturing; they impact society as a whole. The discussion is organized into the following topic areas: (1) lean production and Six Sigma, (2) globalization, (3) environmentally conscious manufacturing, and (4) microfabrication and nanotechnology.

1.5.1 LEAN PRODUCTION AND SIX SIGMA

These are two programs aimed at improving efficiency and quality in manufacturing. They address the demands by customers for the products they buy to be both low in cost and high in quality. The reason why lean and Six Sigma are trends is because they are being so widely adopted by companies, especially in the United States.

Lean production is based on the Toyota Production System developed by Toyota Motors in Japan. Its origins date from the 1950s, when Toyota began using unconventional methods to improve quality, reduce inventories, and increase flexibility in its operations. ***Lean production*** can be defined simply as "doing more work with fewer resources."[2] It means that fewer workers and less equipment are used to accomplish more production in less time, and yet achieve higher quality in the final product. The underlying objective of lean production is the elimination of waste. In the Toyota Production System, the seven forms of waste in production are (1) production of defective parts, (2) production of more parts than required, (3) excessive inventories, (4) unnecessary processing steps, (5) unnecessary movement of workers, (6) unnecessary movement and handling of materials, and (7) workers waiting. The methods used by Toyota to reduce waste include techniques for preventing errors, stopping a process when something goes wrong, improved equipment maintenance, involving workers in process improvements (so-called continuous improvement), and standardized work procedures. Probably the most important development was the just-in-time delivery system, which is described in Section 41.4 in the chapter on production and inventory control.

Six Sigma was started in the 1980s at Motorola Corporation in the United States. The objective was to reduce variability in the company's processes and products to increase customer satisfaction. Today, ***Six Sigma*** can be defined as "a quality-focused program that utilizes worker teams to accomplish projects aimed at improving an organization's operational performance."[3] Six Sigma is discussed in more detail in Section 42.4.2.

1.5.2 GLOBALIZATION AND OUTSOURCING

The world is becoming more and more integrated, creating an international economy in which barriers once established by national boundaries have been reduced or eliminated. This has enabled a freer flow of goods and services, capital, technology, and people among regions and countries. ***Globalization*** is the term that describes this trend, which was recognized in the late 1980s and is now a dominant economic reality. Of interest here is that once underdeveloped

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[2] M. P. Groover, ***Work Systems and the Methods, Measurement, and Management of Work*** [7], p. 514. The term ***lean production*** was coined by researchers at the Massachusetts Institute of Technology who studied the production operations at Toyota and other automobile companies in the 1980s.

[3] Ibid, p. 541.

nations such as China, India, and Mexico have developed their manufacturing infrastructures and technologies to a point where they are now important producers in the global economy. The advantages of these three countries in particular are their large populations (therefore, large workforce pool) and low labor costs. Hourly wages are currently an order of magnitude or more higher in the United States than in these countries, making it difficult for domestic U.S. companies to compete in many products requiring a high labor content. Examples include garments, furniture, many types of toys, and electronic gear. The result has been a loss of manufacturing jobs in the United States and a gain of related work to these countries.

Globalization is closely related to outsourcing. In manufacturing, ***outsourcing*** refers to the use of outside contractors to perform work that was traditionally accomplished in-house. Outsourcing can be done in several ways, including the use of local suppliers. In this case the jobs remain in the United States. Alternatively, U.S. companies can outsource to foreign countries, so that parts and products once made in the United States are now made outside the country. In this case U.S. jobs are displaced. Two possibilities can be distinguished: (1) ***offshore outsourcing,*** which refers to production in China or other overseas locations and transporting the items by cargo ship to the United States, and (2) ***near-shore outsourcing,*** which means the items are made in Canada, Mexico, or Central America and shipped by rail or truck into the United States.

China is a country of particular interest in this discussion of globalization because of its fast-growing economy, the importance of manufacturing in that economy, and the extent to which U.S. companies have outsourced work to China. To take advantage of the low labor rates, U.S. companies have outsourced much of their production to China (and other east Asian countries). Despite the logistics problems and costs of shipping the goods back into the United States, the result has been lower costs and higher profits for the outsourcing companies, as well as lower prices and a wider variety of available products for U.S. consumers. The downside has been the loss of well-paying manufacturing jobs in the United States. Another consequence of U.S. outsourcing to China has been a reduction in the relative contribution of the manufacturing sector to GDP. In the 1990s, the manufacturing industries accounted for about 20% of GDP in the United States. Today that contribution is less than 15%. At the same time, the manufacturing sector in China has grown (along with the rest of its economy), now accounting for almost 35% of Chinese GDP. Because the U.S. GDP is roughly three times China's, the United States' manufacturing sector is still larger. However, China is the world leader in several industries. Its tonnage output of steel is greater than the combined outputs of the next six largest steel producing nations (in order, Japan, United States, Russia, India, South Korea, and Germany).[4] China is also the largest producer of metal castings, accounting for more tonnage than the next three largest producers (in order, United States, Japan, and India) [5].

Steel production and casting are considered "dirty" industries, and environmental pollution is an issue not only in China, but in many places throughout the World. This issue is addressed in the next trend.

1.5.3 ENVIRONMENTALLY CONSCIOUS MANUFACTURING

An inherent feature of virtually all manufacturing processes is waste (Section 1.3.1). The most obvious examples are material removal processes, in which chips are removed from a starting workpiece to create the desired part geometry. Waste in one form or another is a by-product of nearly all production operations. Another unavoidable aspect of manufacturing is that power is required to accomplish any given process. Generating that power requires fossil fuels (at least in the United States and China), the burning of which results in pollution of the environment. At the end of the manufacturing sequence, a product is created that is sold to a

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[4] Source: World Steel Association, 2008 data.

customer. Ultimately, the product wears out and is disposed of, perhaps in some landfill, with the associated environmental degradation. More and more attention is being paid by society to the environmental impact of human activities throughout the world and how modern civilization is using our natural resources at an unsustainable rate. Global warming is presently a major concern. The manufacturing industries contribute to these problems.

Environmentally conscious manufacturing refers to programs that seek to determine the most efficient use of materials and natural resources in production, and minimize the negative consequences on the environment. Other associated terms for these programs include ***green manufacturing, cleaner production,*** and ***sustainable manufacturing***. They all boil down to two basic approaches: (1) design products that minimize their environmental impact, and (2) design processes that are environmentally friendly.

Product design is the logical starting point in environmentally conscious manufacturing. The term ***design for environment*** (DFE) is sometimes used for the techniques that attempt to consider environmental impact during product design prior to production. Considerations in DFE include the following: (1) select materials that require minimum energy to produce, (2) select processes that minimize waste of materials and energy, (3) design parts that can be recycled or reused, (4) design products that can be readily disassembled to recover the parts, (5) design products that minimize the use of hazardous and toxic materials, and (6) give attention to how the product will be disposed of at the end of its useful life.

To a great degree, decisions made during design dictate the materials and processes that are used to make the product. These decisions limit the options available to the manufacturing departments to achieve sustainability. However, various approaches can be applied to make plant operations more environmentally friendly. They include the following: (1) adopt good housekeeping practices—keep the factory clean, (2) prevent pollutants from escaping into the environment (rivers and atmosphere), (3) minimize waste of materials in unit operations, (4) recycle rather than discard waste materials, (5) use net shape processes, (6) use renewable energy sources when feasible, (7) provide maintenance to production equipment so that it operates at maximum efficiency, and (8) invest in equipment that minimizes power requirements.

Various topics related to environmentally conscious manufacturing are discussed in the text. The topics of polymer recycling and biodegradable plastics are covered in Section 8.5. Cutting fluid filtration and dry machining, which reduce the adverse effects of contaminated cutting fluids, are considered in Section 23.4.2.

1.5.4 MICROFABRICATION AND NANOTECHNOLOGY

Another trend in manufacturing is the emergence of materials and products whose dimensions are sometimes so small that they cannot be seen by the naked eye. In extreme cases, the items cannot even be seen under an optical microscope. Products that are so miniaturized require special fabrication technologies. ***Microfabrication*** refers to the processes needed to make parts and products whose features sizes are in the micrometer range $\left(1\ \mu\text{m} = 10^{-3}\ \text{mm} = 10^{-6}\ \text{m}\right)$. Examples include ink-jet printing heads, compact discs (CDs and DVDs), and microsensors used in automotive applications (e.g., air-bag deployment sensors). ***Nanotechnology*** refers to materials and products whose feature sizes are in the nanometer scale $\left(1\ \text{nm} = 10^{-3}\ \mu\text{m} = 10^{-6}\ \text{mm} = 10^{-9}\ \text{m}\right)$, a scale that approaches the size of atoms and molecules. Ultra-thin coatings for catalytic converters, flat screen TV monitors, and cancer drugs are examples of products based on nanotechnology. Microscopic and nanoscopic materials and products are expected to increase in importance in the future, both technologically and economically, and processes are needed to produce them commercially. The purpose here is to make the reader aware of this trend toward miniaturization. Chapters 36 and 37 are devoted to these technologies.

1.6 ORGANIZATION OF THE BOOK

The preceding sections provide an overview of the book. The remaining 41 chapters are organized into 11 parts. The block diagram in previous Figure 1.10 summarizes the major topics that are covered. It shows the production system (outlined in dashed lines) with engineering materials entering from the left and finished products exiting at the right. Part I, Material Properties and Product Attributes, consists of four chapters that describe the important characteristics and specifications of materials and the products made from them. Part II discusses the four basic engineering materials: metals, ceramics, polymers, and composites.

The largest block in Figure 1.10 is labeled "Manufacturing processes and assembly operations." The processes and operations included in the text are those identified in Figure 1.4. Part III begins the coverage of the four categories of shaping processes. Part III consists of six chapters on the solidification processes that include casting of metals, glassworking, and polymer shaping. In Part IV, the particulate processing of metals and ceramics is covered in two chapters. Part V deals with metal deformation processes such as rolling, forging, extrusion, and sheet metalworking. Finally, Part VI discusses the material removal processes. Four chapters are devoted to machining, and two chapters cover grinding (and related abrasive processes) and the nontraditional material removal technologies.

The other types of processing operations, property enhancing and surface processing, are covered in two chapters in Part VII. Property enhancing is accomplished by heat treatment, and surface processing includes operations such as cleaning, electroplating, and coating (painting).

Joining and assembly processes are considered in Part VIII, which is organized into four chapters on welding, brazing, soldering, adhesive bonding, and mechanical assembly.

Several unique processes that do not neatly fit into the classification scheme of Figure 1.4 are covered in Part IX, Special Processing and Assembly Technologies. Its five chapters cover rapid prototyping, processing of integrated circuits, electronics, microfabrication, and nanofabrication.

The remaining blocks in Figure 1.10 deal with the systems of production. Part X, "Manufacturing Systems," covers the major systems technologies and equipment groupings located in the factory: numerical control, industrial robotics, group technology, cellular manufacturing, flexible manufacturing systems, and production lines. Finally, Part XI deals with manufacturing support systems: manufacturing engineering, production planning and control, and quality control and inspection.

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[11] wikipedia.org/wiki/globalization

[12] www.bsdglobal.com/tools

REVIEW QUESTIONS

1.1. What are the differences among primary, secondary, and tertiary industries? Give an example of each category.

1.2. What is a capital good? Provide an example.

1.3. How are product variety and production quantity related when comparing typical factories?

1.4. Define manufacturing capability.

1.5. Name the three basic categories of materials.

1.6. How does a shaping process differ from a surface processing operation?

1.7. What are two subclasses of assembly processes? Provide an example process for each subclass.

1.8. Define batch production and describe why it is often used for medium-quantity production products.

1.9. What is the difference between a process layout and a product layout in a production facility?

1.10. Name two departments that are typically classified as manufacturing support departments.

MULTIPLE CHOICE QUIZ

There are 18 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

1.1. Which of the following industries are classified as secondary industries (three correct answers): (a) beverages (b) financial services, (c) fishing, (d) mining, (e) power utilities, (f) publishing, and, (g) transportation?

1.2. Mining is classified in which one of the following industry categories: (a) agricultural industry, (b) manufacturing industry, (c) primary industry, (d) secondary industry, (e) service industry, or, (f) tertiary industry?

1.3. Inventions of the Industrial Revolution include which one of the following: (a) automobile, (b) cannon, (c) printing press, (d) steam engine, or, (e) sword?

1.4. Ferrous metals include which of the following (two correct answers): (a) aluminum, (b) cast iron, (c) copper, (d) gold, and, (e) steel?

1.5. Which one of the following engineering materials is defined as a compound containing metallic and nonmetallic elements: (a) ceramic, (b) composite, (c) metal, or, (d) polymer?

1.6. Which of the following processes start with a material that is in a fluid or semifluid state and solidifies the material in a cavity (two best answers): (a) casting, (b) forging, (c) machining, (d) molding, (e) pressing, and, (f) turning?

1.7. Particulate processing of metals and ceramics involves which of the following steps (two best answers): (a) adhesive bonding, (b) deformation, (c) forging, (d) material removal, (e) melting, (f) pressing, and, (g) sintering?

1.8. Deformation processes include which of the following (two correct answers): (a) casting, (b) drilling, (c) extrusion, (d) forging, (e) milling, (f) painting, and, (g) sintering?

1.9. Which one of the following is a machine used to perform extrusion: (a) forge hammer, (b) milling machine, (c) rolling mill, (d) press, (e) torch?

1.10. High-volume production of assembled products is most closely associated with which one of the following layout types: (a) cellular layout, (b) fixed position layout, (c) process layout, or, (d) product layout?

1.11. A production planning and control department accomplishes which of the following functions in its role of providing manufacturing support (two best answers): (a) designs and orders machine tools, (b) develops corporate strategic plans, (c) orders materials and purchased parts, (d) performs quality inspections, and, (e) schedules the order of products on a machine?

Part I Material Properties and Product Attributes

2

THE NATURE OF MATERIALS

Chapter Contents

An understanding of materials is fundamental in the study of manufacturing processes. In Chapter 1, manufacturing was defined as a transformation process. It is the material that is transformed; and it is the behavior of the material when subjected to the particular forces, temperatures, and other physical parameters of the process that determines the success of the operation. Certain materials respond well to certain types of manufacturing processes, and poorly or not at all to others. What are the characteristics and properties of materials that determine their capacity to be transformed by the different processes?

Part I of this book consists of four chapters that address this question. The current chapter considers the atomic structure of matter and the bonding between atoms and molecules. It also shows how atoms and molecules in engineering materials organize themselves into two structural forms: crystalline and noncrystalline. It turns out that the basic engineering materials—metals, ceramics, and polymers—can exist in either form, although a preference for a particular form is usually exhibited by a given material. For example, metals almost always exist as crystals in their solid state. Glass (e.g., window glass), a ceramic, assumes a noncrystalline form. Some polymers are mixtures of crystalline and amorphous structures.

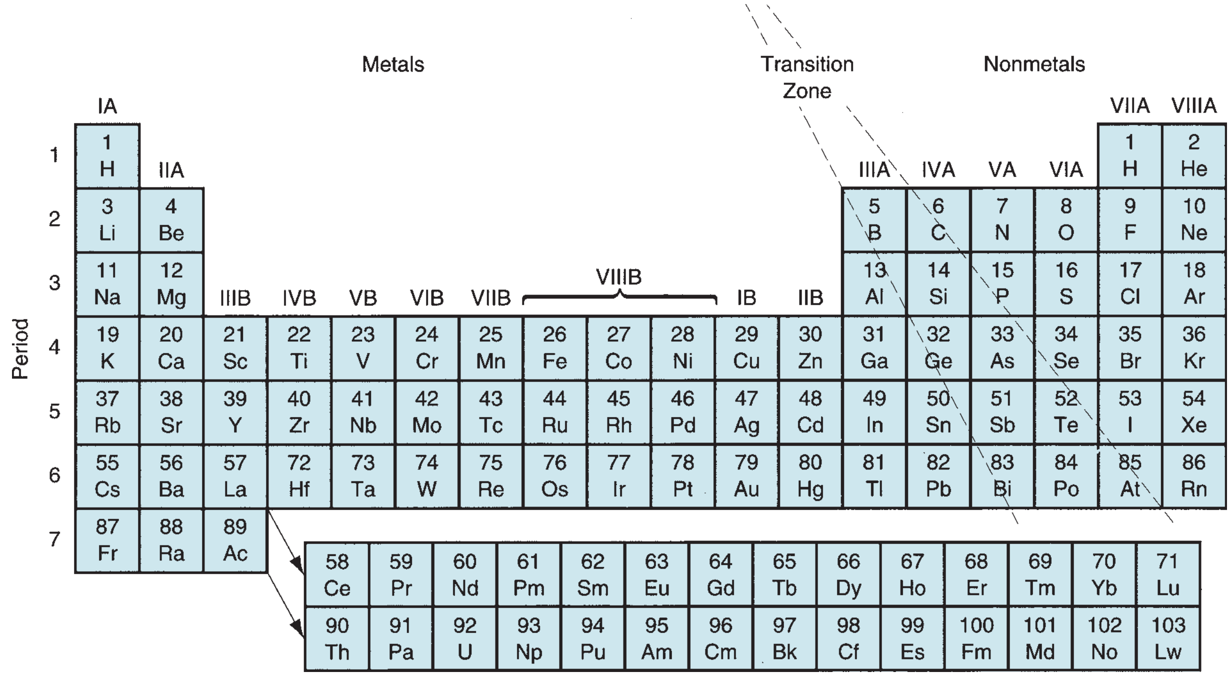
Chapters 3 and 4 discuss the mechanical and physical properties that are relevant in manufacturing. Of course, these properties are also important in product design. Chapter 5 is concerned with several part and product attributes that are specified during product design and must be achieved in manufacturing: dimensions, tolerances, and surface finish. Chapter 5 also describes how these attributes are measured.

2.1 ATOMIC STRUCTURE AND THE ELEMENTS

The basic structural unit of matter is the atom. Each atom is composed of a positively charged nucleus, surrounded by a sufficient number of negatively charged electrons so that the charges are balanced. The number of electrons identifies the atomic number and the element of the atom. There are slightly more than 100 elements (not counting a few extras that have been artificially synthesized), and these elements are the chemical building blocks of all matter.

Just as there are differences among the elements, there are also similarities. The elements can be grouped into families and relationships established between and within the families by means of the Periodic Table, shown in Figure 2.1. In the horizontal direction there is a certain repetition, or periodicity, in the arrangement of elements. Metallic elements occupy the left and center portions of the chart, and nonmetals are located to the right. Between them, along a diagonal, is a transition zone containing elements called ***metalloids*** or ***semimetals.*** In principle, each of the elements can exist as a solid, liquid, or gas, depending on temperature and pressure. At room temperature and atmospheric pressure, they each have a natural phase; e.g., iron (Fe) is a solid, mercury (Hg) is a liquid, and nitrogen (N) is a gas.

In the table, the elements are arranged into vertical columns and horizontal rows in such a way that similarities exist among elements in the same columns. For example, in the extreme right column are the ***noble gases*** (helium, neon, argon, krypton, xenon, and radon), all of which exhibit great chemical stability and low reaction rates. The ***halogens*** (fluorine, chlorine, bromine, iodine, and astatine) in column VIIA share similar properties (hydrogen is not included among the halogens). The ***noble metals*** (copper, silver, and gold) in column IB have similar properties. Generally there are correlations in properties among elements within a given column, whereas differences exist among elements in different columns.



Period	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H																1 H	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac															

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 2.1 Periodic Table of Elements. The atomic number and symbol are listed for the 103 elements.

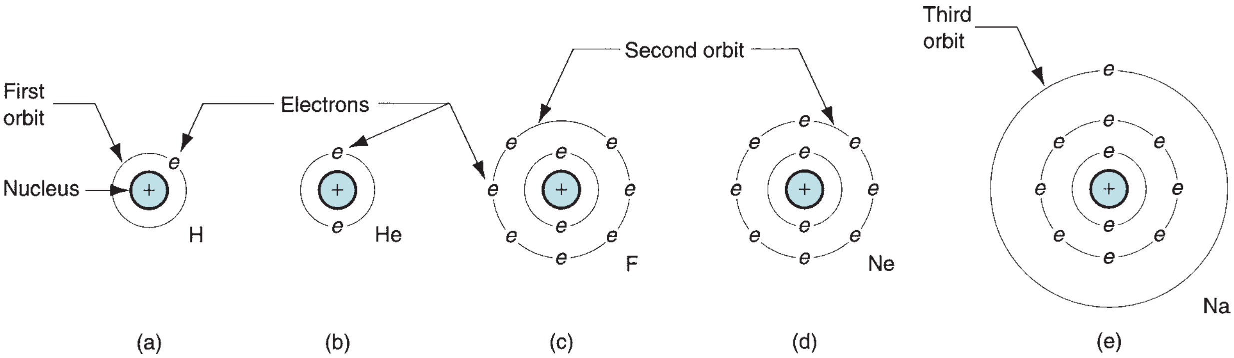


FIGURE 2.2 Simple model of atomic structure for several elements: (a) hydrogen, (b) helium, (c) fluorine, (d) neon, and (e) sodium.

Many of the similarities and differences among the elements can be explained by their respective atomic structures. The simplest model of atomic structure, called the planetary model, shows the electrons of the atom orbiting around the nucleus at certain fixed distances, called shells, as shown in Figure 2.2. The hydrogen atom (atomic number 1) has one electron in the orbit closest to the nucleus. Helium (atomic number 2) has two. Also shown in the figure are the atomic structures for fluorine (atomic number 9), neon (atomic number 10), and sodium (atomic number 11). One might infer from these models that there is a maximum number of electrons that can be contained in a given orbit. This turns out to be correct, and the maximum is defined by

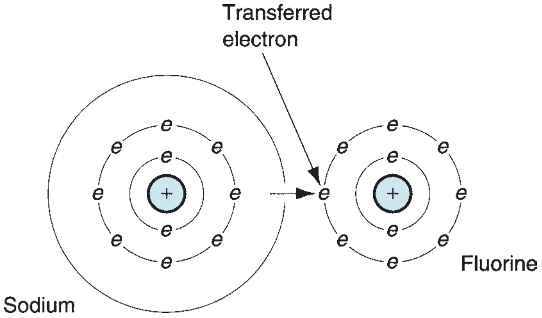
$$\text{Maximum number of electrons in an orbit} = 2n^2 \tag{2.1}$$

where n identifies the orbit, with $n = 1$ closest to the nucleus.

The number of electrons in the outermost shell, relative to the maximum number allowed, determines to a large extent the atom's chemical affinity for other atoms. These outer-shell electrons are called ***valence electrons.*** For example, because a hydrogen atom has only one electron in its single orbit, it readily combines with another hydrogen atom to form a hydrogen molecule H_2. For the same reason, hydrogen also reacts readily with various other elements (e.g., to form H_2O). In the helium atom, the two electrons in its only orbit are the maximum allowed ($2n^2 = 2(1)^2 = 2$), and so helium is very stable. Neon is stable for the same reason: Its outermost orbit ($n = 2$) has eight electrons (the maximum allowed), so neon is an inert gas.

In contrast to neon, fluorine has one fewer electron in its outer shell ($n = 2$) than the maximum allowed and is readily attracted to other elements that might share an electron to make a more stable set. The sodium atom seems divinely made for the situation, with one electron in its outermost orbit. It reacts strongly with fluorine to form the compound sodium fluoride, as pictured in Figure 2.3.

FIGURE 2.3 The sodium fluoride molecule, formed by the transfer of the "extra" electron of the sodium atom to complete the outer orbit of the fluorine atom.



At the low atomic numbers considered here, the prediction of the number of electrons in the outer orbit is straightforward. As the atomic number increases to higher levels, the allocation of electrons to the different orbits becomes somewhat more complicated. There are rules and guidelines, based on quantum mechanics, that can be used to predict the positions of the electrons among the various orbits and explain their characteristics. A discussion of these rules is somewhat beyond the scope of the coverage of materials for manufacturing.

2.2 BONDING BETWEEN ATOMS AND MOLECULES

Atoms are held together in molecules by various types of bonds that depend on the valence electrons. By comparison, molecules are attracted to each other by weaker bonds, which generally result from the electron configuration in the individual molecules. Thus, we have two types of bonding: (1) primary bonds, generally associated with the formation of molecules; and (2) secondary bonds, generally associated with attraction between molecules. Primary bonds are much stronger than secondary bonds.

Primary Bonds Primary bonds are characterized by strong atom-to-atom attractions that involve the exchange of valence electrons. Primary bonds include the following forms: (a) ionic, (b) covalent, and (c) metallic, as illustrated in Figure 2.4. Ionic and covalent bonds are called ***intra***molecular bonds because they involve attractive forces between atoms within the molecule.

In the ***ionic bond,*** the atoms of one element give up their outer electron(s), which are in turn attracted to the atoms of some other element to increase their electron count in the outermost shell to eight. In general, eight electrons in the outer shell is the most stable atomic configuration (except for the very light atoms), and nature provides a very strong bond between atoms that achieves this configuration. The previous example of the reaction of sodium and fluorine to form sodium fluoride (Figure 2.3) illustrates this form of atomic bond. Sodium chloride (table salt) is a more common example. Because of the transfer of electrons between the atoms, sodium and fluorine (or sodium and chlorine) ***ions*** are formed, from which this bonding derives its name. Properties of solid materials with ionic bonding include low electrical conductivity and poor ductility.

The ***covalent bond*** is one in which electrons are shared (as opposed to transferred) between atoms in their outermost shells to achieve a stable set of eight. Fluorine and diamond are two examples of covalent bonds. In fluorine, one electron from each of two atoms is shared to form F_2 gas, as shown in Figure 2.5(a). In the case of diamond, which is carbon (atomic number 6), each atom has four neighbors with which it shares electrons. This produces a very rigid three-dimensional structure, not adequately represented in Figure 2.5(b), and accounts for the extreme high hardness of this material. Other forms of

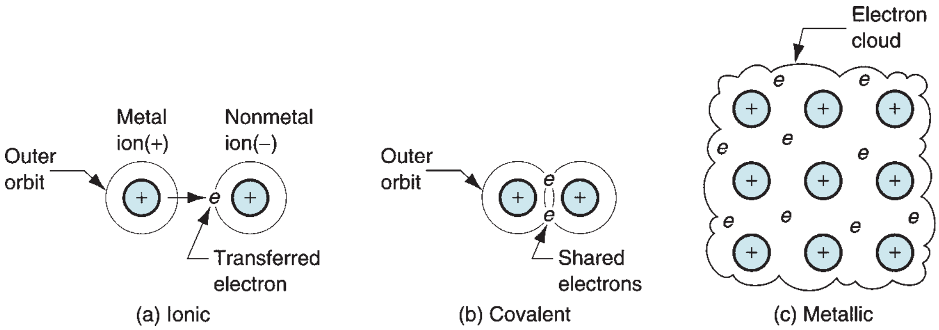
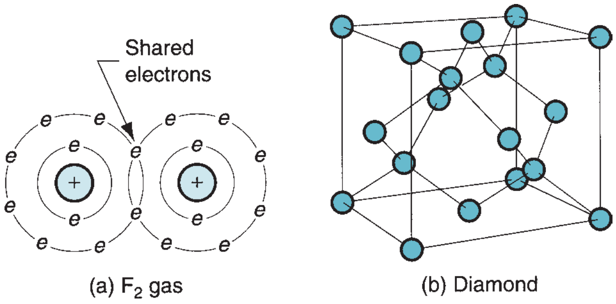


FIGURE 2.4 Three forms of primary bonding: (a) ionic, (b) covalent, and (c) metallic.



(a) F_2 gas

(b) Diamond

FIGURE 2.5 Two examples of covalent bonding: (a) fluorine gas F_2, and (b) diamond.

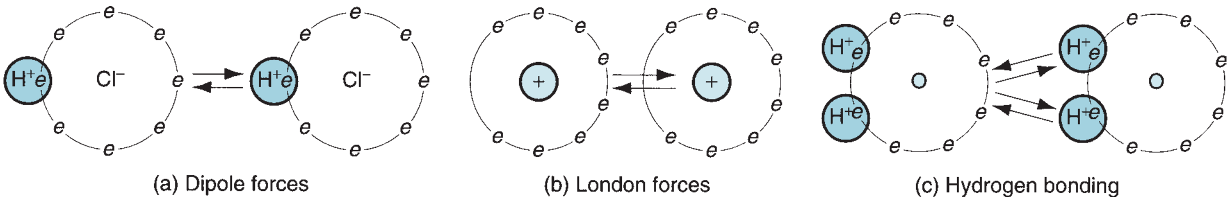
carbon (e.g., graphite) do not exhibit this rigid atomic structure. Solids with covalent bonding generally possess high hardness and low electrical conductivity.

The metallic bond is, of course, the atomic bonding mechanism in pure metals and metal alloys. Atoms of the metallic elements generally possess too few electrons in their outermost orbits to complete the outer shells for all of the atoms in, say, a given block of metal. Accordingly, instead of sharing on an atom-to-atom basis, ***metallic bonding*** involves the sharing of outer-shell electrons by all atoms to form a general electron cloud that permeates the entire block. This cloud provides the attractive forces to hold the atoms together and forms a strong, rigid structure in most cases. Because of the general sharing of electrons, and their freedom to move within the metal, metallic bonding provides for good electrical conductivity. Other typical properties of materials characterized by metallic bonding include good conduction of heat and good ductility. (Although some of these terms are yet to be defined, the text relies on the reader's general understanding of material properties.)

Secondary Bonds Whereas primary bonds involve atom-to-atom attractive forces, secondary bonds involve attraction forces between molecules, or ***inter***molecular forces. There is no transfer or sharing of electrons in secondary bonding, and these bonds are therefore weaker than primary bonds. There are three forms of secondary bonding: (a) dipole forces, (b) London forces, and (c) hydrogen bonding, illustrated in Figure 2.6. Types (a) and (b) are often referred to as ***van der Waals*** forces, after the scientist who first studied and quantified them.

Dipole forces arise in a molecule comprised of two atoms that have equal and opposite electrical charges. Each molecule therefore forms a dipole, as shown in Figure 2.6(a) for hydrogen chloride. Although the material is electrically neutral in its aggregate form, on a molecular scale the individual dipoles attract each other, given the proper orientation of positive and negative ends of the molecules. These dipole forces provide a net intermolecular bonding within the material.

London forces involve attractive forces between nonpolar molecules; that is, the atoms in the molecule do not form dipoles in the sense of the preceding paragraph. However, owing to the rapid motion of the electrons in orbit around the molecule, temporary dipoles form when more electrons happen to be on one side of the molecule than the other, as suggested by



(a) Dipole forces (b) London forces (c) Hydrogen bonding

FIGURE 2.6 Three types of secondary bonding: (a) dipole forces, (b) London forces, and (c) hydrogen bonding.

Figure 2.6(b). These instantaneous dipoles provide a force of attraction between molecules in the material.

Finally, ***hydrogen bonding*** occurs in molecules containing hydrogen atoms that are covalently bonded to another atom (e.g., oxygen in H_2O). Because the electrons needed to complete the shell of the hydrogen atom are aligned on one side of its nucleus, the opposite side has a net positive charge that attracts the electrons of atoms in neighboring molecules. Hydrogen bonding is illustrated in Figure 2.6(c) for water, and is generally a stronger intermolecular bonding mechanism than the other two forms of secondary bonding. It is important in the formation of many polymers.

2.3 CRYSTALLINE STRUCTURES

Atoms and molecules are used as building blocks for the more macroscopic structure of matter that is considered here and in the following section. When materials solidify from the molten state, they tend to close ranks and pack tightly, in many cases arranging themselves into a very orderly structure, and in other cases, not quite so orderly. Two fundamentally different material structures can be distinguished:(1) crystalline and (2) noncrystalline. Crystalline structures are examined in this section, and noncrystalline in the next. The video clip on heat treatment shows how metals naturally form into crystal structures.

VIDEO CLIP

Heat treatment: View the segment titled "metal and alloy structures."

Many materials form into crystals on solidification from the molten or liquid state. It is characteristic of virtually all metals, as well as many ceramics and polymers. A ***crystalline structure*** is one in which the atoms are located at regular and recurring positions in three dimensions. The pattern may be replicated millions of times within a given crystal. The structure can be viewed in the form of a ***unit cell,*** which is the basic geometric grouping of atoms that is repeated. To illustrate, consider the unit cell for the body-centered cubic (BCC) crystal structure shown in Figure 2.7, one of the common structures found in metals. The simplest model of the BCC unit cell is illustrated in Figure 2.7(a). Although this model clearly depicts the locations of the atoms within the cell, it does not indicate the close packing of the atoms that occurs in the real crystal, as in Figure 2.7(b). Figure 2.7(c) shows the repeating nature of the unit cell within the crystal.

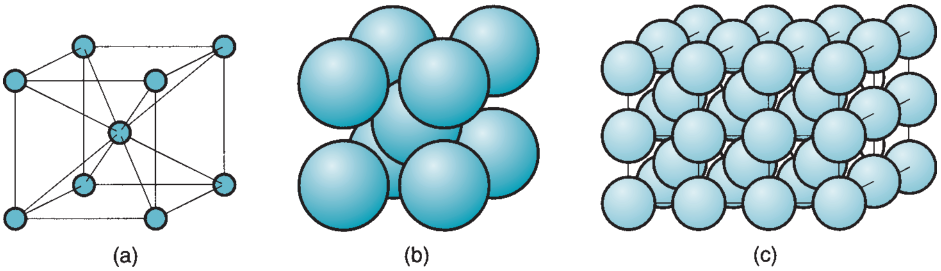


FIGURE 2.7 Body-centered cubic (BCC) crystal structure: (a) unit cell, with atoms indicated as point locations in a three-dimensional axis system; (b) unit cell model showing closely packed atoms (sometimes called the hard-ball model); and (c) repeated pattern of the BCC structure.

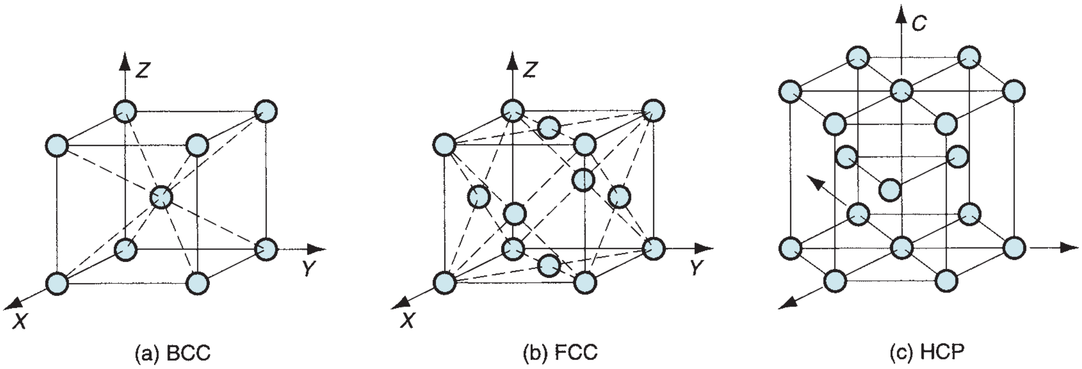


FIGURE 2.8 Three types of crystal structures in metals: (a) body-centered cubic, (b) face-centered cubic, and (c) hexagonal close-packed.

2.3.1 TYPES OF CRYSTAL STRUCTURES

In metals, three lattice structures are common: (1) body-centered cubic (BCC), (2) face-centered cubic (FCC), and (3) hexagonal close-packed (HCP), illustrated in Figure 2.8. Crystal structures for the common metals are presented in Table 2.1. Note that some metals undergo a change of structure at different temperatures. Iron, for example, is BCC at room temperature; it changes to FCC above 912°C (1674°F) and back to BCC at temperatures above 1400°C (2550°F). When a metal (or other material) changes structure like this, it is referred to as being ***allotropic.***

2.3.2 IMPERFECTIONS IN CRYSTALS

Thus far, crystal structures have been discussed as if they were perfect—the unit cell repeated in the material over and over in all directions. A perfect crystal is sometimes desirable to satisfy aesthetic or engineering purposes. For instance, a perfect diamond (contains no flaws) is more valuable than one containing imperfections. In the production of integrated circuit chips, large single crystals of silicon possess desirable processing characteristics for forming the microscopic details of the circuit pattern.

However, there are various reasons why a crystal's lattice structure may not be perfect. The imperfections often arise naturally because of the inability of the solidifying material to continue the replication of the unit cell indefinitely without interruption. Grain boundaries in metals are an example. In other cases, the imperfections are introduced purposely during the

TABLE 2.1 Crystal structures for the common metals (at room temperature).

Body-Centered Cubic (BCC)	Face-Centered Cubic (FCC)	Hexagonal Close-Packed (HCP)
Chromium (Cr)	Aluminum (Al)	Magnesium (Mg)
Iron (Fe)	Copper (Cu)	Titanium (Ti)
Molybdenum (Mo)	Gold (Au)	Zinc (Zn)
Tantalum (Ta)	Lead (Pb)	
Tungsten (W)	Silver (Ag)	
	Nickel (Ni)	

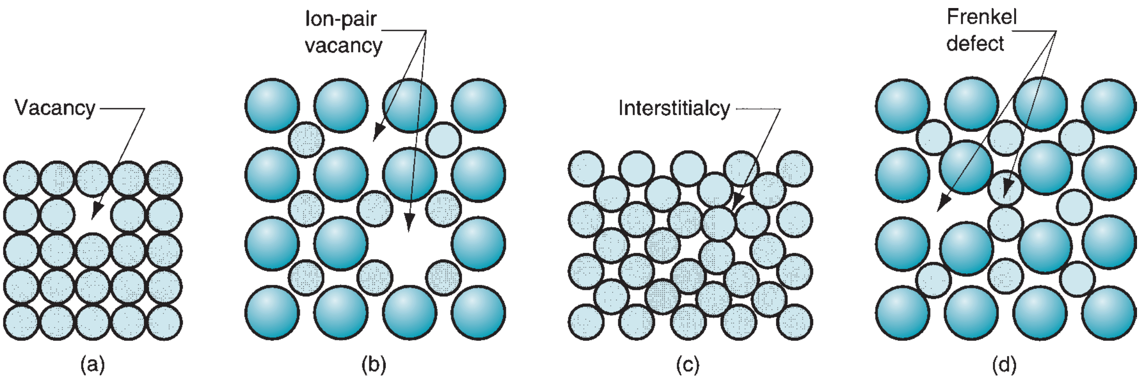


FIGURE 2.9 Point defects: (a) vacancy, (b) ion-pair vacancy, (c) interstitialcy, and (d) displaced ion.

manufacturing process; for example, the addition of an alloying ingredient in a metal to increase its strength.

The various imperfections in crystalline solids are also called defects. Either term, ***imperfection*** or ***defect,*** refers to deviations in the regular pattern of the crystalline lattice structure. They can be catalogued as (1) point defects, (2) line defects, and (3) surface defects.

Point defects are imperfections in the crystal structure involving either a single atom or a few atoms. The defects can take various forms including, as shown in Figure 2.9: (a) ***vacancy,*** the simplest defect, involving a missing atom within the lattice structure; (b) ***ion-pair vacancy,*** also called a ***Schottky defect,*** which involves a missing pair of ions of opposite charge in a compound that has an overall charge balance; (c) ***interstitialcy,*** a lattice distortion produced by the presence of an extra atom in the structure; and (d) ***displaced ion,*** known as a ***Frenkel defect,*** which occurs when an ion becomes removed from a regular position in the lattice structure and inserted into an interstitial position not normally occupied by such an ion.

A ***line defect*** is a connected group of point defects that forms a line in the lattice structure. The most important line defect is the ***dislocation,*** which can take two forms: (a) edge dislocation and (b) screw dislocation. An ***edge dislocation*** is the edge of an extra plane of atoms that exists in the lattice, as illustrated in Figure 2.10(a). A ***screw dislocation,*** Figure 2.10(b), is a spiral within the lattice structure wrapped around an imperfection line, like a screw is wrapped around its axis. Both types of dislocations can arise in the crystal structure during solidification (e.g., casting), or they can be initiated during a

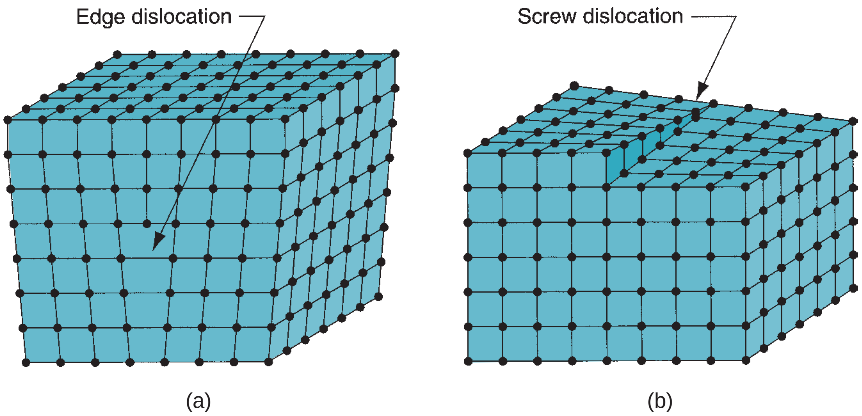


FIGURE 2.10 Line defects: (a) edge dislocation and (b) screw dislocation.

deformation process (e.g., metal forming) performed on the solid material. Dislocations are useful in explaining certain aspects of mechanical behavior in metals.

Surface defects are imperfections that extend in two directions to form a boundary. The most obvious example is the external surface of a crystalline object that defines its shape. The surface is an interruption in the lattice structure. Surface boundaries can also lie inside the material. Grain boundaries are the best example of these internal surface interruptions. Metallic grains are discussed in a moment, but first consider how deformation occurs in a crystal lattice, and how the process is aided by the presence of dislocations.

2.3.3 DEFORMATION IN METALLIC CRYSTALS

When a crystal is subjected to a gradually increasing mechanical stress, its initial response is to deform ***elastically.*** This can be likened to a tilting of the lattice structure without any changes of position among the atoms in the lattice, in the manner depicted in Figure 2.11(a) and (b). If the force is removed, the lattice structure (and therefore the crystal) returns to its original shape. If the stress reaches a high value relative to the electrostatic forces holding the atoms in their lattice positions, a permanent shape change occurs, called ***plastic deformation.*** What has happened is that the atoms in the lattice have permanently moved from their previous locations, and a new equilibrium lattice has been formed, as suggested by Figure 2.11(c).

The lattice deformation shown in (c) of the figure is one possible mechanism, called slip, by which plastic deformation can occur in a crystalline structure. The other is called twinning, discussed later.

Slip involves the relative movement of atoms on opposite sides of a plane in the lattice, called the ***slip plane.*** The slip plane must be somehow aligned with the lattice structure (as indicated in the sketch), and so there are certain preferred directions along which slip is more likely to occur. The number of these ***slip directions*** depends on the lattice type. The three common metal crystal structures are somewhat more complicated, especially in three dimensions, than the square lattice depicted in Figure 2.11. It turns out that HCP has the fewest slip directions, BCC the most, and FCC falls in between. HCP metals show poor ductility and are generally difficult to deform at room temperature. Metals with BCC structure would figure to have the highest ductility, if the number of slip directions were the only criterion. However, nature is not so simple. These metals are generally stronger than the others, which complicates the issue; and the BCC metals usually require higher stresses to cause slip. In fact, some of the BCC metals exhibit poor ductility. Low carbon steel is a notable exception; although relatively strong, it is widely used with great commercial success in sheet-metal-forming operations, in which it exhibits good ductility. The FCC metals are generally the most ductile of the three crystal structures, combining a good number of slip directions with (usually) relatively low to moderate strength. All three of these metal structures become more ductile at elevated temperatures, and this fact is often exploited in shaping them.

Dislocations play an important role in facilitating slip in metals. When a lattice structure containing an edge dislocation is subjected to a shear stress, the material deforms

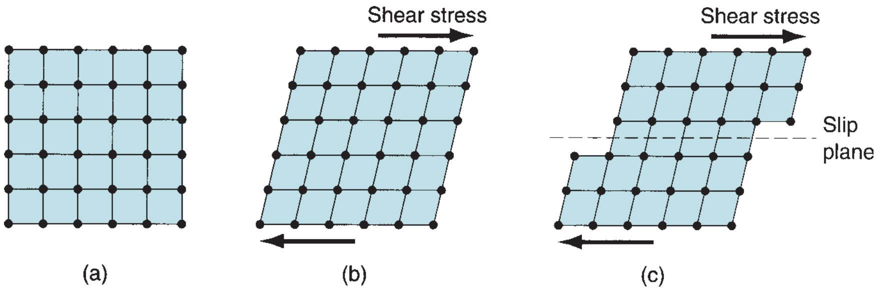


FIGURE 2.11 Deformation of a crystal structure: (a) original lattice; (b) elastic deformation, with no permanent change in positions of atoms; and (c) plastic deformation, in which atoms in the lattice are forced to move to new "homes."

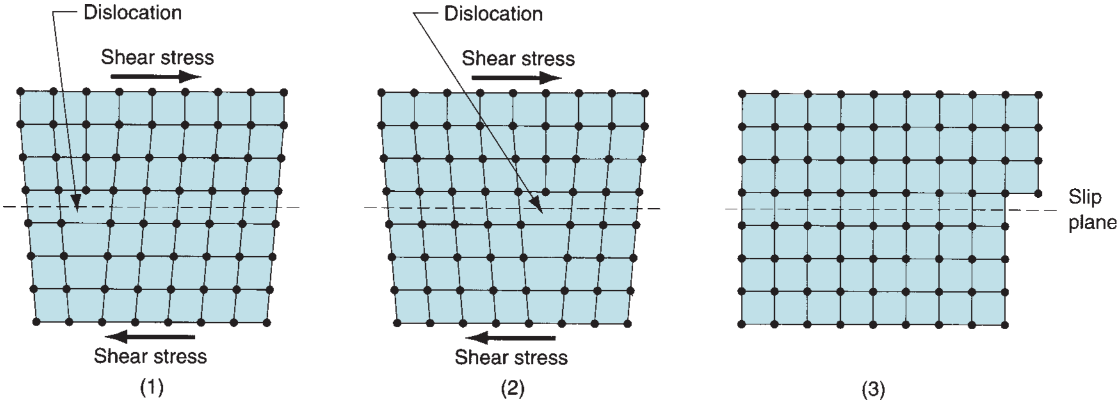


FIGURE 2.12 Effect of dislocations in the lattice structure under stress. In the series of diagrams, the movement of the dislocation allows deformation to occur under a lower stress than in a perfect lattice.

much more readily than in a perfect structure. This is explained by the fact that the dislocation is put into motion within the crystal lattice in the presence of the stress, as shown in the series of sketches in Figure 2.12. Why is it easier to move a dislocation through the lattice than it is to deform the lattice itself? The answer is that the atoms at the edge dislocation require a smaller displacement within the distorted lattice structure to reach a new equilibrium position. Thus, a lower energy level is needed to realign the atoms into the new positions than if the lattice were missing the dislocation. A lower stress level is therefore required to effect the deformation. Because the new position manifests a similar distorted lattice, movement of atoms at the dislocation continues at the lower stress level.

The slip phenomenon and the influence of dislocations have been explained here on a very microscopic basis. On a larger scale, slip occurs many times over throughout the metal when subjected to a deforming load, thus causing it to exhibit the familiar macroscopic behavior. Dislocations represent a good-news–bad-news situation. Because of dislocations, the metal is more ductile and yields more readily to plastic deformation (forming) during manufacturing. However, from a product design viewpoint, the metal is not nearly as strong as it would be in the absence of dislocations.

Twinning is a second way in which metal crystals plastically deform. ***Twinning*** can be defined as a mechanism of plastic deformation in which atoms on one side of a plane (called the twinning plane) are shifted to form a mirror image of the other side of the plane. It is illustrated in Figure 2.13. The mechanism is important in HCP metals (e.g., magnesium, zinc)

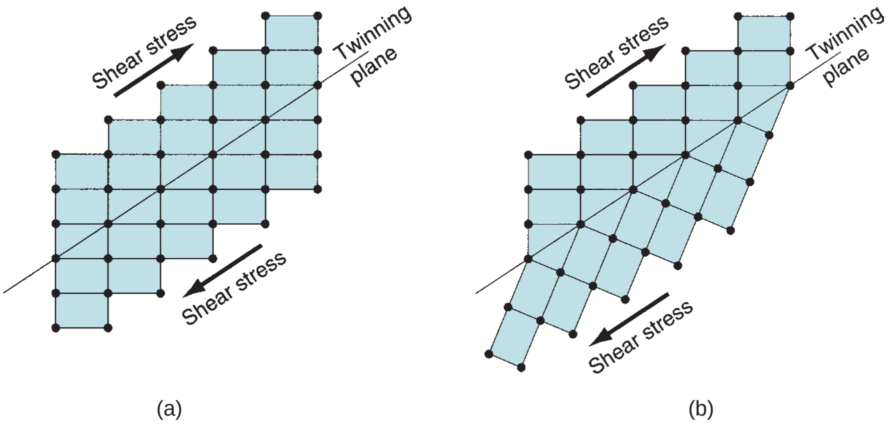


FIGURE 2.13 Twinning involves the formation of an atomic mirror image (i.e., a "twin") on the opposite side of the twinning plane: (a) before, and (b) after twinning.

because they do not slip readily. Besides structure, another factor in twinning is the rate of deformation. The slip mechanism requires more time than twinning, which can occur almost instantaneously. Thus, in situations in which the deformation rate is very high, metals twin that would otherwise slip. Low carbon steel is an example that illustrates this rate sensitivity; when subjected to high strain rates it twins, whereas at moderate rates it deforms by slip.

2.3.4 GRAINS AND GRAIN BOUNDARIES IN METALS

A given block of metal may contain millions of individual crystals, called ***grains.*** Each grain has its own unique lattice orientation; but collectively, the grains are randomly oriented within the block. Such a structure is referred to as ***polycrystalline.*** It is easy to understand how such a structure is the natural state of the material. When the block is cooled from the molten state and begins to solidify, nucleation of individual crystals occurs at random positions and orientations throughout the liquid. As these crystals grow they finally interfere with each other, forming at their interface a surface defect—a ***grain boundary.*** The grain boundary consists of a transition zone, perhaps only a few atoms thick, in which the atoms are not aligned with either grain.

The size of the grains in the metal block is determined by the number of nucleation sites in the molten material and the cooling rate of the mass, among other factors. In a casting process, the nucleation sites are often created by the relatively cold walls of the mold, which motivate a somewhat preferred grain orientation at these walls.

Grain size is inversely related to cooling rate: Faster cooling promotes smaller grain size, whereas slower cooling has the opposite effect. Grain size is important in metals because it affects mechanical properties. Smaller grain size is generally preferable from a design viewpoint because it means higher strength and hardness. It is also desirable in certain manufacturing operations (e.g., metal forming), because it means higher ductility during deformation and a better surface on the finished product.

Another factor influencing mechanical properties is the presence of grain boundaries in the metal. They represent imperfections in the crystalline structure that interrupt the continued movement of dislocations. This helps to explain why smaller grain size—therefore more grains and more grain boundaries—increases the strength of the metal. By interfering with dislocation movement, grain boundaries also contribute to the characteristic property of a metal to become stronger as it is deformed. The property is called ***strain hardening,*** and it is examined more closely in the discussion of mechanical properties in Chapter 3.

2.4 NONCRYSTALLINE (AMORPHOUS) STRUCTURES

Many important materials are noncrystalline—liquids and gases, for example. Water and air have noncrystalline structures. A metal loses its crystalline structure when it is melted. Mercury is a liquid metal at room temperature, with its melting point of −38°C (−37°F). Important classes of engineering materials have a noncrystalline form in their solid state; the term ***amorphous*** is often used to describe these materials. Glass, many plastics, and rubber fall into this category. Many important plastics are mixtures of crystalline and noncrystalline forms. Even metals can be amorphous rather than crystalline, given that the cooling rate during transformation from liquid to solid is fast enough to inhibit the atoms from arranging themselves into their preferred regular patterns. This can happen, for instance, if the molten metal is poured between cold, closely spaced, rotating rolls.

Two closely related features distinguish noncrystalline from crystalline materials: (1) absence of a long-range order in the molecular structure, and (2) differences in melting and thermal expansion characteristics.

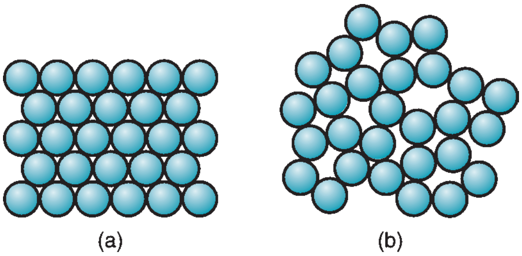


FIGURE 2.14 Illustration of difference in structure between: (a) crystalline and (b) noncrystalline materials. The crystal structure is regular, repeating, and denser, whereas the noncrystalline structure is more loosely packed and random.

The difference in molecular structure can be visualized with reference to Figure 2.14. The closely packed and repeating pattern of the crystal structure is shown on the left; and the less dense and random arrangement of atoms in the noncrystalline material on the right. The difference is demonstrated by a metal when it melts. The more loosely packed atoms in the molten metal show an increase in volume (reduction in density) compared with the material's solid crystalline state. This effect is characteristic of most materials when melted. (Ice is a notable exception; liquid water is denser than solid ice.) It is a general characteristic of liquids and solid amorphous materials that they are absent of long-range order as on the right in our figure.

The melting phenomenon will now be examined in more detail, and in doing so, the second important difference between crystalline and noncrystalline structures will be defined. As indicated, a metal experiences an increase in volume when it melts from the solid to the liquid state. For a pure metal, this volumetric change occurs rather abruptly, at a constant temperature (i.e., the melting temperature T_m), as indicated in Figure 2.15. The change represents a discontinuity from the slopes on either side in the plot. The gradual slopes characterize the metal's ***thermal expansion***—the change in volume as a function of temperature, which is usually different in the solid and liquid states. Associated with the sudden volume increase as the metal transforms from solid to liquid at the melting point is the addition of a certain quantity of heat, called the ***heat of fusion,*** which causes the atoms to lose the dense, regular arrangement of the crystalline structure. The process is reversible; it operates in both directions. If the molten metal is cooled through its melting temperature, the same abrupt change in volume occurs (except that it is a decrease), and the same quantity of heat is given off by the metal.

An amorphous material exhibits quite different behavior than that of a pure metal when it changes from solid to liquid, as shown in Figure 2.15. The process is again reversible, but observe the behavior of the amorphous material during cooling from the liquid state, rather

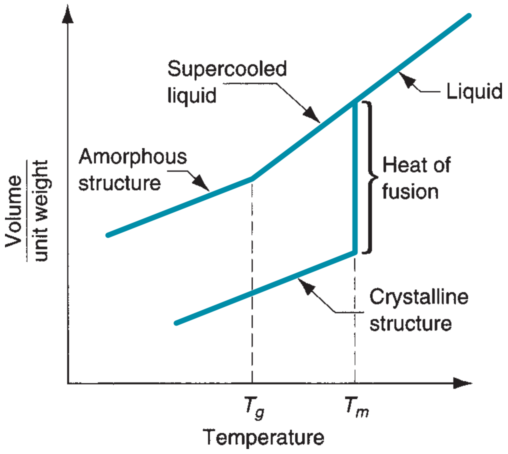


FIGURE 2.15 Characteristic change in volume for a pure metal (a crystalline structure), compared to the same volumetric changes in glass (a noncrystalline structure).

than during melting from the solid, as before. Glass (silica, SiO_2) is used to illustrate. At high temperatures, glass is a true liquid, and the molecules are free to move about as in the usual definition of a liquid. As the glass cools, it gradually transforms into the solid state, going through a transition phase, called a ***supercooled liquid,*** before finally becoming rigid. It does not show the sudden volumetric change that is characteristic of crystalline materials; instead, it passes through its melting temperature T_m without a change in its thermal expansion slope. In this supercooled liquid region, the material becomes increasingly viscous as the temperature continues to decrease. As it cools further, a point is finally reached at which the supercooled liquid converts to a solid. This is called the ***glass-transition temperature*** T_g. At this point, there is a change in the thermal expansion slope. (It might be more precise to refer to it as the thermal contraction slope; however, the slope is the same for expansion and contraction.) The rate of thermal expansion is lower for the solid material than for the supercooled liquid.

The difference in behavior between crystalline and noncrystalline materials can be traced to the response of their respective atomic structures to changes in temperature. When a pure metal solidifies from the molten state, the atoms arrange themselves into a regular and recurring structure. This crystal structure is much more compact than the random and loosely packed liquid from which it formed. Thus, the process of solidification produces the abrupt volumetric contraction observed in Figure 2.15 for the crystalline material. By contrast, amorphous materials do not achieve this repeating and closely packed structure at low temperatures. The atomic structure is the same random arrangement as in the liquid state; thus, there is no abrupt volumetric change as these materials transition from liquid to solid.

2.5 ENGINEERING MATERIALS

Let us summarize how atomic structure, bonding, and crystal structure (or absence thereof) are related to the type of engineering material—metals, ceramics, and polymer.

Metals Metals have crystalline structures in the solid state, almost without exception. The unit cells of these crystal structures are almost always BCC, FCC, or HCP. The atoms of the metals are held together by metallic bonding, which means that their valence electrons can move about with relative freedom (compared with the other types of atomic and molecular bonding). These structures and bonding generally make the metals strong and hard. Many of the metals are quite ductile (capable of being deformed, which is useful in manufacturing), especially the FCC metals. Other general properties of metals related to structure and bonding include: high electrical and thermal conductivity, opaqueness (impervious to light rays), and reflectivity (capacity to reflect light rays).

Ceramics Ceramic molecules are characterized by ionic or covalent bonding, or both. The metallic atoms release or share their outermost electrons to the nonmetallic atoms, and a strong attractive force exists within the molecules. The general properties that result from these bonding mechanisms include: high hardness and stiffness (even at elevated temperatures), brittleness (no ductility), electrical insulation (nonconducting) properties, refractoriness (being thermally resistant), and chemical inertness.

Ceramics possess either a crystalline or noncrystalline structure. Most ceramics have a crystal structure, whereas glasses based on silica (SiO_2) are amorphous. In certain cases, either structure can exist in the same ceramic material. For example, silica occurs in nature as crystalline quartz. When this mineral is melted and then cooled, it solidifies to form fused silica, which has a noncrystalline structure.

Polymers A polymer molecule consists of many repeating ***mers*** to form very large molecules held together by covalent bonding. Elements in polymers are usually carbon plus one or more other elements such as hydrogen, nitrogen, oxygen, and chlorine. Secondary bonding (van der Waals) holds the molecules together within the aggregate material (intermolecular bonding). Polymers have either a glassy structure or mixture of glassy and crystalline. There are differences among the three polymer types. In ***thermoplastic polymers,*** the molecules consist of long chains of mers in a linear structure. These materials can be heated and cooled without substantially altering their linear structure. In ***thermosetting polymers,*** the molecules transform into a rigid, three-dimensional structure on cooling from a heated plastic condition. If thermosetting polymers are reheated, they degrade chemically rather than soften. ***Elastomers*** have large molecules with coiled structures. The uncoiling and recoiling of the molecules when subjected to stress cycles motivate the aggregate material to exhibit its characteristic elastic behavior.

The molecular structure and bonding of polymers provide them with the following typical properties: low density, high electrical resistivity (some polymers are used as insulating materials), and low thermal conductivity. Strength and stiffness of polymers vary widely. Some are strong and rigid (although not matching the strength and stiffness of metals or ceramics), whereas others exhibit highly elastic behavior.

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REVIEW QUESTIONS

2.1. The elements listed in the Periodic Table can be divided into three categories. What are these categories? Give an example of each.
2.2. Which elements are the noble metals?
2.3. What is the difference between primary and secondary bonding in the structure of materials?
2.4. Describe how ionic bonding works.
2.5. What is the difference between crystalline and noncrystalline structures in materials?
2.6. What are some common point defects in a crystal lattice structure?
2.7. Define the difference between elastic and plastic deformation in terms of the effect on the crystal lattice structure.
2.8. How do grain boundaries contribute to the strain hardening phenomenon in metals?
2.9. Identify some materials that have a crystalline structure.
2.10. Identify some materials that possess a noncrystalline structure.
2.11. What is the basic difference in the solidification (or melting) process between crystalline and noncrystalline structures?

MULTIPLE CHOICE QUIZ

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

2.1. The basic structural unit of matter is which one of the following: (a) atom, (b) electron, (c) element, (d) molecule, or (e) nucleus?

2.2. Approximately how many different elements have been identified (one best answer): (a) 10, (b) 50, (c) 100, (d) 200, or (e) 500?

2.3. In the Periodic Table, the elements can be divided into which of the following categories (three best answers): (a) ceramics, (b) gases, (c) liquids, (d) metals, (e) nonmetals, (f) polymers, (g) semimetals, and (h) solids?

2.4. The element with the lowest density and smallest atomic weight is which one of the following: (a) aluminum, (b) argon, (c) helium, (d) hydrogen, or (e) magnesium?

2.5. Which of the following bond types are classified as primary bonds (three correct answers): (a) covalent bonding, (b) hydrogen bonding, (c) ionic bonding, (d) metallic bonding, and (e) van der Waals forces?

2.6. How many atoms are there in the face-centered cubic (FCC) unit cell (one correct answer): (a) 8, (b) 9, (c) 10, (d) 12, or (e) 14?

2.7. Which of the following are not point defects in a crystal lattice structure (three correct answers): (a) edge dislocation, (b) grain boundaries, (c) interstitialcy, (d) Schottky defect, (e) screw dislocation, or (f) vacancy?

2.8. Which one of the following crystal structures has the fewest slip directions, thus making the metals with this structure generally more difficult to deform at room temperature: (a) BCC, (b) FCC, or (c) HCP?

2.9. Grain boundaries are an example of which one of the following types of crystal structure defects: (a) dislocation, (b) Frenkel defect, (c) line defects, (d) point defects, or (e) surface defects?

2.10. Twinning is which of the following (three best answers): (a) elastic deformation, (b) mechanism of plastic deformation, (c) more likely at high deformation rates, (d) more likely in metals with HCP structure, (e) slip mechanism, and (f) type of dislocation?

2.11. Polymers are characterized by which of the following bonding types (two correct answers): (a) adhesive, (b) covalent, (c) hydrogen, (d) ionic, (e) metallic, and (f) van der Waals?

3

MECHANICAL PROPERTIES OF MATERIALS

Chapter Contents

Mechanical properties of a material determine its behavior when subjected to mechanical stresses. These properties include elastic modulus, ductility, hardness, and various measures of strength. Mechanical properties are important in design because the function and performance of a product depend on its capacity to resist deformation under the stresses encountered in service. In design, the usual objective is for the product and its components to withstand these stresses without significant change in geometry. This capability depends on properties such as elastic modulus and yield strength. In manufacturing, the objective is just the opposite. Here, stresses that exceed the yield strength of the material must be applied to alter its shape. Mechanical processes such as forming and machining succeed by developing forces that exceed the material's resistance to deformation. Thus, there is the following dilemma: Mechanical properties that are desirable to the designer, such as high strength, usually make the manufacture of the product more difficult. It is helpful for the manufacturing engineer to appreciate the design viewpoint and for the designer to be aware of the manufacturing viewpoint.

This chapter examines the mechanical properties of materials that are most relevant in manufacturing.

3.1 STRESS–STRAIN RELATIONSHIPS

There are three types of static stresses to which materials can be subjected: tensile, compressive, and shear. Tensile stresses tend to stretch the material, compressive stresses tend to squeeze it, and shear involves stresses that tend to cause adjacent portions of the material to slide against each other. The stress–strain curve is the basic relationship that describes the mechanical properties of materials for all three types.

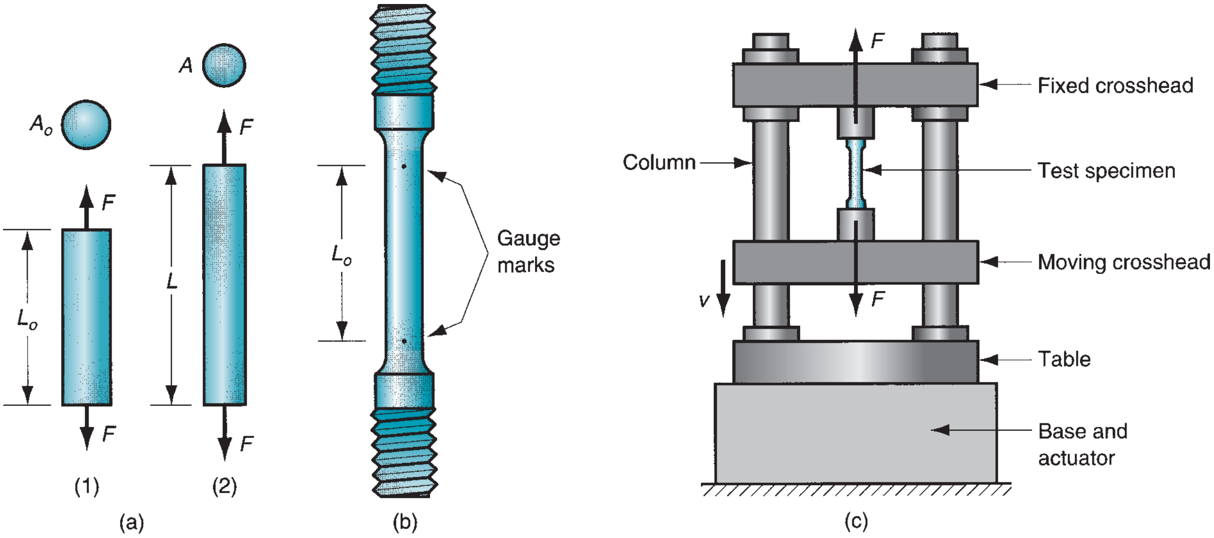

FIGURE 3.1 Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material; (b) typical test specimen; and (c) setup of the tensile test.

3.1.1 TENSILE PROPERTIES

The tensile test is the most common procedure for studying the stress–strain relationship, particularly for metals. In the test, a force is applied that pulls the material, tending to elongate it and reduce its diameter, as shown in Figure 3.1(a). Standards by ASTM (American Society for Testing and Materials) specify the preparation of the test specimen and the conduct of the test itself. The typical specimen and general setup of the tensile test is illustrated in Figure 3.1(b) and (c), respectively.

The starting test specimen has an original length L_o and area A_o. The length is measured as the distance between the gage marks, and the area is measured as the (usually round) cross section of the specimen. During the testing of a metal, the specimen stretches, then necks, and finally fractures, as shown in Figure 3.2. The load and the change in length of the specimen are recorded as testing proceeds, to provide the data required to determine

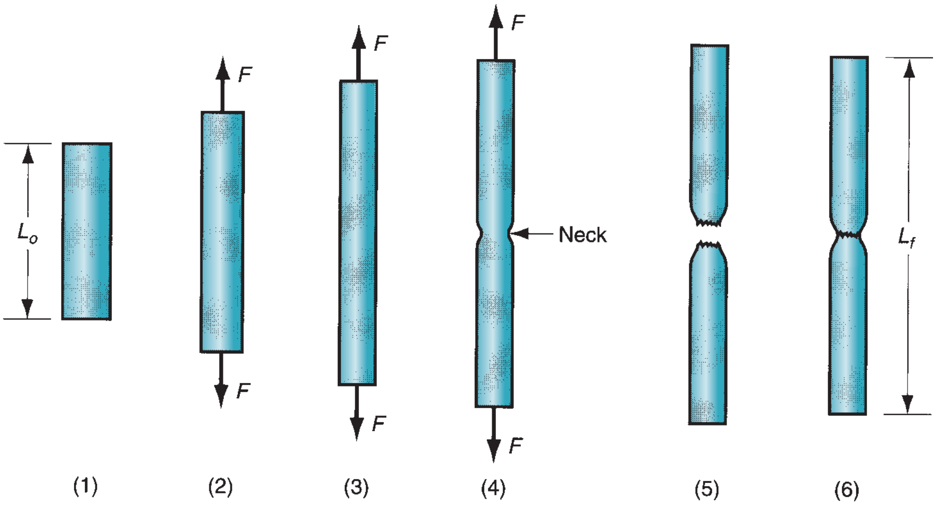

FIGURE 3.2 Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in, (6) final length can be measured.