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 is 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 is to provide a treatment of manufacturing that is more modern and quantitative than competing books. Its claim to be "modern" is based on (1) its more 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 more 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. For example, the volume of polymers processed commercially in the world today exceeds the volume of metals processed. Also, competing books provide minimum coverage of electronics manufacturing. Yet the commercial importance of electronics products and their associated industries has 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 equations 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 third edition is an updated version of the second edition, with a new chapter on nanotechnology fabrication processes, and updated text in several sections. I have attempted to be comprehensive in the book's coverage without allowing it to become oversize. Key features of the new edition include:

• A new chapter on nanotechnology fabrication processes.
• New and revised homework problems, bringing the total number of problems to 565. Nearly all of these problems require quantitative analysis.
• New and revised review questions and multiple choice quizzes for all chapters. There are more than 740 end-of-chapter review questions and almost 500 multiple choice
ACKNOWLEDGMENTS

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In addition, it seems appropriate to acknowledge my Wiley colleagues who have encouraged and participated in the preparation of this third edition. These include Joe Hayton and Maureen Clendenny. Last but certainly not least, I appreciate the kind efforts of production editor Suzanne Ingrao of Ingrao Associates, who seems to be able to find errors in my wording and grammar despite my best efforts to avoid them.

Individual questions or comments may be directed to the author personally at Mikell.Groover@Lehigh.edu.
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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. Holtzman 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 50 technical articles and seven 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


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Manufacturing is important—technologically, economically, and historically. 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 our 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 our society if they could not be manufactured. Manufacturing is the essential 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 20% of gross national product (GNP). A country's natural resources, such as agricultural lands,
mineral deposits, and oil reserves, also create wealth. In the United States, agriculture, mining, and similar industries account for less than 5% of GNP. Construction and public utilities make up slightly more than 5%. And the rest is service industries, which include retail, transportation, banking, communication, education, and government. The service sector accounts for approximately 70% of U.S. GNP. Government alone accounts for about as much of GNP as manufacturing sector, but government services do not create wealth. In the modern international 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.

Historically, the importance of manufacturing in the development of civilization is usually underestimated. But throughout history, human cultures that were better at making things were more successful. By making better tools, they had better crafts and weapons. Better crafts allowed them to live better. Better weapons allowed them to conquer neighboring cultures in times of conflict. In the American Civil War (1861–1865), one of the great advantages of the North over the South was its industrial strength—its capacity to manufacture. In World War II (1939–1945), the United States outproduced Germany and Japan—a decisive advantage in winning the war. To a significant degree, the history of civilization is the history of humankind’s ability to make things.

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 production is accomplished?

### 1.1 WHAT IS MANUFACTURING?

The word *manufacture* is derived from two Latin words, *manus* (hand) and *factum* (made); 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 that is manually supervised (Historical Note 1.1).

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1 As a noun, the word *manufacture* first appeared in English around 1567 a.d. As a verb, it first appeared around 1683 a.d.
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 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 manual labor, as depicted in Figure 1.1(a). 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, we 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 is acceptable.

1.1.2 Manufacturing Industries and Products

Manufacturing is an important activity, but it is not carried out simply for its own sake. It is performed as a commercial activity 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 first examining the types of industries in manufacturing, and then 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 make 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.

In this book, we are 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 our book, manufacturing means production of hardwares, which ranges from nuts and bolts to digital computers and military weapons. We include plastic and ceramic products, but exclude apparel, beverages, chemicals, food, and software. Our short list of manufacturing industries appears in Table 1.3.

Manufactured Products: Final products made by the industries listed in Table 1.3, 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 other companies to produce goods and supply services. Examples of capital goods include aircraft, mainframe computers, railroad equipment, machine tools, and construction equipment.

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
<th>Tertiary (service)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Aerospace</td>
<td>Banking</td>
</tr>
<tr>
<td>Forestry</td>
<td>Apparel</td>
<td>Communications</td>
</tr>
<tr>
<td>Fishing</td>
<td>Anticorrosive</td>
<td>Education</td>
</tr>
<tr>
<td>Livestock</td>
<td>Basic metals</td>
<td>Entertainment</td>
</tr>
<tr>
<td>Quarries</td>
<td>Beverages</td>
<td>Financial services</td>
</tr>
<tr>
<td>Mining</td>
<td>Building materials</td>
<td>Government</td>
</tr>
<tr>
<td>Petroleum</td>
<td>Chemicals</td>
<td>Health and medical</td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td>Home</td>
</tr>
<tr>
<td></td>
<td>Consumer appliances</td>
<td>Information</td>
</tr>
<tr>
<td></td>
<td>Electronics</td>
<td>Tourism</td>
</tr>
<tr>
<td></td>
<td>Equipment</td>
<td>Transportation</td>
</tr>
<tr>
<td></td>
<td>Fabricated metals</td>
<td>Wholesale trade</td>
</tr>
</tbody>
</table>
TABLE 1.3  Manufacturing industries whose materials, processes, and systems are likely to be covered in this book.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Typical Products</th>
<th>Industry</th>
<th>Typical Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace</td>
<td>Commercial and military aircraft</td>
<td>Aerospace</td>
<td>Commercial and military aircraft</td>
</tr>
<tr>
<td>Automotive</td>
<td>Cars, trucks, buses, motorcycles</td>
<td>Automotive</td>
<td>Cars, trucks, buses, motorcycles</td>
</tr>
<tr>
<td>Basic metals</td>
<td>Iron, steel, aluminum, copper, etc.</td>
<td>Basic metals</td>
<td>Iron, steel, aluminum, copper, etc.</td>
</tr>
<tr>
<td>Computers</td>
<td>Mainframe and personal computers</td>
<td>Computers</td>
<td>Mainframe and personal computers</td>
</tr>
<tr>
<td>Consumer goods</td>
<td>Large and small home appliances</td>
<td>Consumer goods</td>
<td>Large and small home appliances</td>
</tr>
<tr>
<td>Electronics</td>
<td>TVs, VCRs, audio equipment</td>
<td>Electronics</td>
<td>TVs, VCRs, audio equipment</td>
</tr>
</tbody>
</table>

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.

In this book we are 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 wires. Long sections made in almost continuous lengths are cut to 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, 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 between the three ranges are somewhat arbitrary (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 we have identified product variety 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. And within each product type, there are differences between 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. We might use the terms "soft" and "hard" to describe these differences in product variety. Soft product variety is when there are only small differences between products, such as the differences between 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 is when the products differ substantially, and there are few common parts, if any. The difference between a car and a truck is hard.

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. We can identify several dimensions of this capability: (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 materials. Certain manufacturing processes are suited to certain materials, while 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 set of production equipment, material handling, storage capability, and plant size 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 where 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. Let us provide an overview of these subjects.

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 dissimilar, 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 (4) composites—nonhomogeneous mixtures of the other three basic types rather than a unique category. The relationship of the four groups is pictured in Figure 1.3. In this section, we survey these materials. In Chapters 6 through 9, we 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 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-quarters 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%–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 (e.g., bridges, I-beams, and rails), transportation (trucks, rails, and rolling stock for railroads), and consumer products (automobiles and appliances).

Cast iron is an alloy of iron and carbon (2%-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, 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, silver, magnesium, nickel, lead, 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 like titanium nitride and boron nitride, used as cutting tools and grinding abrasives.

For processing purposes, ceramics can be divided into (1) crystalline ceramics and (2) 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 monomers, 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 upon 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 agglomeration 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

Manufacturing processes 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 some processing operations are also applicable to assembled items. An assembly operation joins two or more components in order 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

**FIGURE 1.4 Classification of manufacturing processes.**

weldment). A classification of manufacturing processes is presented in Figure 1.4. Most of the manufacturing processes covered in this text can be viewed on the digital video disc (DVD) that comes with this book. We provide alerts on these video clips throughout the text. Some of the basic processes used in modern manufacturing date from antiquity (Historical Note 1.2).

**Historical Note 1.2 Manufacturing materials and processes**

While 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 B.C.). It was during this period that processes such as the following were developed: clearing and other woodworking, hand forging and firing of clay pottery, weaving and spinning 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 man 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 readily be hardened 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
Hampering could both be used. This heralded the important period known as the Bronze Age (circa 3300–1500 B.C.).

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 enormous operations more difficult. Other processing methods were also more difficult for the same reason: Early blacksmiths learned that when iron ores (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 coined the Iron Age (starting around 1600 B.C.). It was not until much later, well into the nineteenth century, that the demand for steel grew significantly and more modern steel-making 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 2.1). 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.

1.3.1 Processing Operations

A processing operation uses energy to alter a workpart’s shape, physical properties, or appearance in order 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 human workers are generally employed to control the machines, to oversee the operations, and to 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.

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 painting and plating. 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.

**Figure 1.5** Casting and molding processes start with a work part heated to a liquid or semisolid 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.
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 prior to 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.

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 discharge, 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, can 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 near-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 and strengthening processes for metals and glasses. Sintering of powdered metals and ceramics, mentioned above, 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 like 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
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 manufacturing products, but also components for other production machines. Both in a historic sense and in a reproductive sense, the machine tool is the mother of all machinery.

Other production machines include presses for stamping operations, forging 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.

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 is 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. In Table 1.4, we list examples of special tooling used in various operations. Details are provided in the chapters that discuss these processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment</th>
<th>Special tooling (function)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting</td>
<td>Molding machine</td>
<td>Mold (ejector for injection)</td>
</tr>
<tr>
<td>Molding</td>
<td>Molding machine</td>
<td>Mold (ejector for hot polymer)</td>
</tr>
<tr>
<td>Rolling</td>
<td>Rolling mill</td>
<td>Roll (reduce work thickness)</td>
</tr>
<tr>
<td>Boring</td>
<td>Forginginance or press</td>
<td>Die (squeeze work to shape)</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Press</td>
<td>Extrusion die (reduce cross-section)</td>
</tr>
<tr>
<td>Stamping</td>
<td>Press</td>
<td>Die (shearing, forming sheet metal)</td>
</tr>
<tr>
<td>Milling</td>
<td>Machine tool</td>
<td>Cutting tool (material removal)</td>
</tr>
<tr>
<td>Grinding</td>
<td>Grinding machine</td>
<td>Fitter (hold workpart)</td>
</tr>
<tr>
<td>Welding</td>
<td>Welding machine</td>
<td>Fitter (hold parts during welding)</td>
</tr>
</tbody>
</table>

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

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. 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 people (blue collar workers) are responsible for operating the manufacturing equipment; and professional staff people (white collar workers) are responsible for manufacturing support systems.

1.4.1 Production Facilities

Production facilities consist of the factory, production equipment, and material handling equipment. The equipment comes in direct physical contact with the parts and 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, let us call them 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 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 in order 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 the 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, 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), we distinguish two different types of facility, 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 system 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 items are manufactured to replenish inventory that has been gradually depleted by demand. The equipment is usually arranged in a process layout (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 type 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 due to 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 4.1). The layout is called a cellular layout (the term group technology layout is also common), 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 (such as 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 (Figures 1.9(b) and (c)).

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 conveyors. 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 is where 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. In order 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 these situations where there is soft variety in the products made on the line. Modern automobile assembly lines are examples. 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 the 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 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 ORGANIZATION OF THE BOOK

The previous three sections provide a preview and an overview of our book. The remaining 44 chapters are organized into 11 parts. The block diagram in 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, titled 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 our text are those identified in Figure 1.4. Part III begins our coverage of the four categories of shaping processes. Part III consists of six chapters on the solidification processes that involve 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 used for 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 Part VII. Its three chapters are heat treatment, cleaning and surface treatments, and coating and deposition processes.

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 our classification scheme of Figure 1.4 are covered in Part IX, titled Special Processing and Assembly Technologies. Its five chapters cover rapid prototyping, processing of integrated circuits, electronics assembly and packaging, microfabrication, and nanofabrication.

The remaining blocks in Figure 1.10 deal with the systems of production. Part X, titled "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, such as manufacturing engineering, production planning and control, quality control, and inspection.

REFERENCES


REVIEW QUESTIONS

1.1. What are the differences between 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 subdivisions of assembly processes? Provide an example process for each subdivision.
1.8. Define batch production and describe why it is often used for medium-quantity production products.

MULTIPLE CHOICE QUIZ

There is a total of 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) beverage, (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. Ferric 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 semi-solid state and solidifies the material in a cavity (two correct 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 correct answers): (a) adhesive bonding, (b) deformation, (c) forging, (d) material removal, (e) rolling, (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) rolling 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 correct answers): (a) 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

THE NATURE OF MATERIALS

CHAPTER CONTENTS
2.1 Atomic Structure and the Elements
2.2 Bonding Between Atoms and Molecules
2.3 Crystalline Structures
2.3.1 Types of Crystal Structures
2.3.2 Imperfections in Crystals
2.3.3 Deformation in Metallic Crystals
2.3.4 Grains and Grain Boundaries in Metals
2.4 Noncrystalline (Amorphous) Structures
2.5 Engineering Materials

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. We find that 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?

In this chapter, we consider the atomic structure of matter and the bonding between atoms and molecules. We also show 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 there is usually a preference for a particular form exhibited by a given material. Metals, for example, almost always exist as crystals in their solid state. Glass (e.g., window glass), a ceramic, assumes a noncrystalline form.

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