Product Design and Process Selection in a Competitive Environment

CHAPTER 40

- Manufacturing high-quality products at the lowest possible cost is critical in a global economy.
- This chapter discusses the many interrelated factors in product design, development, and manufacturing.
- The chapter begins with a discussion of product design and life-cycle considerations in design and manufacturing.
- Material and process selection, together with their effects on design and manufacturing, are then described, followed by a discussion of the important factors involved in the costs associated with a product.
- Finally, the principle of value analysis is described, along with a discussion of how it can help optimize manufacturing operations and minimize product cost.

EXAMPLES:

CASE STUDY:

40.1 Introduction

In an increasingly competitive global marketplace, manufacturing high-quality products at the lowest possible cost requires an understanding of the often complex relationships among numerous factors. It was indicated throughout this text that

1. Product design and selection of materials and manufacturing processes are interrelated, and
2. Designs are periodically modified to,
    - a. Improve product performance,
    - b. Strive for zero-based rejection and waste,
    - c. Make products easier and faster to manufacture,
    - d. Consider new materials and processes that are continually being developed.

Because of the increasing variety of materials and manufacturing processes now available, the task of producing a high-quality product by selecting the best materials and the best processes, and at the same time minimizing costs, continues to be a major challenge, as well as an opportunity. The term **world class** is widely used to indicate high levels of product quality, signifying the fact that products must meet international standards and be marketable and acceptable worldwide. Recall also that world-class status, like product quality, is not a fixed target for a company to reach, but rather a *moving target*, rising to higher and higher levels as time passes (also known as *continued improvement*).

Although the *selection of materials* for products traditionally has required much experience, several databases and expert systems are now available that greatly facilitate the selection process that is aimed at meeting specific requirements. Also, in reviewing the materials used in existing products (from simple hand tools to automobiles and aircraft), there are numerous opportunities for the *substitution of materials* for improved performance and, especially, cost savings.

In the production phase, it is imperative that the *capabilities of manufacturing processes* be properly assessed as an essential guide to the ultimate selection of an appropriate process or sequence of processes. As described throughout this book, there usually is more than one method of manufacturing a product, its components, and its subassemblies.

Increasingly important are the *life-cycle assessment* and *life-cycle engineering* of products, services, and systems, particularly regarding their potentially adverse impact on the environment. The major emphasis now is on *sustainable manufacturing*, with the purpose of reducing or eliminating any and all adverse effects of manufacturing on the environment, while still allowing a company to be profitable.

Although the *economics* of individual manufacturing processes has been described throughout the book, this chapter takes a broader view and summarizes the important overall manufacturing cost factors. It also introduces cost-reduction methods, including *value analysis*, which is a powerful tool to evaluate the cost of each manufacturing step relative to its contribution to a product's value.

40.2 Product Design

Those aspects which are relevant to *design for manufacture and assembly* (DFMA), as well as to competitive manufacturing, have been highlighted throughout various chapters of this text. Several guidelines for the selection of materials and manufacturing processes are given in the references listed in Table 40.1. Major advances are continually being made in design for manufacture and assembly, for which a number of software packages are now available. Although their use requires considerable training, these advances greatly help designers develop high-quality products with fewer components, thus reducing production time and assembly and, consequently, reducing product cost.

Product Design Considerations. In addition to the design guidelines we have given regarding individual manufacturing processes, there are general product design considerations. (See also *robust design*, Section 36.5.1.) Designers often must check and verify whether they have addressed considerations such as the following:

- Have all alternative designs been thoroughly investigated?
- Can the design be simplified and the number of its components minimized without adversely affecting its intended functions and performance?
- Can the design be made smaller and lighter?
- Are there unnecessary features in the product or some of its components, and if so, can they be eliminated or combined with other features?
- Have modular design and building-block concepts been considered for a family of similar products and for servicing and repair, upgrading, and installing options?
- Are the specified dimensional tolerances and surface finish unnecessarily tight, thereby significantly increasing product cost, and if so, can they be relaxed without any adverse effects?

TABLE 40.1

References to Various Topics in This Book (Page numbers are in parentheses)

Material Properties
Tables 2.1 (57), 2.2 (59), 2.3 (62), and Figs. 2.4, 2.6, 2.7, 2.8, 2.15, 2.16, 2.17, 2.29
Tables 3.1 (89), 3.2 (90), and Figs. 3.1, 3.2, 3.3
Tables 5.2 (139), 5.4 (141), and 5.5 (144)
Tables 6.3 through 6.10 (153–162)
Tables 7.1 (172), 7.2 (180), 7.3 (186)
Tables 8.1 (199), 8.2 (202), 8.3 (206)
Tables 9.1 (218), 9.2 (220), 9.3 (228), and Figs. 9.3, 9.5, 9.7
Table 10.1 (248)
Table 11.3 (281)
Tables 12.3 (304), 12.4 (305), 12.5 (305), and Fig. 12.4
Tables 16.2 (392), 16.3 (398), 16.4 (409), and Fig. 16.14
Tables 17.3 (455), 17.4 (455), 17.5 (456), and Fig. 17.10
Table 20.2 (529)
Tables 22.1 (593), 22.2 (594), 22.3 (594), 22.5 (600), and Figs. 22.1, 22.9
Table 26.1 (721)
Table 32.3 (931)

Manufacturing Characteristics of Materials
Table I.3 (16)
Table 4.1 (120)
Table 5.8 (147)
Table 6.2 (152)
Tables 12.1 (297), 12.6 (308)
Table 14.3 (348)
Table 16.3 (398), and Fig. 16.33
Tables 17.1 (447), 17.2 (453)
Tables 21.1 (559), 21.2 (571)
Fig. 22.2

Dimensional Tolerances and Surface Finish
Table 11.2 (261)
Table 23.1 (617), and Figs. 23.13, 23.14
Fig. 25.16
Fig. 27.4
Figs. 35.19, 35.20
Figs. 40.4, 40.5

Capabilities of Manufacturing Processes
Tables 11.1 (259), 11.2 (261)
Table III.1 (315)
Table 14.1 (337), 14.4 (353)
Table 16.1 (383)
Section 17.7 and Fig. 17.14
Table 18.1 (466)
Tables 19.1 (485), 19.2 (521)
Table 20.1 (528)
Tables 23.1 (617), 23.6 (627), 23.8 (635), 23.10 (644)
Tables 26.3 (735), 26.4 (736)
Table 27.1 (761)
Tables 28.1 (801), 28.2 (809), 28.3 (810), and Fig. 28.19
Tables 29.1 (847), 29.3 (856)
Table VI.1 (864)
Table 30.1 (866)
Table 32.4 (932)
Table 34.1 (989)
Table 37.2 (1056), and Fig. 37.3
Table 39.1 (1121)
Tables 40.3 (1146), 40.5 (1153), and Figs. 40.2, 40.3, 40.5

Design Considerations in Processing
Abrasive processes: Section 26.5
Advanced machining: Various sections in Chapter 27
Casting: Section 12.2
Ceramics shaping: Section 18.5
Forging: Section 14.6
Heat Treating: Section 4.13
Joining processes: Various sections in Chapters 30–32
Machining: Sections in Chapters 23–24
Polymers processing: Section 19.15
Powder metallurgy: Section 17.6
Sheet-metal forming: Section 16.13

General Costs and Economics
Tables I.5 (30), I.6 (33), I.7 (34), and Section I.10
Table 6.1 (152)
Section 12.4
Section 14.9
Section 16.15
Table 17.6 (461) and Section 17.8
Table 19.2 (521) and Section 19.16
Section 25.8
Section 26.9 and Fig. 26.35
Section 27.11
Section 31.8
Section 32.7
Section 37.11
Section 39.9
Table 40.6 (1157) and Section 40.9

- Will the product be difficult or excessively time consuming to assemble and disassemble for maintenance, servicing, or recycling of some or all of its components?
- Is the use of fasteners minimized, including their quantity and variety?
- Have environmental considerations been taken into account and incorporated into product design and material and process selection?

- Have green design and life-cycle engineering principles been applied, including recycling and cradle-to-cradle considerations?
- Can any of the design activities be outsourced?

40.2.1 Product Design and Quantity of Materials

Depending on the particular product, the cost of materials can become a significant portion of the total cost. Although material costs cannot be reduced below the often-fluctuating market level, reductions can be made in the *quantity* of the materials used in each of the components of a product. The wide use of available techniques, such as minimum-weight design; design optimization; and computer-aided design, manufacturing, and assembly, as well as the availability of vast resources on materials and their characteristics, have greatly facilitated design analysis, material selection and process, and overall optimization.

Significant reductions in the quantity of materials purchased can be achieved by reducing the component's volume or using materials with higher strength-to-weight or stiffness-to-weight ratios. The latter can be attained by improving and optimizing the product design and by selecting different cross sections, such as those having a high moment of inertia (such as I-beams and channels) or by using tubular or hollow components instead of solid bars.

Implementing such design changes may, however, present significant challenges in manufacturing. Consider, for example, the following:

a. Casting or molding thin cross sections can present difficulties in die and mold filling and in meeting specified dimensional accuracy and surface finish (Section 12.2).

b. Forging of thin sections requires high forces, due to friction, and especially in hot forging, due to rapid chilling of tin regions (Section 14.3).

c. Impact extrusion of thin-walled parts can be difficult, especially when high dimensional accuracy and symmetry are required (Section 15.4.1).

d. The formability of sheet metal may be reduced as sheet thickness decreases; it also can lead to buckling of the part under the high compressive stresses developed in the plane of the sheet during forming (Section 16.3).

e. Machining and grinding of thin workpieces may lead to part distortion, poor dimensional accuracy, and vibration and chatter (Section 26.5); consequently, advanced machining processes have to be considered (Chapter 27).

f. Welding thin sheets or slender structures can cause significant distortion due to thermal gradients developed during welding (Section 30.10).

Conversely, making parts with thick cross sections can have their own adverse effects. Consider, for example, the following:

a. In processes such as die casting (Section 11.4.5) and injection molding (Section 19.3), the production rate can become slower because of the increased cycle time required to allow sufficient time for the thicker regions to cool before removing the part from the mold.

b. Porosity can develop in thicker regions of castings, unless controlled (Fig. 10.14).

c. The bendability of sheet metals decreases as their thickness increases (Section 16.5).

d. In powder metallurgy, there can be significant variations in density and, hence, properties, throughout parts with varying thicknesses (Section 17.6).

e. Welding thick sections can present problems in the quality of the welded joint (Section 30.9).

f. In die-cast parts, thinner sections will have a higher strength per unit thickness (because of the smaller grain size developed), compared with thicker sections (Section 11.4.5).

g. Processing plastic parts requires increased cycle times as their thickness or volume increases; this is because of the longer time required for the parts to cool sufficiently to be removed from the molds (Chapter 19).

EXAMPLE 40.1 An Application of Design for Manufacturing and Assembly

The redesign of the pilot's instrument panel for a military helicopter, built by McDonnell-Douglas, was considered with a view toward reducing the number of parts in the panel (and thus also its weight) and the time required for its fabrication and assembly. The components of the panel consisted of sheet metal, extrusions, and rivets.

Using DFMA software and analyzing the panel in detail, it was estimated that the redesign would lead to the following changes: (a) the number of parts, from 74 down to 9; (b) the panel weight, from 3.00 kg to 2.74 kg; (c) fabrication time, from 305 hrs to 20 hrs; (d) assembly time, from 149 hrs to 8 hours; and (e) total production time, from 697 hrs to 181 hrs. It also was estimated that, as a result of design modifications, cost savings would be 74%. On the basis of these results, other components of the instrument panel were subjected to such analysis as well, resulting in similar savings.

40.3 Product Quality and Life Expectancy

Product quality and the techniques involved in quality assurance and control are described in detail in Chapter 36. Recall that the word *quality* is difficult to define precisely, partly because it includes not only well-defined technical characteristics, but also human, and hence subjective, opinions. Generally, however, a high-quality product is considered to have at least the following characteristics:

- It satisfies the needs and expectations of the customer.
- It has a pleasing appearance and handles well.
- It has high reliability and functions safely over its intended life.
- It is compatible with and responsive to the customer's capabilities and working environment.
- Installation, maintenance, and future improvements are easy to perform and at low cost.

A major priority in product quality is the concept of **continuous improvement**, as exemplified by the Japanese term **kaizen**, meaning *never-ending improvement.* Note, however, that the level of quality a manufacturer chooses to impart to a particular product depends on the particular market for which the product is intended. For example, low-quality, low-cost products have their own market niche, including what are commonly referred to as dollar stores. Conversely, there always is a market for high-quality, expensive products, such as a Rolls-Royce automobile, a gold and diamond-studded wristwatch, high-performance sports equipment, and a high-precision machine tool.

40.3.1 Return on Quality

In implementing quality into products, it is important to understand the concept of *return on quality* (ROQ), because of the following considerations:

- Quality must be viewed as an investment, because of its major influence on customer satisfaction.

- An incremental improvement in quality vis-a-vis the additional costs involved must be carefully investigated.
- There must be a certain limit on how much should be spent on quality improvements.
- Because quality can be rather subjective, all changes to be made must be critically evaluated.

Although customer satisfaction is a qualitative factor and is difficult to include in calculations, satisfaction is increased and customers are more likely to be retained (and become repeat customers) when there are no defects in products.

On the one hand, high-quality products do not necessarily cost more. For example, in industries making computer chips and computer hardware, the ROQ is minimized while the aim is to approach zero defects. (See also *six sigma*, Section 36.7.2.) On the other hand, there are other products, such as ordinary door hinges, water faucets, and hubcaps, for which the additional cost involved in eliminating the final few defects can be unnecessarily high. It also is important to consider the fact that the relative costs involved in identifying and repairing defects in products grow by orders of magnitude, in accordance with the *rule of ten*, as shown in Table I.5.

Life Expectancy of Products. The *average life expectancies* of products are given in Tables I.4 and 36.1. As expected, life expectancies within each group of products can vary significantly; the variations will depend on the materials and production processes employed.

40.4 Life-cycle Assessment and Sustainable Manufacturing

Life-cycle assessment (LCA) is defined, according to the ISO 14000 standard (Section 36.6.3), as "a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts or burdens directly attributable to the functioning of a product, process, or service system throughout its *entire* life cycle." The **life cycle** involves consecutive and interlinked stages of a product or a service, from the very beginning to its disposal or recycling, and includes the following:

a. Extraction of natural resources.
b. Processing of raw materials.
c. Manufacturing of products.
d. Transportation and distribution of the product to the customer.
e. Use, maintenance, and reuse of the product.
f. Recovery, recycling, and reuse of the components of the product, or else their disposal, including metalworking fluids, cleaning solvents, and various liquids used in heat-treating and plating processes.

All of these factors are basically applicable to any type of product. Recall that each type of product has its own metallic and nonmetallic materials, processed into individual components and assembled; thus, each product has its own life cycle. Moreover, (a) some products, particularly those made of paper, cardboard, inexpensive plastic, and glass, are intentionally made to be disposable, but nonetheless are recyclable, and (b) numerous other products are completely reusable.

Life-cycle Engineering. The major aim of *life-cycle engineering* (LCE) is to consider *reusing* and *recycling* the components of a product, beginning with the earliest stage: product design. Life-cycle engineering is also called **green design** or **green engineering.** The considerations involved include environmental factors, optimization, and numerous technical factors regarding each component of a product.

Although life-cycle analysis and engineering are comprehensive and powerful tools, their implementation can be challenging, time consuming, and costly, largely because of uncertainties (regarding materials, processes, long-term effects, costs, etc.) in the input data and the time required to collect reliable data to properly assess the often complex interrelationships among all the components of the whole system. Various software is being developed to expedite these analyses, particularly for the chemical and process industries, because of the higher potential for environmental and ecological damage in their operation. Examples of such software include FeaturePlan and Teamcenter, which runs in a ProEngineer environment.

Cradle-to-cradle Production. In examining the importance of product life-cycle considerations, the principles of *cradle-to-grave* and *cradle-to-cradle* production were described in some detail in Section I.4. The case study that follows illustrates an application of this type of production.

CASE STUDY 40.1 Automobile Tires: From Cradle-to-grave to Cradle-to-cradle

Automobiles, buses, trucks, tractors, and motorcycles are pervasive in modern society. They are depended on for personal transport as well as for commerce, and they bring products to markets that are accessible to consumers.

One major environmental concern associated with such vehicles is caused by the need to periodically purchase new tires. Even though tires have surprisingly high wear resistance, they eventually (after about 65,000 km to 100,000 km) are not suited for further safe operation on vehicles. Traditionally, tires have been removed and replaced with new ones, with the discarded tires typically dumped in landfills. This practice has now become an environmental hazard as the number of discarded tires continues to grow. Each year in the United States, there are around 300 million tires discarded, mostly in landfills.

The traditional model of manufacturing a tire and taking into account its use and disposal is a classic example of *cradle-to-grave* production. However, tires do not fit into the biological *recycling* paradigm, because they do not readily break down into nutrients for organisms and thus take several decades to decompose in landfills. Although tires are flammable, their combustion produces harmful gases and particulates, making incineration an unviable option for disposal. As a result, the traditional life cycle has led to an accumulation of discarded tires.

The product life cycle for tires is being transformed by PermaLife products into a *cradle-to-cradle* model. The company takes discarded tires and processes them as follows:

- In a cryogenic freezing operation, the tire is separated into its major components: rubber, and steel and fiber reinforcement. The rubber is subjected to a temperature below its glass-transition temperature (Section 7.2.3), which, for the type of rubber tires are made of, is −115°C. The steel and fiber reinforcements in the tire are not significantly affected by this operation. At −115°C, the rubber becomes very brittle, and when processed in a hammer mill (shown in Fig. 17.6c), it shatters into millions of small pieces.
- The rubber, in the form of small particles, is then easily separated from the fiber or fiber mesh and the steel reinforcements, which are then recycled separately from the rubber.
- Colors can be added to the granulated material.

The resulting artificial mulch, referred to by its trade name of Permalife Softstuff™, has successfully been used as a playground material, for landscaping, and as a support material beneath artificial turf widely used in sports stadiums around the world. From a functional standpoint, this material can be tailored to the particular application: (a) For playgrounds, a soft material can be developed with a large-size granule to prevent injury in the case of a child falling, while also making its ingestion unlikely. (b) For professional athletic competitions, the material can be made stiffer, so that the likelihood of injury is low while athletic performance is optimized.

The major advantages of this material are as follows:

- The material will not cause splinters or attract insects (as opposed to natural wood mulch).
- Maintenance is less costly and more environmentally friendly, as opposed to natural grass surfaces, which require fertilizer and maintenance for optimum performance.
- The material does not stain, as opposed to wood or grass surfaces.

Source: Courtesy of M. Sergia and N. Menonna, Permalife, Inc.

Sustainable Manufacturing. As is now universally acknowledged, the natural resources on this Earth are limited, thus necessitating conservation of both materials and energy. The concept of *sustainable manufacturing* emphasizes the need for conserving resources, particularly through proper maintenance and reuse. While profitability is important to an organization, sustainable manufacturing is meant to meet purposes such as (a) increasing the life cycle of products, (b) eliminating harm to the environment and the ecosystem, and (c) ensuring our collective well-being, especially that of future generations.

EXAMPLE 40.2 Sustainable Manufacturing in the Production of Nike Athletic Shoes

Among numerous examples from industry, the production of Nike shoes indicates the benefits of sustainable manufacturing. These athletic shoes are assembled with the use of adhesives. Up to around 1990, the adhesives used contained petroleum-based solvents, which pose health hazards to humans and contribute to petrochemical smog. The company cooperated with chemical suppliers to successfully develop a water-based adhesive technology, now used in the majority of shoe-assembly operations. As a result, solvent use in all manufacturing processes in Nike's subcontracted facilities in Asia has been greatly reduced.

Regarding another component of the shoe, the rubber outsoles are made by a process that results in significant amounts of extra rubber around the periphery of the sole (called *flashing*, similar to the flash shown in Fig. 14.5d). With about 40 factories using thousands of molds and producing over a million outsoles a day, flashing constitutes the largest chunk of waste in manufacturing the shoes. In order to reduce this waste, the company developed a technology that grinds the flashing into 500-μm rubber powder, which is then added back into the rubber mixture needed to make the outsole. With this approach, waste was reduced by 40%. Moreover, it was found that the mixed rubber had better abrasion resistance and durability, and its overall performance was higher than the best premium rubber.

40.5 Material Selection for Products

In selecting materials for a product, it is essential to have a clear understanding of the *functional requirements* for each of its individual components. The general criteria for selecting materials were described in Section I.5 of the General Introduction; this section will discuss them in more specific detail.

General Properties of Materials. *Mechanical properties* (Chapter 2) include strength, toughness, ductility, stiffness, hardness, and resistance to fatigue, creep, and impact. *Physical properties* (Chapter 3) include density, melting point, specific heat, thermal and electrical conductivity, thermal expansion, and magnetic properties. *Chemical properties* of primary concern in manufacturing are susceptibility to oxidation and corrosion and to the various surface-treatment processes described in Chapter 34.

The following considerations are significant in the selection of materials for various products:

- Do the materials selected have the appropriate manufacturing characteristics?
- Can some of the materials be replaced by others that are less expensive?
- Do the materials under consideration have properties that meet minimum requirements and specifications?
- Are the raw materials (also called *stock*) specified available in standard shapes, dimensions, tolerances, and surface characteristics?
- Is the supplier of the materials reliable? Can the materials be delivered in the required quantities within the required time frame? Are there likely to be significant price increases or fluctuations?
- Does the material present any environmental hazards or concerns?

Material selection has become easier and faster because of the increasing availability of extensive computer databases that provide greater accessibility and accuracy. In order to facilitate the selection of materials, **expert-system software** (called **smart databases**, Section 39.8) has been developed. With the proper input of product design and functional requirements, these systems are capable of identifying appropriate materials for a specific application, just as an expert or a team of experts would.

Shapes of Commercially Available Materials. After selecting appropriate materials, the next step is to determine the shapes and the sizes in which these materials are available commercially (Table 40.2). Depending on the type of material (metal, polymer, ceramic, etc.) materials generally are available as castings, extrusions, forgings, powder metals, drawn rod and wire, and rolled bars, plates, sheets, and foil.

Purchasing materials in shapes that require the least amount of additional processing obviously is an important economic consideration. Also relevant are such characteristics as surface finish and quality, dimensional tolerances, straightness, and flatness. (See, e.g., Figs. 27.4, 23.13, and 23.14, and Table 11.2.) The better and the

TABLE 40.2

Shapes of Commercially Available Materials

Material	Available as
Aluminum	B, F, I, P, S, T, W
Ceramics	B, p, s, T
Copper and brass	B, f, I, P, s, T, W
Elastomers	b, P, T
Glass	B, P, s, T, W
Graphite	B, P, s, T, W
Magnesium	B, I, P, S, T, w
Plastics	B, f, P, T, w
Precious metals	B, F, I, P, t, W
Steels and stainless steels	B, I, P, S, T, W
Zinc	F, I, P, W

Note: B = bar and rod; F = foil; I = ingots; P = plate and sheet; S = structural shapes; T = tubing; W = wire. Lowercase letters indicate limited availability.

more consistent these characteristics are, the less additional processing will be required. Note, for example, that if we want to produce simple shafts with good dimensional accuracy, roundness, straightness, and surface finish, then we could purchase round bars that are first turned or drawn and then centerless-ground (Fig. 26.22) to the dimensions specified. Unless the facilities in a plant have the capability of producing round bars economically, it generally is cheaper to purchase them. If we need to make a stepped shaft (i.e., a shaft having different diameters along its length, as shown in Fig. IV.3), we could purchase a round bar with a diameter at least equal to the largest diameter of the stepped shaft and then turn it on a lathe or process it by some other means in order to reduce its diameter.

Each manufacturing operation produces parts that have specific shapes, surface finishes, and dimensional accuracies. Consider the following examples:

- Castings generally have lower dimensional accuracy and a poorer surface finish than parts made by cold forging, cold extrusion, or powder metallurgy.
- Hot-rolled or hot-drawn products generally have a rougher surface finish and larger dimensional tolerances than cold-rolled or cold-drawn products.
- Extrusions have smaller cross-sectional tolerances than parts made by roll forming of sheet metal.
- Round bars machined on a lathe have a rougher surface finish than similar bars that are ground.
- The wall thickness of welded tubing is generally more uniform than that of seamless tubing, which is typically produced by the Mannesmann process (Fig. 13.18).

Manufacturing Characteristics of Materials. Manufacturing characteristics of materials generally include castability, workability, formability, machinability, weldability, and hardenability by heat treatment. Raw materials have to be formed, shaped, machined, ground, fabricated, or heat treated into individual components having specific shapes and dimensions; consequently, a knowledge of their manufacturing characteristics is essential.

Recall that the quality of the raw material can greatly influence its manufacturing properties. The following are typical examples (see also individual processes):

- A bar with a longitudinal seam, or lap, will develop cracks during simple upsetting and heading operations.
- Round rods with internal defects such as hard inclusions will crack during further processing.
- Porous castings will develop a poor surface finish when subsequently machined.
- Parts that are nonuniformly heat treated and cold-drawn bars that are not properly stress relieved will distort during subsequent processing.
- Incoming stock that has variations in composition and microstructure cannot be heat treated or machined consistently and uniformly.
- Sheet-metal stock having variations in its cold-worked conditions will exhibit different degrees of springback during bending and other forming operations because of differences in yield stress.
- If prelubricated sheet-metal blanks are supplied with nonuniform lubricant thickness and distribution, their formability, surface finish, and overall quality in subsequent stamping operations will be adversely affected.

Reliability of Material Supplies. There are several factors that influence the reliability of material supplies: shortages, strikes, geopolitical factors, and the reluctance of suppliers to produce materials in a particular shape or quality. Even though raw materials may generally be available throughout a country as a whole, they may not readily be available at a particular plant's location.

Recycling Considerations. Recycling may be relatively simple for products such scrap metal, plastic bottles, etc.; it often requires that individual components of a product be taken apart and separated. Also, obviously, if much effort and time has to be expended in doing so, recycling may become prohibitively expensive. Some general guidelines to facilitate the process during the life cycle of a product are as follows:

- Reduce the number of parts and types of materials in products.
- Reduce the variety of product models.
- Use a modular design to facilitate disassembly.
- For plastic parts, use single types of polymers as much as possible.
- Mark plastic parts for ease of identification, as is done with plastic food containers and bottles (See Section 7.8).
- Avoid using coatings, paints, and plating; instead, use molded-in colors in plastic parts.
- Avoid using adhesives, rivets, and other permanent joining methods in assembly; instead, use fasteners, especially snap-in fasteners.

As an example of this type of approach to recycling, one manufacturer of laser-jet printers reduced the number of parts in a cartridge by 32% and the variety of plastic materials by 55%.

Cost of Materials and Processing. Because of its processing history, the unit cost of a raw material (typically, cost per unit weight) depends not only on the material itself, but also on its shape, size, and condition. For example, because more operations are involved in the production of thin wire than in that of round rod, the unit cost of the thin wire is much higher. Similarly, powder metals generally are more expensive than bulk metals. Furthermore, the cost of materials typically decreases as the quantity purchased increases. Likewise, certain segments of industry (such as automotive companies) purchase materials in very large quantities; the larger the quantity, the lower is the cost per unit weight (bulk discount).

Table 6.1 shows the cost per unit volume relative to that of carbon steel. The benefit of cost per volume can be seen by the following simple example: In the design of a steel cantilevered rectangular beam supporting a certain load at its end, a maximum deflection is specified. Using equations from handbooks, and assuming that the weight of the beam can be neglected, we can determine an appropriate cross section of the beam. Since all dimensions are now known, the volume of the beam can be calculated; then the cost of the beam can be determined by multiplying the volume by the cost of the material per unit volume. Note, on the other hand, if the cost is given per unit weight, we first have to calculate the weight of the beam and then determine the cost.

The cost of a particular material is subject to fluctuations caused by factors as simple as supply and demand or as complex as geopolitics. If a product is no longer cost competitive, alternative and less costly materials may have to be selected. For example, (a) the copper shortage in the 1940s led the U.S. government to mint pennies from zinc-plated steel, (b) when the price of copper increased substantially during the 1960s, electrical wiring in homes was switched to aluminum; however, this substitution led to the redesign of terminals of switches and outlets in order to avoid excessive heating at the junctions, because aluminum has a higher contact resistance than copper.

Scrap. When scrap is produced during manufacturing, as in sheet-metal fabricating, forging, and machining (Table 40.3), the value of the scrap is deducted from the material's cost in order to obtain the net material cost. As expected, the value of the scrap depends on the type of metal and on the demand for it; typically, it is between

TABLE 40.3

Approximate Percentages of Scrap Produced in Various Manufacturing Processes

Process	Scrap (%)	Process	Scrap (%)
Machining	10–60	Permanent-mold casting	10
Hot forging	20–25	Powder metallurgy	<5
Sheet-metal forming	10–25	Rolling	<1
Hot extrusion	15		

10 and 40% of the original cost of the material. Note that, in machining, scrap can be very high, whereas operations such as rolling, ring rolling, and powder metallurgy (all of which are net- or near-net-shape processes) produce the least scrap.

EXAMPLE 40.3 Effect of Workpiece Hardness on Cost in Drilling

Gear blanks forged from 8617 alloy steel and having a hardness range from 149 to 156 HB required the drilling of a hole 75 mm in diameter in the hub. The blanks were drilled with a standard helix drill. After only 10 pieces, however, the drill became dull, temperatures increased excessively, and the drilled holes had developed a rough internal surface finish. In order to improve machinability and reduce galling, the hardness of the gear blanks was increased to range from 217 to 241 HB by heating them to 840°C and then quenching them in oil. When blanks at this hardness level were drilled, galling was reduced, surface finish was improved, drill life increased to 50 pieces, and the cost of drilling was reduced by 80%.

Source: ASM International.

40.6 Material Substitution

There is hardly a product on the global market today for which the *substitution of materials* has not played a major role in helping companies maintain their competitive positions. Automobile and aircraft manufacturing are typical examples of major industries in which the substitution of materials is an ongoing activity; a similar trend is evident in sporting goods and numerous other products.

Although new products continually appear on the market, the majority of the design and manufacturing activities is concerned with improving existing products. There are several reasons for substituting materials in existing products:

1. Reduce the costs of materials and processing.
2. Improve manufacturing, assembly, and installation, and allow conversion to automated assembly.
3. Improve the performance of the product, such as by reducing its weight and by improving resistance to wear, fatigue, and corrosion.
4. Increase stiffness-to-weight and strength-to-weight ratios.
5. Reduce the need for maintenance and repair.
6. Reduce vulnerability to the unreliability of the supply of materials.
7. Improve compliance with legislation and regulations prohibiting the use of certain materials.

8. Improve robustness to reduce variations in performance or environmental sensitivity of the product.
9. Increase the ease of recycling for environmental reasons.

Substitution of Materials in the Automobile Industry. The automobile is a good example of the effective substitution of materials in order to achieve one or more of the objectives outlined previously. Some examples of material substitution in automobiles are as follows:

- Certain components of the metal body replaced with plastic or reinforced-plastic parts.
- Metal bumpers, gears, pumps, fuel tanks, housings, covers, clamps, and various other components replaced with plastics or composites.
- Carbon-steel chassis pillars replaced by TRIP or TWIP steels (see Section 5.5.6).
- Metallic engine components replaced with ceramic and composites parts.
- All-metal driveshafts replaced with composite-material driveshafts.
- Cast-iron engine blocks changed to cast-aluminum, forged crankshafts to cast crankshafts, and forged connecting rods to cast, powder-metallurgy, or composite-material connecting rods.
- Leather seats in automobiles in some luxury cars (including Mercedes) can now be replaced (offered as an option) with synthetic materials in response to concerns raised by advocacy groups.

Because the automobile industry is a major consumer of both metallic and nonmetallic materials, there is constant competition among suppliers, particularly in steel, aluminum, and plastics. Industry engineers and management continually are investigating the relative advantages and limitations of these principal materials in their applications, recycling and other environmental considerations, and relative costs and benefits (in particular).

Substitution of Materials in the Aircraft and Aerospace Industries

- Conventional aluminum alloys (particularly 2000 and 7000 series) are being replaced with aluminum–lithium alloys, titanium alloys, polymer-reinforced composites, and **glass-reinforced aluminum** because of the higher strength-to-weight ratios of these materials. (See Example 9.4.)
- Forged parts are being replaced with powder-metallurgy parts that are manufactured with better control of impurities and microstructure; the powder-metallurgy parts also require less machining and produce less scrap of expensive materials.
- Advanced composite materials and honeycomb structures are replacing traditional aluminum airframe components (Fig. 40.1), and metal-matrix composites are replacing some of the aluminum and titanium in structural components.

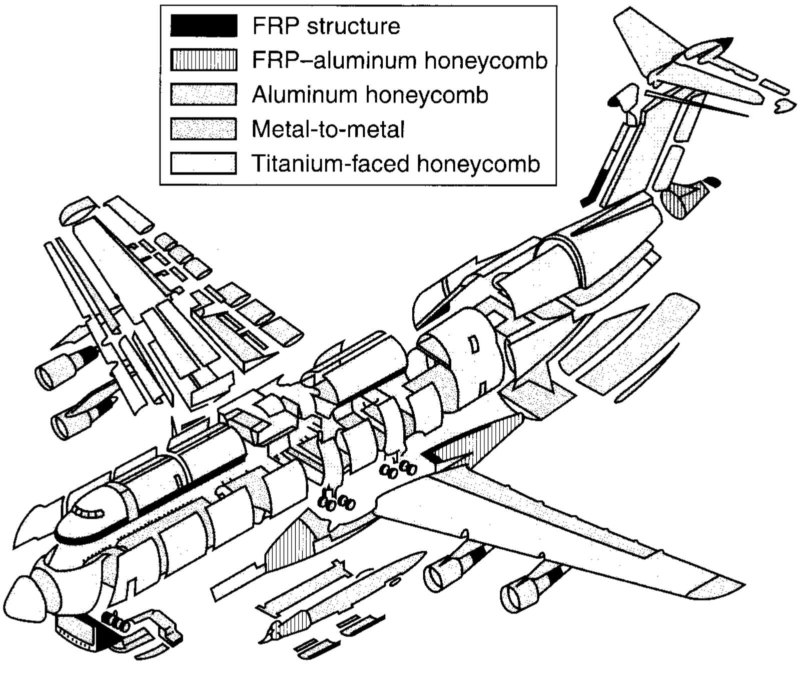

FIGURE 40.1 Advanced materials in the Lockheed C-5A transport aircraft. *Note*: FRP = fiber-reinforced plastic.

EXAMPLE 40.4 **Material Substitution in Common Products**

In the following list, the commonly available products can be made of either set of materials mentioned:

a. Metal vs. wooden baseball bat.

b. Metal vs. reinforced-plastic or wood handle for a hammer.

c. Plastic vs. metal intake manifold.

d. Cast-iron vs. aluminum lawn chair.

e. Plastic vs. sheet-metal light-switch plate.

These products are given as typical examples, and on the basis of the topics covered in various chapters throughout this book, the choice of materials can be reviewed with regard to their respective advantages and limitations.

EXAMPLE 40.5 **Material Changes between C-5A and C-5B Military Cargo Aircraft**

Table 40.4 shows the changes made in materials for various components of the two aircraft listed and the reasons for the changes.

Source: After H.B. Allison, Lockheed-Georgia.

TABLE 40.4

Material Changes from C-5A to C-5B Military Cargo Aircraft

Item	C-5A Material	C-5B Material	Reason for change
Wing panels	7075-T6511	7175-T73511	Durability
Main frame:			
Forgings	7075-F	7049-01	Stress-corrosion resistance
Machined frames	7075-T6	7049-T73	Stress-corrosion resistance
Frame straps	7075-T6 plate	7050-T7651 plate	Stress-corrosion resistance
Fuselage skin	7079-T6	7475-T61	Material availability
Fuselage underfloor	7075-T6 forging	7049-T73 forging	Stress-corrosion resistance end fittings
Wing–pylon attach fitting	4340 alloy steel	PH13-8Mo	Corrosion prevention
Aft ramp lock hooks	D6-AC	PH13-8Mo	Corrosion prevention
Hydraulic lines	AM350 stainless steel	21-6-9 stainless steel	Improved field repair
Fuselage failsafe straps	6Al-4V titanium	7475-T61 aluminum	Titanium strap debonding

40.7 Manufacturing Process Capabilities

Process capability is the ability of a particular manufacturing process to produce, under controlled production conditions, defect-free parts within certain limits of precision. (See also Section 36.8.2.) The capabilities of several manufacturing processes regarding their dimensional limits are shown in Fig. 40.2. Note, for instance, that sand casting (Section 11.2.1) cannot produce thin parts, whereas cold rolling (Section 13.3) is a process capable of producing very thin materials, as evidenced by a product such as aluminum foil.

Equally important as to overall dimensions are the capabilities of various processes to meet stringent dimensional tolerance and surface-finish requirements, as shown in Fig. 40.3. Note, for example, how sand casting is at the extreme opposite corner of microfabrication (Chapters 28 and 29). The importance of emphasizing the term "under controlled conditions" can be appreciated when one views the size of the envelopes in the figure. Note, for instance, the large envelope for machining and finishing operations, with boundaries that span three orders of magnitude. Thus, if a turning

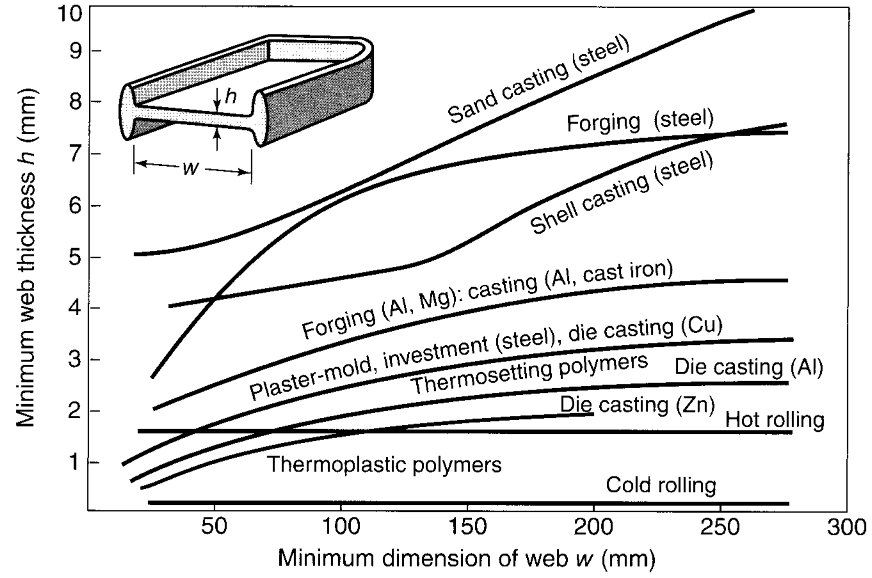

FIGURE 40.2 Manufacturing process capabilities for minimum part dimensions. *Source*: After J.A. Schey.

operation is carried out on an old lathe using inappropriate tools and processing parameters, then the tolerances and surface finish will, of course, be poor.

In the sections that follow, we describe important aspects of process capabilities as they relate to manufacturing processes and production operations.

Dimensional Tolerances and Surface Finish. The dimensional tolerances and surface finish produced are particularly important in subsequent assembly operations (because of possible difficulties in fitting the parts together for assembly) and in the proper operation of machines and instruments (because their performance can affect tolerances and finish). The dimensional tolerance and surface finish typically obtained by various manufacturing processes are illustrated qualitatively in Fig. 40.3.

Closer tolerances and better surface finish can be achieved by subsequent additional finishing operations (Section 26.7), but at higher cost, as shown in Fig. 40.4. Also, the finer the surface finish required, the longer is the manufacturing time (Fig. 40.5). In the machining of aircraft structural members made of titanium alloys, it has been observed that as much as 60% of the cost of machining may be expended in the final machining pass in order to maintain proper tolerances and surface finish. Thus, unless otherwise required, and with appropriate technical and economic justification, parts should be made with as rough a surface finish and as wide a dimensional tolerance as functionally and aesthetically will be acceptable.

Production Quantity. Depending on the type of product, the production quantity (also known as *lot size*) varies widely. For example, bearings, bolts, spark plugs, plastic containers, tires, automobiles, and lawn mowers are produced in very large quantities, whereas jet engines, diesel engines, locomotives, and medical equipment are produced in limited quantities. Production quantity also plays a significant role in process and equipment selection. In fact, an entire manufacturing discipline (called *economic order quantity*) is devoted to mathematically determining the optimum production quantity.

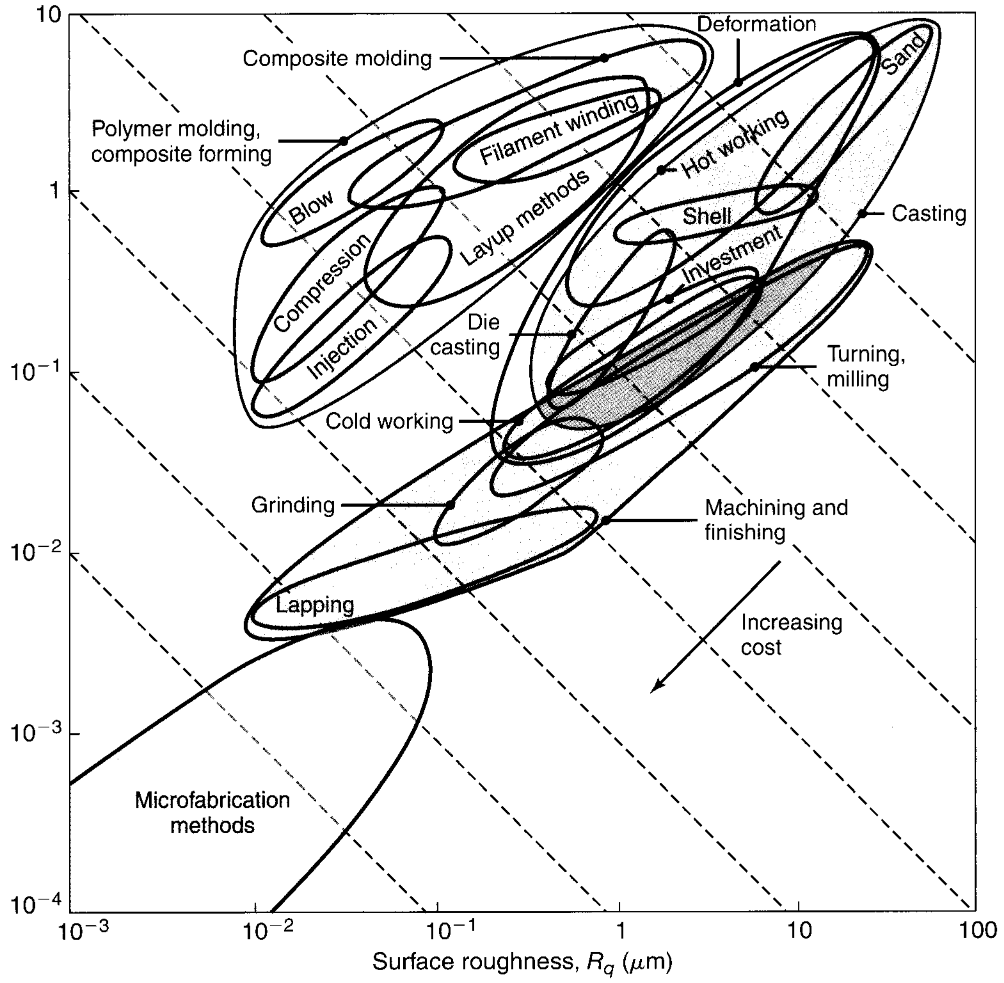

FIGURE 40.3 A plot of achievable tolerance versus surface roughness for assorted manufacturing operations. The dashed lines indicate cost factors, where an increase in precision corresponding to the separation of two neighboring lines gives an increase in cost for a given process (within a factor of two). *Source*: M.F. Ashby, *Materials Selection in Design*, Butterworth-Heineman, 1999.

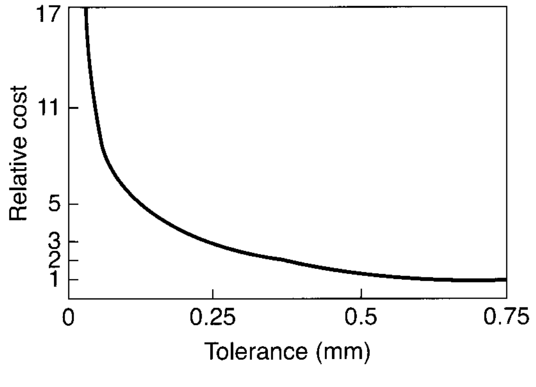

FIGURE 40.4 Dependence of manufacturing cost on dimensional tolerances.

Production Rate. An important factor in manufacturing process selection is the production rate, defined as the number of pieces to be produced per unit of time, such as per hour, per day, or per year. The production rate obviously can be increased by using multiple equipment and highly automated machines. Recall that processes such as die casting, powder metallurgy, deep drawing, wire drawing, and roll forming are high-production-rate operations. By contrast, sand casting, conventional and electrochemical machining, metal spinning, superplastic forming, adhesive and diffusion bonding, and the processing of reinforced plastics generally are relatively slow operations.

Lead Time. Lead time generally is defined as the length of time between the receipt of an order for a product and its delivery to the customer at a specified time. The selection of a manufacturing process and operation is greatly influenced by the time required to start production. Depending on the die's shape complexity, size, and material, the lead time for such processes as forging, extrusion, die casting, roll forming, and sheet-metal forming can range from weeks to months. Lead time can be a critical factor in an increasingly competitive marketplace, as well as under adverse conditions such as emergencies and wartime.

By contrast to the processes listed in the previous paragraph, processes such as machining, grinding, and advanced material-removal processes have significant built-in flexibility, due to the fact that they utilize machinery and tooling that can readily be adapted to most production requirements in a very short time. Recall that machining centers, flexible manufacturing cells, and flexible manufacturing systems are all capable of responding rapidly and effectively to product changes and to production quantities. (See also *rapid prototyping*, Chapter 20.)

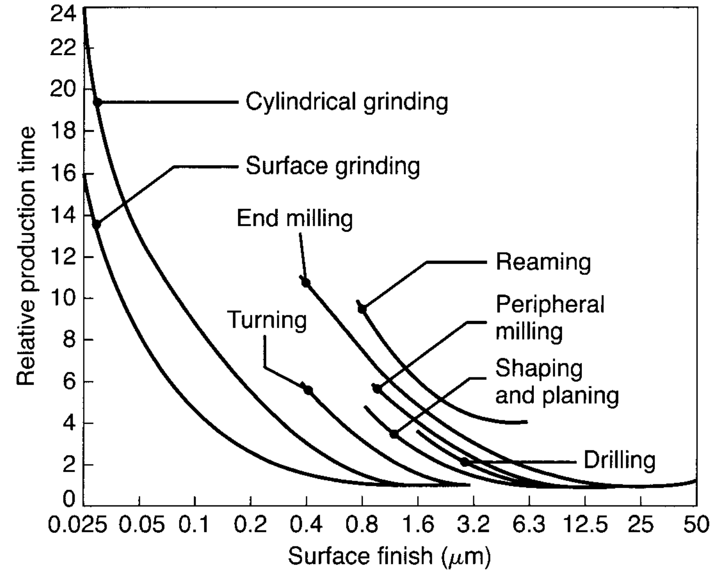

FIGURE 40.5 Relative production time as a function of surface finish produced by various manufacturing processes. (See also Fig. 26.35.)

Robustness of Manufacturing Processes and Machinery. *Robustness* was described in Section 36.5.1 as characterizing a design, a process, or a system that continues to function within acceptable parameters despite variabilities in its environment. In order to appreciate the importance of robustness in manufacturing processes, let's briefly consider a situation in which a simple plastic gear is being produced by injection molding (Section 19.3), but significant and unpredictable variations in quality arise as the gears are being produced. There are several well-understood variables and parameters in the injection molding of plastics, including the effects of raw-material (such as pellets) quality, speed, and temperatures within the system; all these are independent variables; hence, they can be controlled.

However, there are certain other variables, called *noise*, that are largely beyond the control of the operator. Among these are ambient-temperature and humidity variations in the plant throughout the day, dust in the air entering the plant from an open door (and thus possibly contaminating the pellets being fed into the hoppers of the injection-molding machine), and variability in the performance of individual operators during different shifts. Obviously, these variables are difficult or impossible to control precisely.

In order to obtain or sustain good product quality, it is necessary to understand the effects, if any, of each element of noise in the operation. For example, (a) Why and how does the ambient temperature affect the quality and surface characteristics of the molded gears? (b) Why and how does the dust coating on a pellet affect its behavior in the molding machine? (c) How different are the performances of different operators during different shifts, and why are they different? and (d) Are there inherent variations in machine performance during the day and, if so, how and why?

Such an investigation will make it possible to establish new operating parameters so that variations in, say, ambient temperature and the plant environment do not affect gear quality adversely. Note that these considerations are equally valid for any manufacturing operation, although some (such as bulk-deformation processes) are less sensitive to noise than others (especially microelectronics manufacturing).

40.8 Process Selection

Process selection is intimately related to the characteristics of the materials to be processed, as shown in Table 40.5.

Characteristics and Properties of the Workpiece Materials. Recall that some materials can be processed at room temperature, whereas others require elevated temperatures—and hence furnaces, appropriate tooling, and various controls. Some materials are easy to work with because they are soft and ductile. Other materials, such as those which are hard, brittle, and abrasive, require special processing technologies and equipment.

Materials have different manufacturing characteristics, such as castability, forgeability, workability, machinability, and weldability. Note from Table 40.5 that few materials have favorable characteristics in all of these relevant categories. For example, a material that is castable or forgeable may later present difficulties in subsequent processes, such as machining, grinding, and finishing, that may be required for an acceptable surface finish and dimensional accuracy.

Materials have different responses to the rate of deformation (strain-rate sensitivity, Sections 2.2.7 and 7.3) to which they are subjected. Thus, the speed at which a particular machine is operated can affect product quality, including the development of external and internal defects. Impact extrusion or drop forging, for example, may not be appropriate for materials with high strain-rate sensitivity, whereas such materials will perform well in a hydraulic press or in direct extrusion.

Geometric Features of the Part. Features such as part shape, size, and thickness, dimensional tolerances, and surface-finish requirements greatly influence the selection of a process or processes, as described throughout this chapter and various other chapters in the book.

Production Rate and Quantity. These requirements dictate process selection by way of the productivity of a process, machine, or system. (See Section 40.7.)

Process Selection Considerations. The factors involved in process selection are summarized by the following questions:

1. Are some or all of the parts or components that are needed commercially available as standard items?
2. Which components of the product have to be manufactured in the plant?
3. Is the tooling that is required available in the plant? If not, can it be purchased as a standard item?
4. Can group technology be implemented for parts with similar geometric and manufacturing attributes?
5. Have all alternative manufacturing processes been investigated?
6. Are the methods selected economical for the type of material, the part shape to be produced, and the required production rate?
7. Can the requirements for dimensional tolerances, surface finish, and product quality be met consistently, or can they be relaxed?
8. Can the part be produced to final dimensions without requiring additional processing or finishing operations?
9. Are all processing parameters optimized?
10. Is scrap produced, and if so, is it minimized? What is the value of the scrap?
11. Have all the automation and computer-control possibilities been explored for all phases of the total manufacturing cycle?
12. Are all in-line, automated inspection techniques and quality control being implemented properly?

TABLE 40.5

General Characteristics of Manufacturing Processes for Various Metals and Alloys

	Carbon steels	Alloy steels	Stainless steels	Tool and die steels	Aluminum alloys	Magnesium alloys	Copper alloys	Nickel alloys	Titanium alloys	Refractory alloys
Casting										
Sand	A	A	A	B	A	A	A	A	B	A
Plaster	—	—	—	—	A	A	A	—	—	—
Ceramic	A	A	A	A	B	B	A	A	B	A
Investment	A	A	A	—	A	B	A	A	A	A
Permanent	B	B	—	—	A	A	A	—	—	—
Die	—	—	—	—	A	A	A	—	—	—
Forging										
Hot	A	A	A	A	A	A	A	A	A	A
Cold	A	A	A	—	A	B	A	—	—	—
Extrusion										
Hot	A	A	A	B	A	A	A	A	A	A
Cold	A	B	A	—	A	—	A	B	—	—
Impact	—	—	—	—	A	A	A	—	—	—
Rolling	A	A	A	—	A	A	A	A	A	B
Powder metals	A	A	A	A	A	A	A	A	A	A
Sheet-metal forming	A	A	A	—	A	A	A	A	A	A
Machining	A	A	A	—	A	A	A	B	A	B
Chemical	A	B	A	B	A	A	A	B	B	B
ECM	—	A	B	A	—	—	B	A	A	A
EDM	—	B	B	A	B	—	B	B	B	A
Grinding	A	A	A	A	A	A	A	A	A	A
Welding	A	A	A	—	A	A	A	A	A	A

Note: A = Generally processed by this method; B = Can be processed by this method, but may present some difficulties; — = Usually not processed by this method. Product quality and productivity depend greatly on the techniques and equipment used, operator skill, and proper control of processing variables.

EXAMPLE 40.6 Process Substitution in Making Common Products

The following list gives some typical choices that can be made in process selection for the products listed:

- **a.** Forged vs. cast crankshaft.
- **b.** Forged vs. powder-metallurgy connecting rod.
- **c.** Sheet metal vs. cast hubcap.
- **d.** Machining vs. precision forming of a large gear.
- **e.** Forging vs. powder-metallurgy production of a spur gear.
- **f.** Thread rolling vs. machining a threaded fastener.
- **g.** Casting vs. stamping a metal frying pan.
- **h.** Formed aluminum tubing vs. cast iron for outdoor furniture.
- **i.** Welding vs. mechanical fastening of machine-tool structures.

EXAMPLE 40.7 Process Selection in Making a Simple Part

You are asked to produce the simple axisymmetric part shown in Fig. 40.6a; it is 125 mm long, and its large and small diameters are, respectively, 38 mm and 25 mm. Assume that this part must be made of metal because of functional requirements such as strength, stiffness, hardness, wear resistance, and resistance to elevated temperatures.

Which manufacturing process would you choose, and how would you organize the production facilities to manufacture a cost-competitive, high-quality product? Recall that, as much as possible, parts should be produced at or near their final shape (net- or near-net-shape manufacturing), under an approach that largely eliminates much secondary processing and thus reduces the total manufacturing time and cost. Because it is relatively simple, this part can be manufactured by (a) casting or powder metallurgy, (b) forging, or upsetting, (c) extrusion, (d) machining, or (e) joining two separate pieces together.

For net-shape production, the two suitable processes are *casting* and *powder metallurgy;* each of these two processes has its own characteristics, need for specific tooling, labor skill, and costs. The part can also be made by cold, warm, or hot *forming*. One method is upsetting (heading, Fig. 14.11) a 25-mm round bar in a suitable die to form the larger end. Another possibility is partial direct *extrusion* of a 38-mm diameter bar to reduce its diameter to 25 mm. Note that each of these processes produces little or no material waste, an important factor in green manufacturing.

The part also can be made by *machining* a 38-mm-diameter bar stock to reduce the lower section to 25 mm. Machining this part will require much more time than forming it, and a considerable amount of material inevitably will be wasted as metal chips (Table 40.3). However, unlike net-shape processes, which generally require special dies, machining

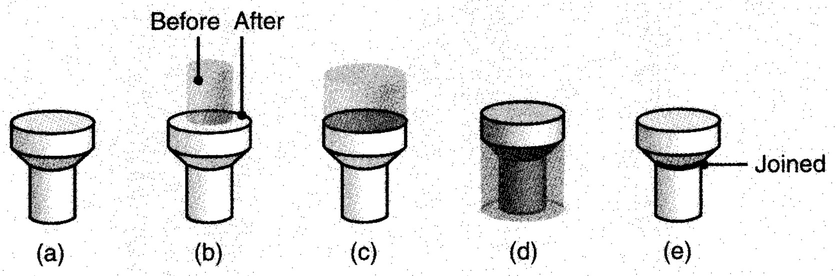

FIGURE 40.6 Various methods of making a simple part: (a) casting or powder metallurgy, (b) forging or upsetting, (c) extrusion, (d) machining, and (e) joining two pieces.

involves no special tooling, and this operation can be carried out easily on a CNC lathe at high rates. Note that, alternatively, the part can be made in two separate pieces and then *joined* by welding, brazing, or adhesive bonding.

After these initial considerations, it appears that if only a few parts are needed, machining this part is the most economical method. For a high production quantity and rate, producing the part by a heading operation or by cold extrusion (a variation of closed-die forging, Section 15.4) would be an appropriate choice. Finally, note that if, for some technical reason, the top and bottom portions of the part must be made of different materials, the part can be made in two pieces, and joining them would be the most appropriate choice.

EXAMPLE 40.8 Manufacturing a Sheet-metal Part by Different Methods

A simple, dish-shaped part can be formed from sheet metal by placing a round, flat piece of sheet metal between a pair of male and female dies in a press and then closing the dies by applying a vertical force (Fig. 40.7a). Parts like this typically are formed in such manner at high production rates; the method is generally known as *stamping* or *pressworking*.

Assume now that the size of the part is very large, say, 2 m in diameter and that the lot size is only 50 parts. We now have to reexamine the total operation. Is it economical to manufacture a set of dies 2 m in diameter (which would be very costly; see Section 14.7) when the total production quantity is very low? Are presses available with sufficient capacity to accommodate such large dies? Are there alternative methods of manufacturing this part? Does the part have to be made in one piece?

This part also can be made by *welding* smaller pieces of sheet metal, formed by other methods, as described in Chapter 16. (Note that large municipal water tanks and ships are made by this method.) Would a part manufactured by welding be acceptable for its intended purpose in the environment in which it will be used? Will it have the required properties and the desired shape after welding, or will it require additional processing?

The part also can be made by *explosive forming*, as shown in Fig. 40.7b. Because of the nature of the process, the deformation of the material in explosive forming takes place at a very high rate. Consequently, a series of questions has to be asked regarding this process (Section 16.11):

a. Is the material capable of undergoing deformation at high rates without fracture or any detrimental effect on the final properties of the formed part?

b. Can the dimensional tolerances and surface finish be held within acceptable limits?

c. Is the life of the die sufficiently long, given that the die is subjected to the very high transient pressures generated in explosive forming?

d. Can this operation be performed in a manufacturing plant within city limits, or should it be carried out in open country?

e. Although explosive forming has the advantage of requiring only one die, is the operation economical?

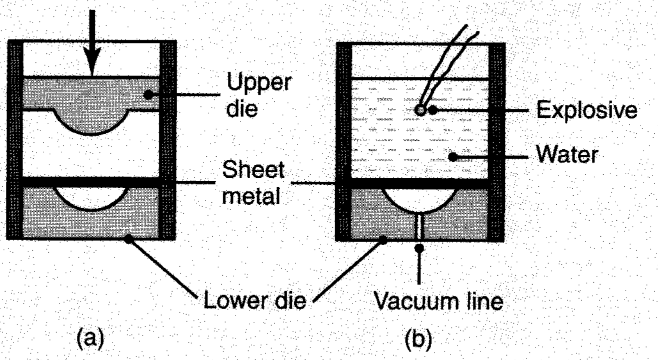

FIGURE 40.7 Two methods of making a dish-shaped sheet-metal part: (a) pressworking using a male and female die and (b) explosive forming using one die only.

40.9 Manufacturing Costs and Cost Reduction

The total cost of a product generally consists of material costs, tooling costs, fixed costs, variable costs, direct-labor costs, and indirect-labor costs. As a general guide to the costs involved, see the sections on the *economics* of each chapter concerning individual groups of manufacturing processes and operations: Part II (casting); Part III (rolling, forging, extrusion, drawing, sheet-metal working, powder metallurgy, ceramics, polymer processing); Part IV (machining, abrasive processing, advanced machining); and Part VI (welding and various joining processes).

Depending on the particular company and the type of products made, different methods of cost accounting may be used, with methodologies of accounting procedures that can be complex and even controversial. Moreover, because of the many technical and operational factors involved, calculating individual cost factors correctly can be challenging, time consuming, and not always reliable.

Costing systems, also called *cost justification*, typically include the following considerations: (a) intangible benefits of quality improvements and inventory reduction, (b) life-cycle costs, (c) machine usage, (d) cost of purchasing machinery compared with that of leasing it, (e) financial risks involved in implementing highly automated systems, and (f) new technologies and their impact on products. Additionally, the costs to a manufacturer that are attributed directly to *product liability* continue to be a matter of major concern, and every product now has a built-in added cost to cover possible product liability claims. It has been estimated that liability suits against car manufacturers in the United States add about $500 to the indirect cost of an automobile, and 20% of the price we pay for a ladder is attributed to potential product liability costs.

Materials Costs. Some cost data on materials are given in various tables throughout this book, as also listed in Table 40.1. Because of the different operations required in producing raw materials, their costs depend not only on the type of material (ferrous, nonferrous, nonmetallic, etc.), but also on its processing history (ingot, powder, drawn rod, extrusion), as well as its size, shape, and surface characteristics. For example, per unit weight, (a) drawn round bars are less expensive than bars that are ground to close tolerances and a fine surface finish, (b) square bars are more expensive than round bars, (c) cold-rolled plate is more expensive than hot-rolled plate, (d) thin wire is more expensive than thick wire, and (e) hot-rolled bars are much less expensive than metal powders of the same type.

Tooling Costs. Costs are involved in making the tools, dies, molds, patterns, and special jigs and fixtures required for manufacturing a product. Tooling costs can be very high, but they can be justified in high-volume production, such as automotive applications, where die costs can be on the order of $2 million. The expected life of tools and die, and their obsolescence because of product changes, also are important considerations.

Tooling costs are greatly influenced by the production process selected. For example, (a) the tooling cost of die casting is higher than that of sand casting; (b) the tooling cost of machining or grinding is much lower than that of powder metallurgy, forging, or extrusion; (c) carbide tools are more expensive than high-speed steel tools, but their life is longer; (d) if a part is to be manufactured by spinning, the tooling cost of conventional spinning is much lower than that of shear spinning; and (e) tooling for rubber-forming processes is less expensive than that of the die sets (male and female) used for the deep drawing and stamping of sheet metals.

Fixed Costs. These costs include electric power, fuel, taxes on real estate, rent, insurance, and capital (including depreciation and interest). The company has to meet fixed costs regardless of whether or not it has made a particular product; thus, fixed costs are not sensitive to production volume.

Capital Costs. These costs represent machinery, tooling, equipment, and investment in buildings and land. As can be seen in Table 40.6 the cost of machines and systems can vary widely, depending on numerous factors. In view of the generally high equipment costs (particularly those involving transfer lines and flexible-manufacturing

TABLE 40.6

Relative Costs for Machinery and Equipment

Automatic screw machine	M-H
Boring mill, horizontal	M-H
Broaching	M-H
Deep drawing	M-H
Die casting	M-H
Drilling	L-M
Electrical-discharge machining	L-M
Electron-beam welding	M-H
Extruder, polymer	L-M
Extrusion press	M-H
Flexible manufacturing cell and system	H-VH
Forging	M-H
Fused deposition modeling	L
Gas tungsten-arc welding	L
Gear shaping	L-H
Grinding	L-H
Headers	L-M
Honing, lapping	L-M
Injection molding	M-H
Laser-beam welding	M-H
Lathes	L-M
Machining center	L-M
Mechanical press	L-M
Milling	L-M
Powder-injection molding	M-H
Powder metallurgy	L-M
Powder metallurgy, HIP	M-H
Resistance spot welding	L-M
Ring rolling	M-H
Robots	L-M
Roll forming	L-M
Rubber forming	L-M
Sand casting	L-M
Spinning	L-M
Stereolithography	L-M
Stamping	L-M
Stretch forming	M-H
Transfer lines	H-VH
Ultrasonic welding	L-M

Note: L = low; M = medium; H = high; VH = very high. Costs vary greatly, depending on size, capacity, options, and level of automation and computer controls. See also the sections on economics in various chapters.

cells and systems), high production quantities and rates are essential to justify such large expenditures, as well as to keep product costs at or below the all-important competitive level. Lower unit costs (cost per piece) can be achieved by continuous production, involving around-the-clock operation (as long as demand warrants it). Equipment maintenance also is essential to ensure high productivity. Any breakdown of machinery leading to *downtime* can be very costly, by as much as thousands of dollars per hour.

Direct-labor Costs. Direct-labor costs are for labor that is directly involved in manufacturing products (also known as *productive labor*). These costs include the costs of all labor, from the time raw materials are first handled by the worker to the time when the product is manufactured, a period generally referred to as *floor-to-floor time*. Direct-labor costs are calculated by multiplying the labor rate (the hourly wage, including benefits) by the amount of time that the worker spends producing the particular part.

The time required for producing a part depends not only on its specified size, shape, dimensional accuracy, and surface finish, but also on the workpiece material itself. The cutting speeds for machining high-temperature alloys, for example, are lower than those for machining aluminum or plain-carbon steels. Consequently, the cost of machining aerospace materials is much higher than that of machining more common alloys, such as those of aluminum and steel.

Labor costs in manufacturing and assembly vary greatly from country to country (see Table I.4 in the General Introduction). It is not surprising that most of the products one purchases today are either made or assembled in countries where labor costs are low. On the other hand, firms located in countries with high labor rates tend to emphasize high value-added manufacturing tasks or high automation levels, so the labor component of the cost is significantly reduced.

For labor-intensive industries, such as machine building, steelmaking, petrochemicals, and chemical processing, manufacturers generally consider moving production to countries with a lower labor rate, a practice known as **outsourcing**. While this approach can be financially attractive, the cost savings anticipated may not always be realized, because of the following hidden costs associated with outsourcing:

- International shipping is far more involved and time consuming than domestic shipping. For example, it takes roughly four to six weeks for a container ship to bring a product from China to the United States or Europe, an interval that continues to increase because of important homeland security issues.
- Lengthy shipping times indicate that the benefits of just-in-time manufacturing approaches (Section 39.5) and their associated cost savings may not be realized. Also, because of the long shipping times, schedules are rigid, design modifications cannot be made easily, and companies cannot readily address changes in the market or in demand. Thus, companies that outsource can lose agility and may have difficulties in following lean-manufacturing approaches.
- Legal systems are not as well established in countries with lower labor rates as they are in other countries. Procedures that are common in the United States and the European Union, such as accounting audits, protection of patented designs and intellectual property, and conflict resolution, are more difficult to enforce or obtain in other countries.
- Because payments typically are expected on the basis of units completed, product defect rates can be significant.
- There are various other hidden costs, such as increased paperwork and documentation, lower productivity from existing employees because of lower morale, and difficulties in communication.

Indirect-labor Costs. These costs are generated in the servicing of the total manufacturing operation. They generally consist of the costs of such activities as supervision, maintenance, quality control, repair, engineering, research, and sales, as well as the cost of office staff. Because they do not contribute directly to the production of finished parts, or they are not chargeable to a specific product, these costs are referred to as the *overhead* or *burden rate*, and are charged proportionally to all products. The personnel involved in these activities are categorized as **nonproductive labor.**

Manufacturing Costs and Production Quantity. One of the most significant factors in manufacturing costs is the production quantity. Obviously, a large production quantity requires high production rates, which, in turn, require the use of mass-production techniques that involve special machinery (*dedicated machinery*) and employ proportionally less direct labor. At the other extreme, a smaller production quantity usually means a larger direct-labor involvement.

Small-batch production usually involves general-purpose machines, such as lathes, milling machines, and hydraulic presses. The equipment is versatile, and parts with different shapes and sizes can be produced by appropriate changes in the tooling. However, direct-labor costs are high because these machines usually are operated by skilled labor.

In *medium-batch production*, the quantities are larger and general-purpose machines are equipped with various jigs and fixtures, or they can be computer controlled. To further reduce labor costs, machining centers and flexible-manufacturing systems are important alternatives. Generally, for quantities of 100,000 or more, the machines are designed for specific purposes, and they perform a variety of specific operations with very little direct labor involved.

Cost Reduction. Cost reduction requires a study of how the costs described previously are interrelated, using *relative costs* as an important parameter. As we have seen, the unit cost of a product can vary widely. For example, some parts may be made from expensive materials, but require very little processing—as in the case of minted gold coins. Consequently, the cost of materials relative to that of direct labor is high.

By contrast, some products may require several complex and expensive production steps to process relatively inexpensive materials, such as carbon steels. For example, an electric motor is made of relatively inexpensive materials, yet several different manufacturing operations are involved in the making of the housing, rotor, bearings, brushes, and various other components. Unless highly automated, assembly operations for such products can become a significant portion of the overall cost (Section 37.9).

A typical breakdown of the costs in modern manufacturing is as follows:

Design	5%
Material	50%
Manufacturing	
Direct Labor	15%
Overhead	30%

In the 1960s, labor accounted for as much as 40% of the production cost; today, it can be as low as 5%, depending on the type of product and level of automation. In the foregoing breakdown, note the very small contribution of the *design phase*, yet the design phase generally has the largest influence on the *quality* and *success* of a product in the marketplace. The various opportunities for cost reduction have been discussed in a number of chapters throughout this book. Among these opportunities are the following:

- Simplifying both part design and the number of subassemblies required.
- Reducing the amount of materials used.
- Specifying broader dimensional tolerances and allowing rougher surface finish
- Using less expensive materials.
- Investigating alternative methods of manufacturing.
- Using more efficient machinery, systems, and equipment.

The introduction of more automated systems and the adoption of up-to-date technology in a manufacturing facility is an obvious means of reducing some costs. However, this approach must be undertaken with due care and only after a thorough **cost–benefit analysis**, which requires reliable input data and a consideration of the technical as well as the human factors involved. Advanced technologies, which can be very costly to implement, should be implemented only after a complete analysis of the more obvious cost factors, known as **return on investment** (ROI).

40.9.1 Value Analysis

Manufacturing adds *value* to materials as they become discrete products and are marketed. Because this value is added in individual stages during the creation of the product, the utilization of value analysis (also called *value engineering, value control,* and *value management*) is important. *Value analysis* is a system that evaluates each step in design, material and process selection, and operations in order to manufacture a product that performs all of its intended functions and does so at the lowest possible cost.

A monetary value is established for each of two product attributes: (a) **use value**, reflecting the functions of the product, and (b) **esteem** or **prestige value**, reflecting the attractiveness of the product that makes its ownership desirable. The *value of a product* is then defined as

$$\text{Value} = \frac{\text{Product function and performance}}{\text{Product cost}}. \tag{40.1}$$

Thus, the goal of value analysis is to obtain maximum performance per unit cost. Value analysis generally consists of the following six phases:

1. *Information phase*: to gather data and determine costs.
2. *Analysis phase*: to define functions and identify problems as well as opportunities.
3. *Creativity phase*: to seek ideas in order to respond to problems and opportunities without judging the value of each idea.
4. *Evaluation phase*: to select the ideas to be developed and identify the costs involved.
5. *Implementation phase*: to present facts, costs, and values to the company management; to develop a plan and to motivate positive action, all in order to obtain a commitment of the resources necessary to accomplish the task.
6. *Review phase*: to reexamine the overall value-analysis process in order to make necessary adjustments.

Value analysis is an important and all-encompassing interdisciplinary activity, usually coordinated by a value engineer and conducted jointly by designers, manufacturing engineers, and quality-control, purchasing, and marketing personnel and managers. In order for value analysis to be effective, it must have the full support of a company's top management. The implementation of value analysis in manufacturing can result in such benefits as (a) significant cost reduction, (b) reduced lead times, (c) better product quality and performance, (d) a reduced time for manufacturing the product, and (e) reduced product weight and size.

An example of product weight reduction is the development of the antilock braking system (ABS) for automotive applications. In 1989, the typical weight of a Bosch brand system was 6.2 kg. In 2001, its weight was 1.8 kg, a reduction of 70%, which also helped reduce the weight of the automobile. Note that, considering the function of the product and the fact that weight is related to the product's volume, reducing the size indicates that the ratio of surface area to volume increases.

SUMMARY

- Regardless of how well a product meets design specifications and quality standards, it also must meet economic criteria in order to be competitive in the domestic and global marketplace. Several guidelines have been established for designing products for economic production.
- Important considerations in product design and manufacturing include manufacturing characteristics of materials, product life expectancy, life-cycle engineering, and an awareness of minimizing any potential harm to our environment and the ecosystem.
- Substitution of materials, modification of product design, and relaxing of dimensional tolerance and surface finish requirements are important methods of cost reduction.
- The total cost of a product includes several elements, such as the costs of materials, tooling, capital, labor, and overhead. Material costs can be reduced through careful selection without compromising design and service requirements, functions, specifications, or standards for good product quality.
- Labor costs generally are becoming an increasingly smaller percentage of production costs in highly industrialized countries, but to counteract lower wages in developing countries, labor costs can be reduced further through highly automated and computer-controlled manufacturing operations.

KEY TERMS

Burden rate
Capital costs
Cost–benefit analysis
Cost justification
Cost reduction
Cradle-to-cradle
Cradle-to-grave
Dedicated machines
Direct labor
Downtime
Economic order quantity
Fixed costs
Floor-to-floor time
Indirect labor
Lead time
Life-cycle assessment
Nonproductive labor
Outsourcing
Overhead
Process capabilities
Production quantity
Production rate
Recycling
Relative costs
Return on investment
Scrap
Smart databases
Sustainable manufacturing
Value
Value analysis

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REVIEW QUESTIONS

40.1. Explain what is meant by "manufacturing properties" of materials.

40.2. Why is material substitution an important aspect of manufacturing engineering?

40.3. What factors are involved in the selection of manufacturing processes? Explain why they are important.

40.4. How is production quantity significant in process selection? Explain.

40.5. List and describe the major costs involved in manufacturing.

40.6. Explain the difference between direct-labor cost and indirect-labor cost.

40.7. Describe your understanding of the following terms: (a) life expectancy, (b) life-cycle engineering, (c) sustainable manufacturing, and (d) green manufacturing.

40.8. Is there a significant difference bewteen cradle-to-grave and cradle-to-cradle production? Explain.

40.9. How would you define value? Explain.

40.10. What is the meaning and significance of the term "return on investment"? Explain.

QUALITATIVE PROBLEMS

40.11. Describe the major considerations involved in selecting materials for products.

40.12. What is meant by manufacturing process capabilities? Select four different manufacturing processes and describe their capabilities.

40.13. Comment on the magnitude and range of scrap shown in Table 40.3 and the reasons for the variations.

40.14. Explain why the value of the scrap produced in a manufacturing process depends on the type of material and processes involved.

40.15. Describe your observations concerning the information given in Table 6.1 and the reasons for those observations.

40.16. Other than the size of the machine, what factors are involved in the range of prices in each machine category shown in Table 40.6? Explain.

40.17. Explain how the high cost of some of the machinery listed in Table 40.6 can be justified.

40.18. On the basis of the topics covered in this book, explain the reasons for the relative positions of the curves shown in Fig. 40.2.

40.19. What factors are involved in the shape of the curve shown in Fig. 40.4? Explain.

40.20. Describe the problems that may have to be faced in reducing the quantity of materials in products. Give some examples.

40.21. Explain the reasons that there is a strong desire in industry to practice near-net-shape manufacturing.

40.22. State and explain your thoughts concerning cradle-to-cradle manufacturing.

40.23. List and explain the advantages and disadvantages of outsourcing manufacturing activities to countries with low labor costs.

SYNTHESIS, DESIGN, AND PROJECTS

40.24. As you can see, Table 40.5 lists only metals and their alloys. On the basis of the information given in various chapters in this book and in other sources, prepare a similar table for nonmetallic materials, including ceramics, plastics, reinforced plastics, and both metal-matrix and ceramic-matrix composite materials.

40.25. Is it always desirable to purchase stock that is close to the final dimensions of a part to be manufactured? Explain why or why not and give some examples.

40.26. What course of action would you take if the supply of a raw material selected for a product line becomes unreliable? Explain.

40.27. Estimate the position of the curves for the following processes in Fig. 40.5: (a) centerless grinding, (b) electrochemical machining, (c) chemical milling, and (d) extrusion.

40.28. Review Fig. I.3 in the General Introduction and present your own thoughts concerning the two flowcharts. Would you want to make any modifications, and if so, what would they be?

40.29. Over the years, numerous consumer products (such as rotary-dial telephones, analog radio tuners, turntables, and vacuum tubes) have become obsolete or nearly so, while many new products have entered the market. Make two lists: a comprehensive list of obsolete products that you can think of and a list of new products. Comment on the reasons for the changes you observe.

40.30. List and discuss the different manufacturing methods and systems that have enabled the manufacture of new products. (These products and systems are known as *enabling technologies*).

40.31. Select three different products, and make a survey of the changes in their prices over the past 10 years. Discuss the possible reasons for the changes.

40.32. Describe your own thoughts concerning the replacement of aluminum beverage cans with cans made of steel.

40.33. Select three different products commonly found in homes. State your opinions on (a) what materials were used in each product, (b) why those particular materials were chosen, (c) how the products were manufactured, and (d) why those particular processes were used.

40.34. Comment on the differences, if any, among the designs, materials, and processing and assembly methods used for making products such as hand tools and ladders for professional use and those for consumer use.

40.35. The cross section of a jet engine is shown in Fig. 6.1. On the basis of the topics covered in this book, select any three individual components of such an engine and describe the materials and processes that you would use in making them in quantities of, say, 1000.

40.36. Inspect some products around your home, and describe how you would go about taking them completely apart quickly and recycling their components. Comment on their design regarding the ease with which they can be disassembled.

40.37. What products do you know of that would be very difficult to disassemble for recycling purposes? Explain.

Index

LIST OF TABLES

General Introduction

Part I Fundamentals of Materials: Behavior and Manufacturing Properties

Part II Metal-Casting Processes and Equipment

Part III Forming and Shaping Processes and Equipment

Part IV Machining Processes and Machine Tools

Part V Micromanufacturing and Fabrication of Microelectronic Devices

Part VI Joining Processes and Equipment

Part VII Surface Technology

Part VIII Common Aspects of Manufacturing

Part IX Manufacturing in a Competitive Environment

REFERENCES TO VARIOUS TOPICS (Page Numbers are in Parentheses)

Material Properties

Tables 2.1 (57), 2.2 (59), 2.3 (62), and Figs. 2.4, 2.6, 2.7, 2.8, 2.15, 2.16, 2.17, 2.29
Tables 3.1 (89), 3.2 (90), and Figs. 3.1, 3.2, 3.3
Tables 5.2 (139), 5.4 (141), and 5.5 (144)
Tables 6.3 through 6.10 (153–162)
Tables 7.1 (172), 7.2 (180), 7.3 (186)
Tables 8.1 (199), 8.2 (202), 8.3 (206)
Tables 9.1 (218), 9.2 (220), 9.3 (228), and Figs. 9.3, 9.5, 9.7
Table 10.1 (248)
Table 11.3 (281)
Tables 12.3 (304), 12.4 (305), 12.5 (305), and Fig. 12.4
Tables 16.2 (392), 16.3 (398), 16.4 (409), and Fig. 16.14
Tables 17.3 (455), 17.4 (455), 17.5 (456), and Fig. 17.10
Table 20.2 (529)
Tables 22.1 (593), 22.2 (594), 22.3 (594), 22.5 (600), and Figs. 22.1, 22.9
Table 26.1 (721)
Table 32.3 (931)
Section 17.7 and Fig. 17.14
Table 18.1 (466)
Tables 19.1 (485), 19.2 (521)
Table 20.1 (528)
Tables 23.1 (617), 23.6 (627), 23.8 (635), 23.10 (644)
Tables 26.3 (735), 26.4 (736)
Table 27.1 (761)
Tables 28.1 (801), 28.2 (809), 28.3 (810), and Fig. 28.19
Tables 29.1 (847), 29.3 (856)
Table VI.1 (864)
Table 30.1 (866)
Table 32.4 (932)
Table 34.1 (989)
Table 37.2 (1056), and Fig. 37.3
Table 39.1 (1121)
Tables 40.3 (1146), 40.5 (1153), and Figs. 40.2, 40.3, 40.5

Manufacturing Characteristics of Materials

Table I.3 (16)
Table 4.1 (120)
Table 5.8 (147)
Table 6.2 (152)
Tables 12.1 (297), 12.6 (308)
Table 14.3 (348)
Table 16.3 (398), and Fig. 16.33
Tables 17.1 (447), 17.2 (453)
Tables 21.1 (559), 21.2 (571)
Fig. 22.2

Dimensional Tolerances and Surface Finish

Table 11.2 (261)
Table 23.1 (617), and Figs. 23.13, 23.14
Fig. 25.16
Fig. 27.4
Figs. 35.19, 35.20
Figs. 40.4, 40.5

Capabilities of Manufacturing Processes

Tables 11.1 (259), 11.2 (261)
Table III.1 (315)
Table 14.1 (337), 14.4 (353)
Table 16.1 (383)

Design Considerations in Processing

Abrasive Processes: Section 26.5
Advanced Machining: Various sections in Chapter 27
Casting: Section 12.2
Ceramics Shaping: Section 18.5
Forging: Section 14.6
Heat Treating: Section 4.13
Joining Processes: Various sections in Chapters 30–32
Machining: Sections in Chapters 23–24
Polymers Processing: Section 19.15
Powder Metallurgy: Section 17.6
Sheet-metal Forming: Section 16.13

General Costs and Economics

Tables I.5 (30), I.6 (33), I.7 (34), and Section I.10
Table 6.1 (152)
Section 12.4
Section 14.9
Section 16.15
Table 17.6 (461) and Section 17.8
Table 19.2 (521) and Section 19.16
Section 25.8
Section 26.9 and Fig. 26.35
Section 27.11
Section 31.8
Section 32.7
Section 37.11
Section 39.9
Table 40.6 (1157) and Section 40.9

CONVERSION FACTORS

1 in. = 25.4 mm = 0.0254 m
1 mm = 0.0394 in.
1 ft = 0.3048 m
1 lb (force) = 4.448 N
1 lb (mass) = 0.4536 kg
1 ton = 2240 lb

1 tonne = 1000 kg
1 psi = 6.895 kPa
1 ksi = 6.895 MPa
1 MPa = 145 psi
1 ft·lb = 1.356 J
1 BTU = 1055 J = 778 ft·lb

1 hp = 746 W = 550 ft·lb/s
1 kW = 1.34 hp = 3413 BTU/hr
°F = 9/5 °C + 32
°C = 5/9 (°F − 32)
K = °C + 273.15

LIST OF EXAMPLES