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DESIGN FOR MANUFACTURING

13.1 ROLE OF MANUFACTURING IN DESIGN

Producing the design is a critical link in the chain of events that starts with a creative idea and ends with a successful product in the marketplace. With modern technology the function of production no longer is a mundane activity. Rather, design, materials selection, and processing are inseparable, as shown in Fig. 11.1.

There is confusion of terminology concerning the engineering function called *manufacturing*. Materials engineers use the term *materials processing* to refer to the conversion of semifinished products, like steel blooms or billets, into finished products, like cold-rolled sheet or hot-rolled bar. A mechanical, industrial, or manufacturing engineer is more likely to refer to the conversion of the sheet into an automotive body panel as *manufacturing*. Processing is the more generic term, but manufacturing is the more common term. Production engineering is a term used in Europe to describe what we call manufacturing in the United States. We will use the term *manufacturing* in this text to refer to converting a design into a finished product.

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The first half of the 20th century saw the maturation of manufacturing operations in the western world. Increases in the scale and speed of operations brought about increases in productivity, and manufacturing costs dropped while wages and the standard of living rose. There was a great proliferation of available materials as basic substances were tailor-made to have selectively improved properties. One of the major achievements of this era was the development of the production line for mass-producing automobiles, appliances, and other consumer goods. Because of the preeminence in manufacturing that developed in the United States, there has been a recent tendency to take the production function for granted. Manufacturing has been downplayed in the education of engineers. Manufacturing positions in industry have been considered routine and not challenging, and as a result they have not attracted their share of the most talented engineering graduates. Fortunately, this situation is improving as the rapid rise of manufacturing in Asia has threatened jobs for a large segment of the workforce in the western world. The nature and perception of manufacturing is being changed by increasing automation and computer-aided manufacturing.

Peter Drucker, the prominent social scientist and management expert, has termed the current manufacturing situation "the third industrial revolution." The use of power, whether generated by falling water or a steam engine, determined the first industrial revolution. The second industrial revolution began roughly a century ago when machines were first driven directly by fractional-horsepower motors. Before machines were direct-driven by electric motors, they were driven by belts and pulleys, which meant that the equipment had to be very close to the source of power. Thus, the second industrial revolution brought flexibility and economy to manufacturing. The third industrial revolution combines information processing capabilities with machines and tools. It is converting production into a knowledge-based operation.

A serious problem facing manufacturing companies has been the tendency to separate the design and manufacturing functions into different organizational units. Barriers between design and manufacturing decision making can inhibit the close interaction that the two engineering functions should have, as discussed previously under concurrent engineering (Sec. 2.4.4). When technology is sophisticated and fast-changing, a close partnership between the people in research, design, and manufacturing is very necessary.

That has been demonstrated best in the area of solid-state electronic devices. As semiconductor devices replaced vacuum tubes, it became apparent that design and processing could no longer be independent and separable functions. Design using vacuum-tube technology was essentially a linear process in which specialists in materials passed on their input to specialists in components who passed on their input to circuit designers who, in turn, communicated with system designers. With the advent of transistors, the materials, device construction, and circuit design functions became closely coupled. Then, with the microelectronics revolution of large-scale integrated circuits, the entire operation from materials to system design became interwoven, and manufacturing became inseparable from design. The result was a situation of rapid technical advance requiring engineers of great creativity, flexibility, and breadth. The payoff in making the personal computer and workstations a reality has been huge. Never has productivity been enhanced as rapidly as during the microelectronics revolution. This should serve as a model of the great payoff that can be achieved by closer integration of research, design, and manufacturing.

The need to break down barriers between design and manufacturing is widely recognized today and is accomplished by the use of concurrent engineering and the involvement of manufacturing engineers in product design and development teams. Also, focus on improving the link between manufacturing and design has increased emphasis on codifying a set of practices that designers should follow to make their designs easier to manufacture. This topic, *design for manufacture* (DFM), is the emphasis of this chapter.

13.2 MANUFACTURING FUNCTIONS

More conventional manufacturing is divided into the following functions: (1) process engineering, (2) tool engineering, (3) work standards, (4) plant engineering, and (5) administration and control. *Process engineering* is the development of a step-by-step sequence of operations for production. The overall product is subdivided into its components and subassemblies, and the steps required to produce each component are arranged in logical sequence. An important part of process engineering is to specify the related tooling. Vital parameters in process engineering are the rate of production and the cost of manufacturing a component. *Tool engineering* is concerned with the design of tools, jigs, fixtures, and gages to produce the part. *Jigs* both hold the part and guide the tool during manufacture, while *fixtures* hold a part to be joined, assembled, or machined. Tools do the machining or forming, gages determine whether the dimensions of the part are within specification. *Work standards* are time values associated with each manufacturing operation that are used to determine standard costs to make the part. Other standards that need to be developed in manufacturing are tool standards and materials standards. *Plant engineering* is concerned with providing the plant facilities (space, utilities, transportation, storage, etc.) needed to carry out the manufacturing process. *Administration and control* deals with production planning, scheduling, and supervising to assure that materials, machines, tools, and people are available at the right time and in the quantities needed to produce the part.

During the last century modern manufacturing was typified by the automotive assembly line. Now mass production manufacturing systems account for less than 25 percent of components manufactured. In fact, 75 percent of the parts manufactured are produced in lots of fewer than 50 pieces. About 40 percent of the employment in manufacturing is in such job-shop operations. Studies of batch-type metal-cutting production shops have shown that, on the average, a workpiece in such a shop is on a machine tool being productively processed only 5 percent of the time. Ninety-five percent of the time the workpiece is in the shop, it is waiting in an inventory of unfinished parts. Moreover, of the very small fraction of time the part is being worked on, it is being cut by the tool only about 30 percent of the time. The remaining 70 percent of the time is taken up by loading and unloading, positioning the workpiece, gaging the part, and other activities. Thus, there is a major opportunity for greatly increasing manufacturing productivity in small-lot manufacture.

Computer-automated machine tool systems, which include industrial robots and computer software for scheduling and inventory control, have demonstrated the ability to increase machine utilization time from an average of 5 percent to as much as 90 percent. The introduction of computer-controlled machining centers that can perform many operations in a single machine greatly increases the productivity of the machine tool. The computer-automated factory—in which all steps in part manufacturing will be optimized by computer software systems, the machine tools will be under computer control, and at least half of the machines will be part of a versatile manufacturing system that features multiple machining capability and automatic parts handling between workstations—has been demonstrated at many plant sites. This automated factory differs from the automotive transfer line in that it is a flexible manufacturing

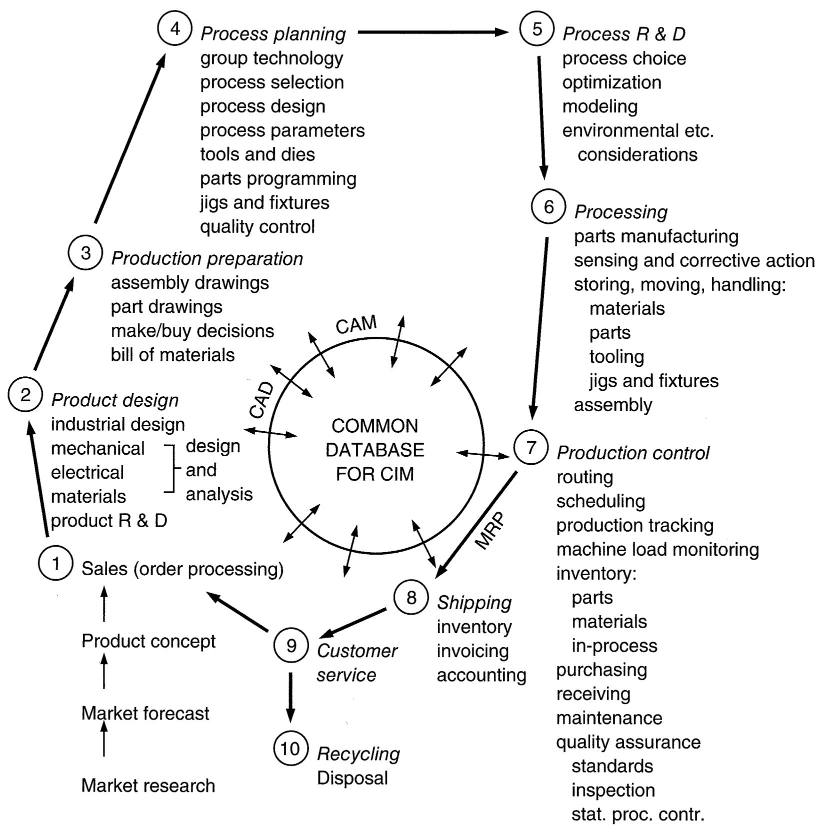

FIGURE 13.1
Spectrum of activities that are encompassed by manufacturing.

system capable of producing a wide variety of parts under computer control. This broad-based *effort throughout industry to link computers into all aspects of manufacturing is called computer-integrated manufacturing* (CIM).

Figure 13.1 shows the broad spectrum of activities that are encompassed by manufacturing. It begins in step 4, when design engineering turns the complete information for the design over to the process planners. As mentioned earlier, many tasks of process planning are done concurrently with the detail design phase. Process selection and design of tooling are major functions in this step. Step 5 involves fine-tuning a process, often by computer modeling or optimization processes, to improve throughput or improve yield (reduce defects) or decrease cost. Actual part manufacturing, step 6, involves production team training and motivation. In many instances a considerable amount of materials handling is required. The many issues involved with step 7 are vital for an effective manufacturing operation. Finally, in step 8, the product is shipped and sold to the customer. Customer service, step 9, handles warranty and repair issues, and eventually the product is retired from service, hopefully by recycling.

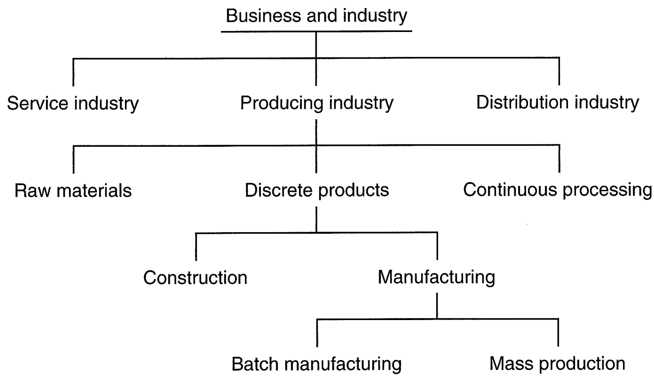

FIGURE 13.2
A simple hierarchical classification of business and industry.

The information gathered from customer service operations is fed back into the design of new products, step 2; the cycle is completed.

13.3 CLASSIFICATION OF MANUFACTURING PROCESSES

It is not an easy task to classify the tremendous variety of manufacturing processes. We start with the hierarchical classification of business and industry shown in Fig. 13.2. The service industries consist of enterprises, such as education, banking, insurance, communication, and health care that provide important services to modern society but do not create wealth by converting raw materials. The producing industries acquire raw materials (minerals, natural products, or petroleum) and process them, through the use of energy, machinery, and brainpower, into products that serve the needs of society. The distribution industries, such as merchandising and transportation, make those products available to the general public.

A characteristic of modern industrialized society is that an increasingly smaller percentage of the population produces the wealth that makes our affluent society possible. Just as the past century saw the United States change from a predominantly agrarian society to a nation in which only 3 percent of the population works in agriculture, so we are becoming a nation in which an ever-decreasing percentage of the workforce is engaged in manufacturing. In 1947 about 30 percent of the workforce was in manufacturing; in 1980 it was about 22 percent. By the year 2004 about 15 percent of U.S. workers were engaged in manufacturing.

The producing industries can be divided conveniently into raw materials producers (mining, petroleum, agriculture), producers of discrete products (autos, consumer electronics, etc.), and industries engaged in continuous processing (gasoline, paper, steel, chemicals, etc.). Two major divisions of discrete products are construction (buildings, roads, bridges, etc.) and manufacturing. Under manufacturing we recognize batch (low-volume) manufacturing and mass production as categories.

13.3.1 Types of Manufacturing Processes

A manufacturing process converts a material into a finished part or product. The changes that take place occur with respect to part geometry, or they can affect the internal microstructure and therefore the properties of the material. For example, a sheet of brass that is being drawn into the cylindrical shape of a cartridge case is also being hardened and reduced in ductility by the process of dislocation glide on slip planes.

Recall from Chap. 6 that the functional decomposition of a design was described initially in terms of energy, material, and information flows. These same three factors are present in manufacturing. Thus, a manufacturing process requires an energy flow to cause the material flow that brings about changes in shape. The information flow, which consists of both shape and material property information, depends on the type of material, the process used—that is, whether mechanical, chemical, or thermal—the characteristics of the tooling used, and the pattern of movement of the material relative to the tooling.

A natural division among the hundreds of manufacturing processes is whether the process is *mass conserving* or *mass reducing.* In a mass conserving process the mass of the starting material is approximately equal to the mass of the final part. Most processes are of this type. A *shape replication* process is a mass conserving process in which the part replicates the information stored in the tooling by being forced to assume the shape of the surface of the tool cavity. Casting, injection molding, and closed-die forging are examples. In a *mass reducing* process, the mass of the starting material is greater than the mass of the final part. Such processes are *shape-generation* processes because the part shape is produced by the relative motion between the tool and the workpiece. Material removal is caused by controlled fracture, melting, or chemical reaction. A machining process, such as milling, is an example of controlled fracture.

A different way of dividing manufacturing processes is to classify them into three broad families: (1) primary processes, (2) secondary processes, and (3) finishing processes.

- **Primary processes** take raw materials and create a shape. The chief categories are casting processes, polymer processing or molding processes, deformation processes, and powder processes.
- **Secondary processes** modify shape by adding features such as keyways, screw threads, and grooves. Machining processes are the main type of secondary processes. Other important categories are joining processes that fasten parts together, and heat treatment to change mechanical properties.
- **Finishing processes** produce the final appearance and feel of a product by processes such as coating, painting, or polishing.

The taxonomy structure used to classify materials in Sec. 11.2.1 can be applied to manufacturing processes. For example, the **Family** of Shaping Processes can be divided into the **Classes** of Casting, Polymer Molding, Deformation, and Powder processes. The class Deformation Processes can, in turn, be broken into many **Member** processes such as rolling, drawing, cold forming, swaging, sheet metal forming, and spinning. Then, for each process we would need to determine **Attributes** or *process characteristics* (PC) such as its applicability to certain ranges of part size, the minimum thickness that can be consistently produced by the process, the typical tolerance on dimensions and surface roughness produced by the process, and its economical batch size.

13.3.2 Brief Description of the Classes of Manufacturing Processes

This section provides further understanding of the major classes of manufacturing processes.[1]

1. Casting (solidification) processes: Molten liquid is poured into a mold and solidified into a shape defined by the contours of the mold. The liquid fills the mold by flow under its own weight or with a modest pressure. Cast shapes are designed so the liquid flows to all parts of the mold cavity, and solidification occurs progressively so there are no trapped liquid pockets in a solidified shell. This requires a low-viscosity liquid, so casting is usually done with metals and their alloys. The various casting processes, and their costs differ chiefly according to the expense and care used to prepare the mold. Great progress has been made using computer models to predict and control the flow and solidification of the liquid material, thereby minimizing casting defects.
2. Polymer processing (molding): The wide use of polymers has brought about the development of processes tailored to their high viscosity. In most of these processes a hot viscous polymer is either compressed or injected into a mold. The distinction between casting and molding is the viscosity of the material being worked. Molding can take such extreme forms as compression molding plastic pellets in a hot mold, or blowing a plastic tube into the shape of a milk bottle against a mold wall.
3. Deformation processes: A material, usually metal, is plastically deformed hot or cold to give it improved properties and change its shape. Deformation processes are also called metal-forming processes. Typical processes of this type are forging, rolling, extrusion, and wire drawing. Sheet-metal forming is a special category in which the deformation occurs in a two-dimensional stress state instead of three dimensions.
4. Powder processing: This rapidly developing manufacturing area involves the consolidation of particles of metal, ceramics, or polymers by pressing and sintering, hot compaction, or plastic deformation. It also includes the processing of composite materials. Powder metallurgy is used to make small parts with precision dimensions that require no machining or finishing. Powder processing is the best route for materials that cannot be cast or deformed, such as very high melting point metals and ceramics.

1. A six-page taxonomy of manufacturing processes leading to many illustrated descriptions of processes is given at http://en.wikipedia.org/wiki/Taxonomy_of_manufacturing_processes.
Also see http://www.designsite.dk/Processes. Accessed January 7, 2007.

5. Material removal or cutting (machining) processes: Material is removed from a workpiece with a hard, sharp tool by a variety of methods such as turning, milling, grinding, and shaving. Material removal occurs by controlled fracture, producing chips. Machining is one of the oldest manufacturing processes, dating back to the invention of the power lathe early in the Industrial Revolution. Essentially any shape can be produced by a series of machining operations. Because a machining operation starts with a manufactured shape, such as bar stock, casting, or forging, it is classified as a secondary process.
6. Joining processing: Included in joining processing are all categories of welding, brazing, soldering, diffusion bonding, riveting, bolting, and adhesive bonding. These operations attach the parts to one another. Fastening occurs in the assembly step of manufacturing.
7. Heat treatment and surface treatment: This category includes the improvement of mechanical properties by thermal heat treatment processes as well as the improvement of surface properties by diffusion processes like carburizing and nitriding or by alternative means such as sprayed or hot-dip coatings, electroplating, and painting. The category also includes the cleaning of surfaces preparatory to surface treatment. This class of processes can be either secondary or finishing processes.
8. Assembly processes: In this, usually the final step in manufacturing, a number of parts are brought together and combined into a subassembly or finished product.

13.3.3 Sources of Information on Manufacturing Processes

In this book we cannot describe the many processes used in modern manufacturing in detail. Table 13.1 lists several readily available texts that describe the behavior of the material, the machinery, and the tooling to present a good understanding of how each process works.

13.3.4 Types of Manufacturing Systems

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There are four general types of manufacturing systems: job shop, batch, assembly line, and continuous flow.[2] The characteristics of these production systems are listed in Table 13.2. The *job shop* is characterized by small batches of a large number of different part types every year. There is no regular work flow, so work-in-process must often wait in a queue for its turn on the machine. Hence, it is difficult to specify job shop capacity because it is highly dependent on the product mix. *Batch flow*, or decoupled flow line, is used when the product design is relatively stable and produced in periodic batches, but the volume for an individual product is not sufficient to warrant the cost of specialized, dedicated equipment. Examples are the production of heavy equipment or ready-to-wear clothing. With *assembly-line production,* the equipment

2. G. Chryssolouris, *Manufacturing Systems,* 2d ed., Springer, New York, 2006.

TABLE 13.1
Basic Texts on Manufacturing Processes

DeGarmo, E. P., J. T. Black, and R. Kohser, *Materials and Processes in Manufacturing,* 9th ed., John Wiley & Sons, New York, 2003.

Groover, M. P., *Fundamentals of Modern Manufacturing,* 2d ed., John Wiley & Sons, New York, 2002.

Kalpakjian, S., and S. R. Schmid, *Manufacturing Engineering and Technology,* 5th ed., Pearson Prentice Hall, Upper Saddle River, NJ, 2006.

Schey, J. A., *Introduction to Manufacturing Processes,* 3d ed., McGraw-Hill, New York, 2000.

Also, Section 7, Manufacturing Aspects of Design, in *ASM Handbook* Vol. 20 gives an overview of each major process from the viewpoint of the design engineer.

The most important reference sources giving information on industrial practices are *Tool and Manufacturing Engineers Handbook,* 4th ed., published in nine volumes by the Society of Manufacturing Engineers, and various volumes of *ASM Handbook* published by ASM International devoted to specific manufacturing processes, see Table 13.5. More books dealing with each of the eight classes of manufacturing processes are listed below. Most of these books give more advanced treatments than the texts listed in Table 13.1.

Casting Processes

M. Blair and T. L. Stevens, eds., *Steel Castings Handbook,* 6th ed., ASM International, Materials Park, OH, 1995.

J. Campbell, *Casting,* Butterworth-Heinemann, Oxford, UK, 1991.

H. Fredriksson and U. Åkerlind, *Material Processing During Casting,* John Wiley & Sons, Chichester, UK, 2006.

S. P. Thomas, ed., *Design and Procurement of High-Strength Structural Aluminum Castings,* American Foundrymen's Society, Cleveland, 1995.

Casting, ASM Handbook, Vol. 15, ASM International, Materials Park, OH, 1988.

Polymer Processing

E. A. Muccio, *Plastics Processing Technology,* ASM International, Materials Park, OH, 1994.

A. B. Strong, *Plastics: Materials and Processing,* 3d ed., Prentice Hall, Upper Saddle River, NJ, 2006.

Plastics Parts Manufacturing, Tool and Manufacturing Engineers Handbook, Vol. 8, 4th ed., Society of Manufacturing Engineers, Dearborn, MI, 1995.

J. F. Agassant, P. Avenas, J. Sergent, and P. J. Carreau, *Polymer Processing: Principles and Modeling,* Hanser Gardner Publications, Cincinnati, OH 1991.

Z. Tadmor and C. G. Gogas, *Principles of Polymer Processing,* 2d ed., Wiley-Interscience, Hoboken, NJ, 2006.

Deformation Processes

W. A. Backofen, *Deformation Processing,* Addison-Wesley, Reading, MA, 1972.

W. F. Hosfordt and R. M. Caddell, *Metal Forming: Mechanics and Metallurgy,* 2d ed., Prentice Hall, Upper Saddle River, NJ, 1993.

E. Mielnik, *Metalworking Science and Engineering,* McGraw-Hill, New York, 1991.

R. H. Wagoner and J-L Chenot, *Metal Forming Analysis,* Cambridge University Press, Cambridge, UK, 2001.

K. Lange, ed., *Handbook of Metal Forming,* Society of Manufacturing Engineers, Dearborn, MI, 1985.

R. Pearce, *Sheet Metal Forming,* Adam Hilger, Bristol, UK, 1991.

Metalworking: Bulk Forming, *ASM Handbook,* Vol. 14A, ASM International, Materials Park, OH 2005.

Metalworking: Sheet Forming. *ASM Handbook,* Vol. 14B, ASM International, Materials Park, OH 2006.

TABLE 13.1
(continued)

Z. Marciniak and J. L. Duncan, *The Mechanics of Sheet Metal Forming,* Edward Arnold, London, 1992.

Powder Processing

R. M. German, *Powder Metallurgy Science,* Metal Powder Industries Federation, Princeton, NJ, 1985.

R. M. German, *Powder Metallurgy of Iron and Steel,* John Wiley & Sons, New York, 1998.

ASM Handbook, Vol. 7, *Powder Metal Technologies and Applications,* ASM International, Materials Park, OH, 1998.

Powder Metallurgy Design Manual, 2d ed., Metal Powder Industries Federation, Princeton, NJ, 1995.

Material Removal Processes

G. Boothroyd and W. W. Knight, *Fundamentals of Machining and Machine Tools,* 3d ed., Taylor & Francis, Boca Raton, FL, 2006.

T. C. Childs, K. Maekowa, T. Objkawa, and T. Yamada, *Metal Cutting Theory and Applications,* John Wiley & Sons, New York, 2002.

W. R. DeVries, *Analysis of Metal Removal Processes,* Springer-Verlag, New York, 1992.

S. Malkin, *Grinding Technology: Theory and Applications,* Ellis Horwood, New York, 1989.

M. C. Shaw, *Metal Cutting Principles,* 4th ed., Oxford University Press, New York, 1984.

Machining, Tool and Manufacturing Engineers Handbook, Vol. 1, 4th ed., Society of Manufacturing Engineers, Dearborn, MI, 1983.

ASM Handbook, Vol. 16, *Machining,* ASM International, Materials Park, OH, 1989.

Joining Processes

S. Kuo, *Welding Metallurgy,* John Wiley & Sons, New York, 1987.

R. W. Messler, *Principles of Welding,* John Wiley and Sons, New York, 1999.

Engineered Materials Handbook, Vol. 3, *Adhesives and Sealants,* ASM International, Materials Park, OH, 1990.

R. O. Parmley, ed., *Standard Handbook for Fastening and Joining,* 3d ed., McGraw-Hill, New York, 1997.

ASM Handbook, Vol. 6, *Welding, Brazing, and Soldering,* ASM International, Materials Park, OH, 1993.

Welding Handbook, 9th ed., American Welding Society, Miami, FL, 2001.

Heat Treatment and Surface Treatment

Heat Treating, *ASM Handbook,* Vol. 4, ASM International, Materials Park, OH, 1991.

ASM Handbook, Vol. 5, *Surface Engineering,* ASM International, Materials Park, OH, 1994.

Tool and Manufacturing Engineers Handbook, Vol. 3, *Materials, Finishing, and Coating,* 4th ed., Society of Manufacturing Engineers, Dearborn, MI, 1985.

Assembly Processes

G. Boothroyd, *Assembly Automation and Product Design,* Marcel Dekker, New York, 1992.

E. K. Henriksen, *Jig and Fixture Design,* Industrial Press, New York, 1973.

P. H. Joshi, *Jigs and Fixtures Design Manual,* McGraw-Hill, New York, 2003.

A. H. Redford and J. Chal, *Design for Assembly,* McGraw-Hill, New York, 1994.

Fundamentals of Tool Design, 5th ed., Society of Manufacturing Engineers, Dearborn, MI, 2003.

Tool and Manufacturing Engineers Handbook, Vol. 9, *Assembly Processes,* 4th ed., Society of Manufacturing Engineers, Dearborn, MI, 1998.

TABLE 13.2
Characteristics of Production Systems

Characteristic	Job Shop	Batch Flow	Assembly Line	Continuous Flow
Equipment and Physical Layout				
Batch size	Low (1–100 units)	Moderate (100–10,000 units)	Large (10,000–millions/year)	Large. Measured in tons, gals., etc.
Process flow	Few dominant flow patterns	Some flow patterns	Rigid flow patterns	Well defined and inflexible
Equipment	General-purpose	Mixed	Specialized	Specialized
Setups	Frequent	Occasional	Few and costly	Rare and expensive
Process changes for new products	Incremental	Often incremental	Varies	Often radical
Information and Control				
Production information requirements	High	Varies	Moderate	Low
Raw material inventory	Small	Moderate	Varies; frequent deliveries	Large
Work-in-process	Large	Moderate	Small	Very small

is laid out in the sequence of usage. The large number of assembly tasks is divided into small subsets to be performed at successive workstations. Examples are the production of automobiles or power hand tools. Finally, a *continuous-flow process* is the most specialized type. The equipment is highly specialized, laid out in a circuit, and usually automated. The material flows continuously from input to output. Examples are a gasoline refinery or a paper mill.

A process is said to be *mechanized* when it is being carried out by powered machinery and not by hand. Nearly all manufacturing processes in developed countries are mechanized. A process is *automated* when the steps in the process, along with the movement of material and inspection of the parts, are automatically performed or controlled by self-operating devices. Automation involves mechanization plus sensing and controlling capabilities (programmable logic controllers and PCs). Hard automation is hard-linked and hard-wired, while flexible automation includes the added capability of being reprogrammed to meet changing conditions.

13.4 MANUFACTURING PROCESS SELECTION

The factors that influence the selection of a process to make a part are:

- Quantity of parts required
- Complexity—shape, size, features
- Material

- Quality of part
- Cost to manufacture
- Availability, lead time, and delivery schedule

As emphasized in Chap. 11, there is a close interdependance between material selection and process selection.

The steps in selecting a manufacturing process are:

- Based on the part specification, identify the material class, the required number of parts, and the size, shape, minimum thickness, surface finish, and tolerance on critical dimensions of the part. These constitute constraints on the selection of the process.
- Decide what the objective of the process selection process is. Generally, the objective is to minimize the cost of the manufactured part. However, it might be to maximize the quality of the part, or to minimize the time to make it.
- Using the identified constraints, screen a large number of processes to eliminate the processes incapable of meeting them. This can be done using the information sources given in this chapter, or the screening charts found in M.F. Ashby, *Materials Selection in Mechanical Design,* 3d ed., Butterworth-Heinemann, Oxford, UK, 2005. The Cambridge Engineering Selector v. 4 software from Granta Design Ltd., Cambridge, UK, 2006 greatly facilitates this process. It links material selection with possible processes and provides extensive data about each process. Figure 13.3 shows an example of the information provided about a process.
- Having narrowed the possible processes to a smaller number, they should be ranked based on manufacturing cost. A quick ranking can be based on the economic batch size (Sec. 13.4.1), but a cost model is needed (Sec. 13.4.6) for making the final decision. However, before making this decision it is important to seek supporting information from among the references given in Sec. 13.3.3 and elsewhere in this chapter. Look for case studies and examples of industry practice that will lend credibility and support your decision.

Each factor affecting the selection of a manufacturing process for a particular part is discussed in the following sections.

13.4.1 Quantity of Parts Required

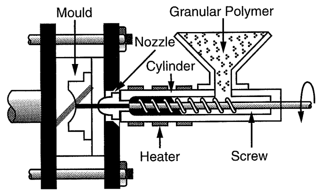
Two important factors in the choice of processes are the total number of parts to be produced and the rate of production, in units per time period. All manufacturing processes have a minimum number of pieces (volume) that must be made to justify their use. Some processes, like an automatic screw machine, are inherently high-volume processes, in that the setup time is long relative to the time needed to produce a single part. Others, like the hand layup of a fiberglass plastic boat, are low-volume processes. Here the setup time is minimal but the time to make a part is much longer.

The total volume of production often is insufficient to keep a production machine continuously occupied. As a result, production occurs in *batches* or *lots* representing a fraction of the number of parts needed for a year of product production. The batch size is influenced by the cost and inconvenience of setting up for a new production run

INJECTION MOLDING of thermoplastics is the equivalent of pressure die casting of metals. Molten polymer is injected under high pressure into a cold steel mold. The polymer solidifies under pressure and the molding is then ejected.

Various types of injection molding machines exist, but the most common in use today is the reciprocating screw machine (shown schematically). Capital and tooling costs are very high. Production rate can be high, particularly for small moldings. Multicavity molds are often used. The process is used almost exclusively for large-volume production. Prototype moldings can be made using cheaper single-cavity molds of cheaper materials. Quality can be high but may be traded off against production rate. The process may also be used with thermosets and rubbers. Some modifications are required—this is dealt with separately. Complex shapes are possible, though some features (e.g., undercuts, screw threads, inserts) may result in increased tooling costs.

Process Schematic



Physical Attributes				
Adjacent section ratio	1	–	2	
Aspect ratio	1	–	250	
Mass range	0.02205	–	55.12	lb
Minimum hole diameter	0.02362	–		in
Minimum corner radius	0.05906	–		in
Range of section thickness	0.01575	–	0.248	in.
Roughness	7.874e-3	–	0.06299	mil
Quality factor (1–10)	1	–	6	
Tolerance	3.937e-3	–	0.03937	in.
Econonic Attributes				
Economic batch size (mass)	1.102e4	–	1.102e6	lb
Economic batch size (units)	1e4	–	1e6	
Cost Modelling				
Relative cost index (per unit)	18.16	–	113.3	
Parameters: Material Cost = 4.309USD/lb, component Mass = 2.205lb, Batch size = 1000,				
Capital cost	3.77e4	–	8.483e5	USD
Lead time	4	–	6	week(s)
Material utilization fraction	0.6	–	0.9	
Production rate (mass)	66.14	–	2205	lb/hr
Production rate (units)	60	–	3000	/hr
Tool life (mass)	1.102e4	–	1.102e6	lb
Tool life (units)	1e4	–	1e6	

Supporting Information

Design guidelines

Complex shapes are possible. Thick sections or large changes in section are not recommended. Small reentrant angles are possible.

Technical nodes

Most thermoplastics can be injection moulded. Some high melting point polymers (e.g., PTFE) are not suitable. Thermoplastic based composites (short fibre and particulate filled) are also processed.

Injection-moulded parts are generally thin-walled.

Typical uses

Extremely varied. Housings, containers, covers, knobs, tool handles, plumbing fittings, lenses, etc.

The economics

Tooling cost range covers small, simple to large, complex moulds. Production rate depends on complexity of component and number of mould cavities.

The environment

Thermoplastic sprues can be recycled. Extraction may be required for volatile fumes. Significant dust exposures may occur in the formulation of the resins. Thermostatic controller malfunctions can be extremely hazardous.

FIGURE 13.3
Typical process data sheet from CES EduPack, 2006 Granta Design Limited, Cambridge, UK, 2006.

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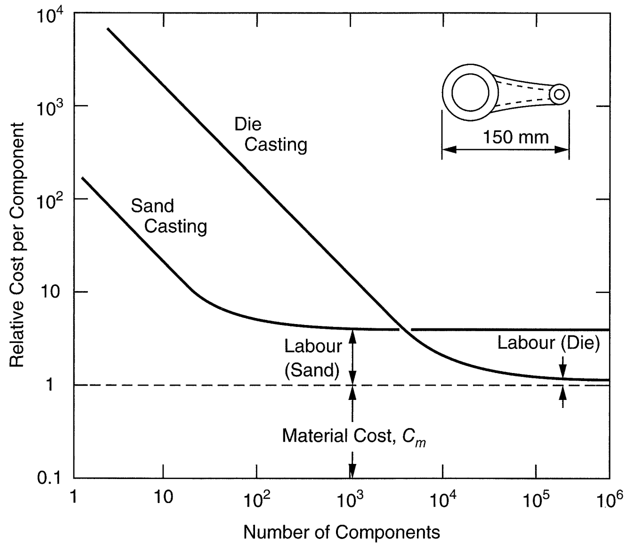

FIGURE 13.4
The relative cost of casting a part versus the number of parts produced using the sand casting and die casting processes. (From M. F. Ashby, *Materials Selection in Mechanical Design*, 2d ed., p. 278, Copyright Elsevier, 1999. Used with permission.)

on a particular machine, and by the cost of maintaining parts in inventory in a warehouse between production runs.

Figure 13.4 compares the cost of making an aluminum connecting rod by sand casting and die casting to illustrate the interplay between tooling and setup cost and quantity on process cost per part. Sand casting uses cheaper equipment and tooling, but it is more labor intensive to build the sand molds. Pressure die casting uses more costly equipment and expensive metal molds, but it is less labor intensive. The cost of material is the same in both processes. For a small number of parts the unit cost is higher for die casting, chiefly because of the more expensive tooling. However, as these costs are shared with a larger number of parts, the unit cost is decreased, and at about 3000 parts the die casting process has a lower unit cost. Note that the sand casting process leveled out at about 100 parts, maintaining a constant unit cost that is determined by the material cost plus the labor cost. The same thing happens for the die casting process, only here the labor cost is very low relative to the material cost.

The number of parts at which the unit cost of one process becomes lower than that of its competitors is called the *economic batch size*. The economic batch size for sand casting in this example is from 1 to 3600 parts, while that for die casting is 3600 and beyond. The economic batch size is a good rough guide to the cost structure of a process. It is a useful screening parameter for differentiating among candidate processes, as shown by Fig. 13.5. A more detailed cost model (Sec. 13.4.6) is then used to refine the ranking of the most promising process candidates.

The *flexibility* of the process is related to the economic batch size. Flexibility in manufacturing is the ease with which a process can be adapted to produce different

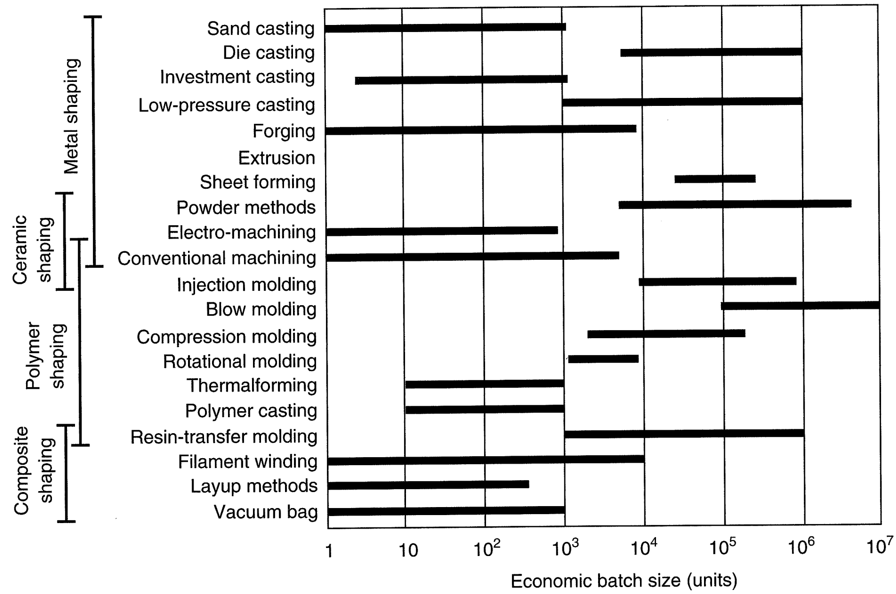

FIGURE 13.5
Range of economic batch size for typical manufacturing processes. (From M. F. Ashby, *Materials Selection in Mechanical Design*, 3d ed., p. 205, Copyright Elsevier, 2005. Used with permission.)

products or variations of the same product. It is greatly influenced by the time needed to change and set up tooling. At a time when product customization is increasingly important, this process attribute has gained importance.

EXAMPLE 13.1

With the drive to reduce the weight of automobiles, there is strong interest in plastic bumpers. Such a bumper must have good rigidity to maintain dimensional limits, low-temperature impact resistance (for crashworthiness), and dimensional stability over the operating range of temperature.[3] In addition, it must have the ability to be finished to match the adjoining painted metal parts. With these critical-to-quality performance requirements of chief importance, four polymeric materials were chosen from the large number of engineering plastics.

- Polyester reinforced with chopped-glass fiber to improve toughness
- Polyurethane with glass-flake filler to increase stiffness
- Rubber-modified polypropylene to decrease the ductile-brittle transition to below 30°C
- A polymer blend of polyester and polycarbonate to combine the excellent solvent resistance of the former with the high toughness of the latter.

Four polymer processes are under consideration for making the bumpers from these polymers. Each works well with the engineered plastics chosen, but they vary greatly in tooling costs and flexibility.

3. L. Edwards and M. Endean, eds., *Manufacturing with Materials,* Butterworth, Boston, 1990.

Process	Mold cost	Labor input/unit
Injection molding	\$450,000	3 min = \$1
Reaction injection molding	\$90,000	6 min = \$2
Compression molding	\$55,000	6 min = \$2
Contact molding	\$20,000	1 h = \$20

Then, the part cost is the sum of the mold cost per part plus the labor input, neglecting the material cost, which is roughly the same for each.

	Cost per part			
Process	**1000 parts**	**10,000 parts**	**100,000 parts**	**1,000,000 parts**
Injection molding	\$451	\$46	\$5.50	\$1.45
Reaction injection molding	\$92	\$11	\$2.90	\$2.09
Compression molding	\$57	\$7.50	\$2.55	\$2.06
Contact molding	\$40	\$22	\$20.20	\$20.02

Note how the unit part cost varies greatly with the quantity of parts required. The hand layup process of contact molding is the least expensive for a low part volume, while the low-cycle-time injection molding process excels at the highest part volume. Assuming that the material cost for the bumper is \$30 per part, we see how material cost represents the largest fraction of the total cost as the part volume increases.

13.4.2 Shape and Feature Complexity

The complexity of a part refers to its *shape* and type and number of *features* that it contains. One way of expressing the complexity of a component is through its information content *I*, expressed in number of digital bits of information.

$$I = n \log_2\left(\frac{\bar{l}}{\overline{\Delta l}}\right) \tag{13.1}$$

where n = number of dimensions of the component

$\bar{l} = (l_1 \bullet l_2 \bullet l_3 \ldots l_n)^{1/n}$ is the geometric mean dimension

$\overline{\Delta l} = (\Delta l_1 \bullet \Delta l_2 \bullet \Delta l_3 \ldots \Delta l_n)^{1/n}$ is the geometric mean of the tolerance

$$\log_2(x) = \frac{\log_{10}(x)}{\log_{10}(2)}$$

Simple shapes contain only a few bits of information. Complex shapes, like integrated circuits, contain very many. A cast engine block might have 10^3 bits of information, but after machining the various features the complexity increases by both adding new dimensions (n) and improving their precision (reducing $\overline{\Delta l}$).

Most mechanical parts have a three-dimensional shape, although sheet metal fabrications are basically two-dimensional. Figure 13.6 shows a useful shape classifica-

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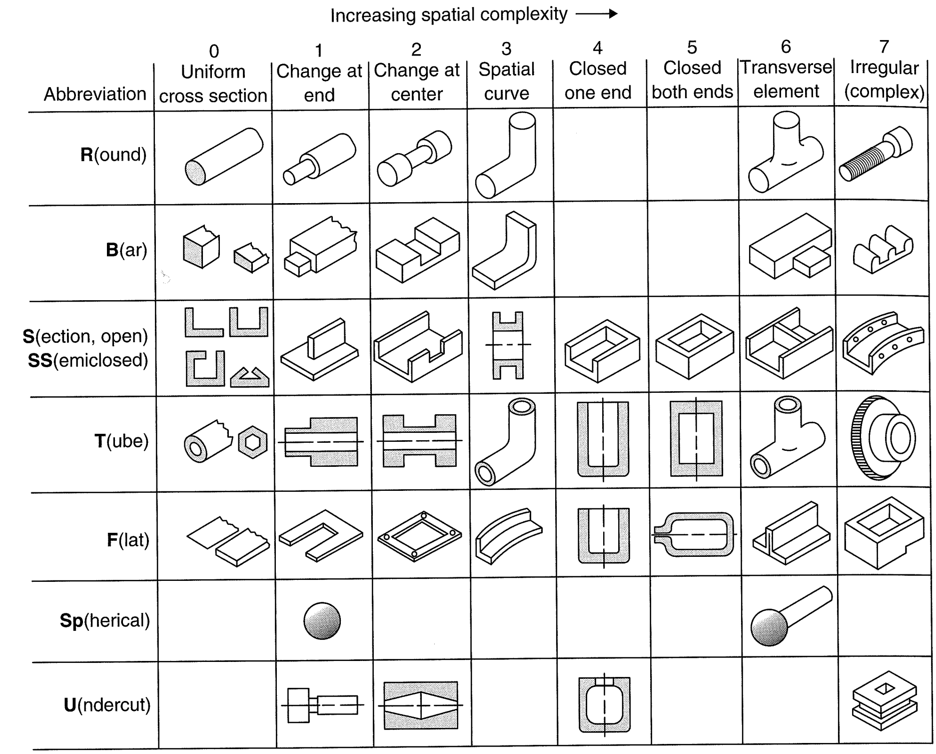

FIGURE 13.6
A classification system for basic shapes in design. (J. A. Schey, *Introduction to Manufacturing Processes,* 3d ed. McGraw-Hill, 2000)

tion system. In this schema a shape of uniform cross section is given a complexity rating of 0.

The shape complexity increases from left to right in Fig. 13.6 with the addition of greater geometric complexity and added features, that is, greater information content. Note that a small increase in information content can have major significance in process selection for making a part. Moving from the solid shape R0 (shape in column 0 of the Round row) to the hollow shape T0 (shape in column 0 of the Tube row) adds only one additional dimension (the hole diameter), but the change excludes some processes as the best choice for making the part or adds an additional operation step in other processes.

Different manufacturing processes vary in their limitations for producing complex shapes. For example, there are many processes that do not allow the making of *undercuts*, shown in the bottom row in Fig. 13.6. Undercuts make it impossible to extract the part from the mold without complicated and expensive tooling. Other processes have limitations on how thin the wall thickness can be, or require the part to have uniform wall thickness. Extrusion processes require a part that is axially symmetric. Powder metallurgy cannot make parts with sharp corners or acute angles because the unsintered powder will crumble when transferring from the die. Lathe turning requires a part with cylindrical symmetry. Table 13.3 associates the shapes defined in Fig. 13.6 with the ability of various manufacturing processes to create them.

TABLE 13.3
Ability of Manufacturing Processes to Produce Shapes in Fig. 13.6

Process	Capability for producing shapes
Casting processes	
Sand casting	Can make all shapes
Plaster casting	Can make all shapes
Investment casting	Can make all shapes
Permanent mold	Can make all shapes except T3, T5; F5; U1, U5, U7
Die casting	Same as permanent mold casting
Deformation processes	
Open-die forging	Best for R0 to R3; all B shapes; T1; F0; Sp6
Hot impression die forging	Best for all R, B, and S shapes; T1, T2; Sp
Hot extrusion	All 0 shapes
Cold forging/ cold extrusion	Same as hot die forging or extrusion
Shape drawing	All 0 shapes
Shape rolling	All 0 shapes
Sheet-metal working processes	
Blanking	F0 to F2; T7
Bending	R3; B3; S0, S2, S7; T3; F3, F6,
Stretching	F4; S7
Deep drawing	T4; F4, F7
Spinning	T1, T2, T4, T6; F4, F5
Polymer processes	
Extrusion	All 0 shapes
Injection molding	Can make all shapes with proper coring
Compression molding	All shapes except T3, T5, T6, F5, U4
Sheet thermoforming	T4, F4, F7, S5
Powder metallurgy processes	
Cold press and sinter	All shapes except S3, T2, T3, T5, T6, F3, F5, all U shapes
Hot isostatic pressing	All shapes except T5 and F5
Powder injection molding	All shapes except T5, F5, U1, U4
PM forging	Same shape restrictions as cold press and sinter
Machining processes	
Lathe turning	R0, R1, R2, R7; T0, T1, T2; Sp1, Sp6; U1, U2
Drilling	T0, T6
Milling	All B, S, SS shapes; F0 to F4; F6, F7, U7
Grinding	Same as turning and milling
Honing, lapping	R0 to R2; B0 to B2; B7; T0 to T2, T4 to T7; F0 to F2; Sp

Based on data from J.A. Schey, *Introduction to Manufacturing Processes.*

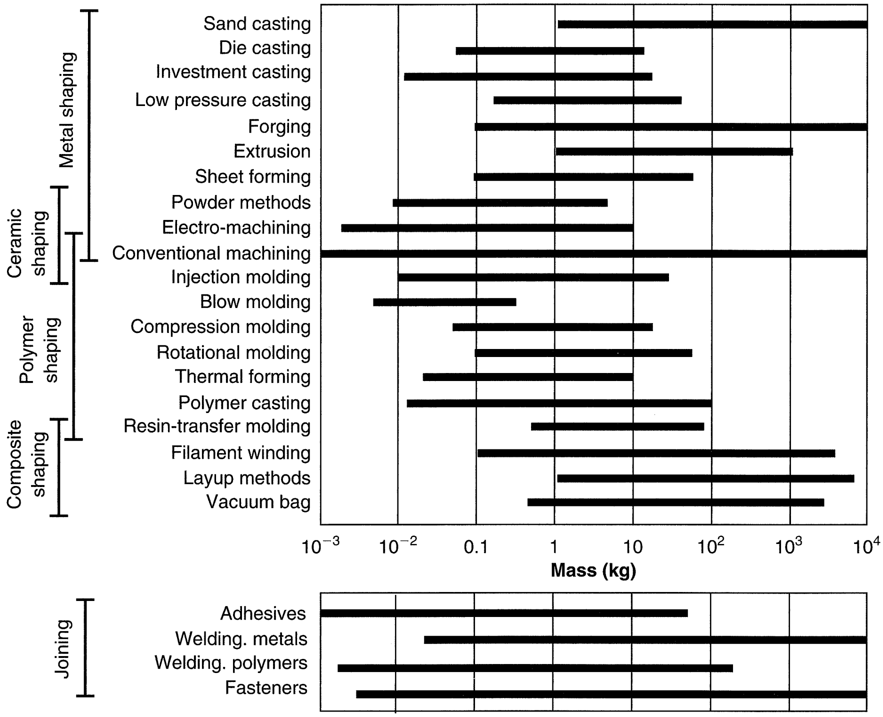

FIGURE 13.7
Process selection chart. Process versus range of size (mass). (From M. F. Ashby, *Materials Selection in Mechanical Design*, 3d ed., p. 199, Copyright Elsevier, 2005. Used with permission.)

13.4.3 Size

Parts vary considerably in size. Because of the nature of the equipment used in a manufacturing process, each process has a range of part sizes for which it is economical to use that process. Figure 13.7 shows this.

Note that machining processes (i.e., removal of metal by cutting) span the complete range of sizes, and that machining, casting, and forging are able to produce the largest mass objects. However only a limited number of plants in the world can make very large parts. Therefore, to make very large products like aircraft, ships, and pressure vessels, it is necessary to assemble them from many parts using joining methods such as welding and riveting.

A limiting geometric factor in process selection often is section thickness. Figure 13.8 displays capabilities for achieving thickness according to process. Gravity-fed castings have a minimum wall thickness that they can produce due to surface tension and heat flow considerations. This can be extended by using pressure die casting. The availability of press tonnage and the occurrence of friction in metal deformation processes create a similar restriction on minimum section thickness. In injec-

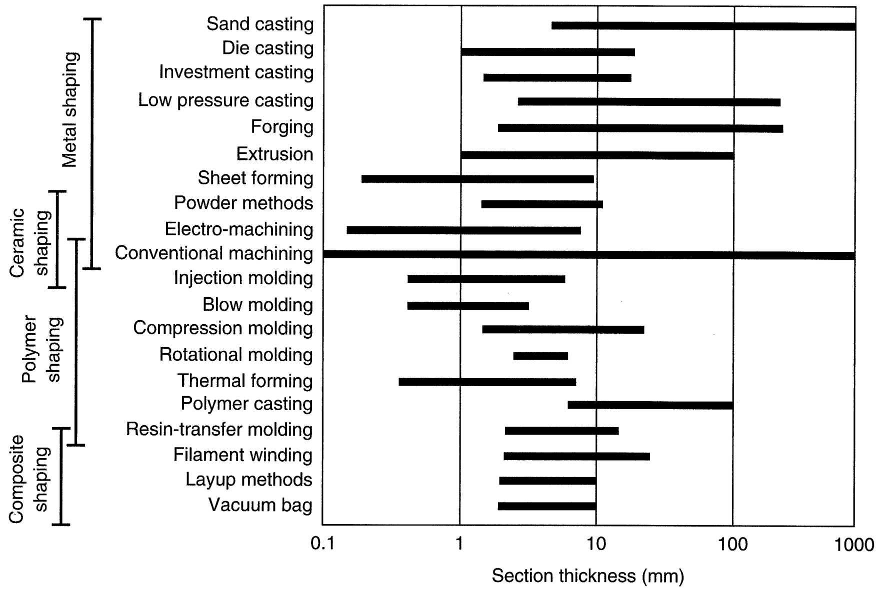

FIGURE 13.8
Range of available section thickness provided by different processes. (From M. F. Ashby, *Materials Selection in Mechanical Design*, 3d ed., p. 200, Copyright Elsevier, 2005. Used with permission.)

tion molding there must be sufficient time for the polymer to harden before it can be ejected from the molding machine. Because high production rates are desired, the slow rate of heat transfer severely limits the maximum thickness that can be obtained.

13.4.4 Influence of Material on Process Selection

Just as shape requirements limit the available selection of processes, the selection of a material also places certain restrictions on the available manufacturing processes. The melting point of the material and its level of deformation resistance and ductility are the chief factors. The melting point of the material determines the casting processes that can be employed. Low-melting-point metals can be used with a wide number of casting processes, but as the melting point rises, problems with mold reaction and atmosphere contamination limit the available processes. Some materials, like ceramics, may be too brittle for shape creation by deformation processes, while others are too reactive to have good weldability.

Figure 13.9 shows a matrix laying out the manufacturing processes generally used with the most common classes of engineering materials. The table is further divided with respect to the quantity of parts needed for economical production. Use this matrix as a way to narrow down the possibilities to a manageable few processes for final evaluation and selection. This table is part of the PRocess Information MAps

MATERIAL / QUANTITY	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGNESIUM & ALLOYS	ZINC & ALLOYS	TIN & ALLOYS
VERY LOW 1 TO 100	[1.5] [1.6] [1.7] [4.M]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1] [1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[1.6] [1.7] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.5] [1.7] [3.6] [4.M] [5.1]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.5]	[1.6] [1.7] [3.10] [4.M] [5.1][5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]
LOW 100 TO 1,000	[1.2] [1.5] [1.6] [1.7] [4.M] [5.3] [5.4]	[1.2] [1.6] [1.7] [1.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.1] [1.2] [1.7] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6] [5.7]	[1.2] [1.7] [3.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.2] [1.3] [1.5] [1.7] [1.8] [3.3] [3.6] [4.M] [5.1] [5.3] [5.4]	[1.2] [1.5] [1.7] [1.8] [3.7] [3.10] [4.M] [5.3] [5.4] [5.5]	[1.6] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]
LOW TO MEDIUM 1,000 TO 10,000	[1.2] [1.3] [1.5] [1.6] [1.7] [3.11] [4.A] [5.2]	[1.2] [1.3] [1.5] [1.7] [3.1] [3.3] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[1.2] [1.5] [1.7] [3.1] [3.4] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[1.2] [1.5] [1.7] [3.1] [3.2] [3.7] [3.10] [3.11] [4.A.] [5.2] [5.3] [5.4] [6.0]	[1.2] [1.3] [1.5] [1.8] [3.1] [3.2] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4]	[1.2] [1.3] [1.4] [1.5] [3.1] [3.3] [3.7] [3.10] [3.11] [4.A] [5.3] [5.4] [5.5]	[1.3] [1.5] [1.8] [3.1] [3.3] [3.4] [3.10] [4.A] [5.5]	[1.3] [1.8] [3.3] [3.10] [4.A] [5.5]	[1.3] [1.5] [3.2] [3.10]
MEDIUM TO HIGH 10,000 TO 100,000	[1.2] [1.3] [3.11] [4.A]	[1.0] [2.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1] [3.4] [3.5] [3.11] [3.12] [4.A] [5.2]	[1.0] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2] [1.4] [1.8] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2] [1.3] [1.4] [1.8] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A] [5.5]	[1.3] [1.4] [3.1] [3.3] [3.4] [3.5] [3.12] 4.A]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.12]
HIGH 100,000+	[1.2] [1.3] [3.11] [4.A]	[1.9] [3.1] [3.2] [3.3] [3.4] [3.5] [3.12] [4.A]	[4.A]	[1.9] [3.2] [3.3] [4.A]	[1.2] [1.M] [3.1] [3.2] [3.3] [3.4] [3.5] [3.7] [3.8] [3.11] [3.12] [4.A]	[1.2] [1.3] [1.4] [1.6] [3.1] [3.2] [3.3] [3.4] [3.5] [3.8] [3.12] [4.A]	[1.3] [1.4] [3.1] [3.3] [3.4] [3.8] [3.12] [4.A]	[1.4] [3.2] [3.3] [3.4] [3.5] [4.A]	[1.4] [3.3] [3.4] [4.A]
ALL QUANTITIES	[1.1]	[1.1] [1.5] [3.0] [3.0] [3.0]	[1.6] [3.6]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.1] [1.6] [3.6] [3.8] [3.9] 5.5]	[1.1] [1.6] [3.4] [3.5] [3.6]	[1.1] [3.5] [3.6] [3.8]	[3.6] [3.8] [3.9]	

MATERIAL / QUANTITY	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
VERY LOW 1 TO 100	[1.1] [3.10] [4.M] [5.5]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[2.5] [2.7]	[2.5] [3.7]	[2.2] [2.6] [5.7]	[1.5] [5.1] [5.5] [5.6] [5.7]	[1.1] [5.7]	[5.5]
LOW 100 TO 1,000	[1.1] [1.8] [3.10] [4.M] [5.5]	[1.2] [1.5] [1.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6] [5.7]	[2.3] [2.5] [2.7]	[2.2] [2.3]	[2.2] [2.3] [2.6] [5.7]	[5.1] [5.3] [5.5] [5.6] [5.7]	[5.7]	[5.5]
LOW TO MEDIUM 1,000 TO 10,000	[1.3] [1.5] [3.3] [3.10]	[1.2] [1.3] [1.5] [1.7] [3.1] [3.2] [3.11] [4.A] [5.1] [5.3] [5.4] [5.5] [3.10]	[3.1] [3.7] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[2.3] [2.5] [2.6] [2.7]	[2.2] [2.3] [2.4]	[2.1] [2.2] [2.3]	[5.2] [5.3] [5.4] [5.5]		[5.5]
MEDIUM TO HIGH 10,000 TO 100,000	[1.3] [1.4] [3.3] [3.4] [3.8] [3.12] [4.A]	[3.1] [3.3] [3.5] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[2.1] [2.3] [2.6] [2.7] [2.8]	[2.1] [2.3] [2.9]	[2.1] [2.3]	[3.11]	[3.12]	[3.5]
HIGH 100,000+	[1.4] [3.2] [3.3] [3.4] [4.A]	[3.2] [3.3] [4.A]	[4.A]	[2.1] [2.6] [2.8]	[2.1] [2.3] [2.4] [2.9]		[3.7] [3.11]		[3.5]
ALL QUANTITIES	[3.5]	[1.1] [1.6] [3.4] [3.5] [3.8]	[3.8] [3.9]				[5.5]	[1.5]	[1.6]

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
[1.1] SAND CASTING
[1.2] SHELL MOULDING
[1.3] GRAVITY DIE CASTING
[1.4] PRESSURE DIE CASTING
[1.5] CENTRIFUGAL CASTING
[1.6] INVESTMENT CASTING
[1.7] CERAMIC MOULD CASTING
[1.8] PLASTER MOULD CASTING
[1.9] SQUEEZE CASTING

PLASTIC & COMPOSITE PROCESSING
[2.1] INJECTION MOULDING
[2.2] REACTION INJECTION MOULDING
[2.3] COMPRESSION MOULDING
[2.4] TRANSFER MOULDING
[2.5] VACUUM MOULDING
[2.6] BLOW MOULDING
[2.7] ROTATIONAL MOULDING
[2.8] CONTACT MOULDING
[2.9] CONTINUOUS EXTRUSION (PLASTICS)

FORMING PROCESSES
[3.1] CLOSED DIE FORGING
[3.2] ROLLING
[3.3] DRAWING
[3.4] COLD FORMING
[3.5] COLD HEADING
[3.6] SWAGING
[3.7] SUPERPLASTIC FORMING
[3.8] SHEET-METAL SHEARING
[3.9] SHEET-METAL FORMING
[3.10] SPINNING
[3.11] POWDER METALLURGY
[3.12] CONTINUOUS EXTRUSION (METALS)

MACHINING PROCESSES
[4.A] AUTOMATIC MACHINING
[4.M] MANUAL MACHINING

(THE ABOVE HEADINGS COVER A BROAD RANGE OF MACHINING PROCESSES AND LEVELS OF CONTROL TECHNOLOGY. FOR MORE DETAIL, THE READER IS REFERRED TO THE INDIVIDUAL PROCESSES.)

NTM PROCESSES
[5.1] ELECTRICAL DISCHARGE MACHINING (EDM)
[5.2] ELECTROCHEMICAL MACHINING (ECM)
[5.3] ELECTRON BEAM MACHINING (EBM)
[5.4] LASER BEAM MACHINING (LBM)
[5.5] CHEMICAL MACHINING (CM)
[5.6] ULTRASONIC MACHINING (USM)
[5.7] ABRASIVE JET MACHINING (AJM)

FIGURE 13.9
PRIMA selection matrix showing which materials and processes are usually used together. based on common practice. (From K. G. Swift and J. D. Booker, *Process Selection*, 2d ed., p. 23, Copyright Elsevier, 2003. Used with permission.)

(PRIMA) methodology for manufacturing process selection.[4] The PRIMA method is discussed in greater detail in Sec. 13.4.8.

Steels, aluminum alloys, and other metallic alloys can be purchased in a variety of metallurgical conditions other than the annealed (soft) state. Examples are quenched and tempered steel bars, solution-treated and cold-worked and aged aluminum alloys, or cold-drawn and stress-relieved brass rods. It may be more economical to have the metallurgical strengthening produced in the workpiece by the material supplier than to heat-treat each part separately after it has been manufactured.

When parts have very simple geometric shapes, as straight shafts and bolts have, the form in which the material is obtained and the method of manufacture are readily apparent. However, as the part becomes more complex in shape, it becomes possible to make it from several forms of material and by a variety of manufacturing methods. For example, a small gear may be machined from bar stock or, perhaps more economically, from a precision-forged gear blank. The selection of one of several alternatives is based on overall cost of a finished part (see Chap. 16 for details of cost evaluation). Generally, the production quantity is an important factor in cost comparisons, as was shown in Fig. 13.4. There will be a break-even point beyond which it is more economical to invest in precision-forged preforms in order to produce a gear with a lower unit cost than to machine it from bar stock. As the production quantity increases, it becomes easier economically to justify a larger initial investment in tooling or special machinery to lower the unit cost.

13.4.5 Required Quality of the Part

The quality of the part is defined by three related sets of characteristics: (1) freedom from external and internal defects, (2) surface finish, and (3) dimensional accuracy and tolerance. To a high degree, the achievement of high quality in these areas is influenced by the workability or formability of the material.[5] While different materials exhibit different workability in a given process, the same material may show different workability in different processes. For example, in deformation processing, the workability increases with the extent that the process provides a condition of hydrostatic compression. Thus, steel has greater workability in extrusion than in forging, and even less in drawing, because the hydrostatic component of the stress state decreases in the order of the processes listed. An approximate evaluation of overall workability of materials is given in Fig. 13.17.

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Defects

Defects may be internal to the part or concentrated mainly at the surface. Internal defects are such things as voids, porosity, cracks, or regions of different chemical-composition (segregation). Surface defects can be surface cracks, rolled-in oxide, extreme roughness, or surface discoloration or corrosion. The amount of material used

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4. K.G. Swift and J.D. Booker, *Process Selection,* 2d ed., Butterworth-Heinemann, Oxford, UK, 2003.

5. G.E. Dieter, H.A. Kuhn, and S.L. Semiatin, *Handbook of Workability and Process Design,* ASM International, Materials Park, OH, 2003.

to make the part should be just enough larger than the final part to allow for removal of surface defects by machining or another surface conditioning method. Thus, extra material in a casting may be needed to permit machining the surface to a specified finish, or a heat-treated steel part may be made oversized to allow for the removal of a decarburized layer.[6]

Often the manufacturing process dictates the use of extra material, such as sprues and risers in castings and flash in forgings and moldings. At other times extra material must be provided for purposes of handling, positioning, or testing the part. Even though extra material removal is costly, it usually is cheaper to purchase a slightly larger workpiece than to pay for a scrapped part.

Computer-based process modeling is being used effectively to investigate the design of tooling and the flow of material to minimize defect formation. Also, improved nondestructive inspection methods make more certain the detection of defects before a part is placed into service. Defects such as voids can often be eliminated by subjecting the part to a high hydrostatic pressure, such as 15,000 psi, at elevated temperature, in a process called hot-isostatic pressing (HIP).[7] HIPing has been used effectively with investment casting to replace parts previously made by forging.

Surface Finish

The surface finish of a part determines its appearance, affects the assembly of the part with other parts, and may influence its resistance to corrosion and wear. The surface roughness of a part must be specified and controlled because of its influence on fatigue failure, friction and wear, and assembly with other parts.

No surface is smooth and flat like the straight line we make on an engineering drawing. When viewed on a highly magnified scale it is rough, as sketched in Fig. 13.10. Surface roughness is measured with a profilometer, a precision instrument that traverses a line(typically a travel of 1 mm) with a very fine-tipped stylus. Several parameters are used to describe the state of surface roughness.[8]

R_t is the height measured from maximum peak to the deepest trough. It is not the most commonly used measure of surface roughness, but it is an important value when roughness needs to be removed by polishing.

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R_a is the arithmetic average based on the absolute value of the deviations from the mean surface line. The mean surface is drawn such that the area under the peaks and valleys is equal. This measure of roughness is also called the centerline average.

$$R_a = \frac{y_1 + y_2 + y_3 + \cdots + y_n}{n} \tag{13.2}$$

6. For photographs and discussion of the formation of defects in deformation processing, see *ASM Handbook,* Vol. 11, *Failure Analysis and Prevention,* pp. 81–102, ASM International, Materials Park, OH, 2002.

7. H. V. Atkinson and B. A. Rickinson, *Hot Isostatic Pressing,* Adam Huger, Bristol, UK, 1991.

8. See Surface texture, ANSI Standard B46.1, ASME, 1985.

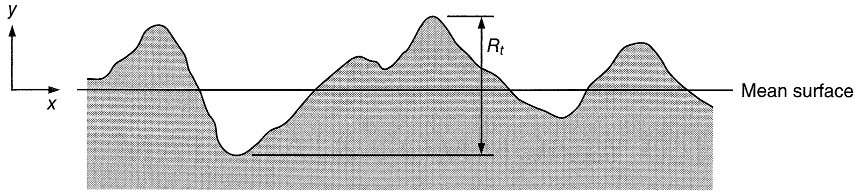

FIGURE 13.10
Cross-sectional profile of surface roughness with vertical direction magnified.

This measure of surface roughness is commonly used in industry. However, it is not particularly useful for evaluating bearing surfaces.[9]

R_q is the root-mean square of the deviations from the mean surface.

$$R_q = \left(\frac{y_1^2 + y_2^2 + y_3^2 + \cdots + y_n^2}{n} \right)^{1/2} \tag{13.3}$$

R_q is sometimes given as an alternative to R_a because it gives more weight to the higher peaks in the surface roughness. As an approximation, $R_q / R_a \approx 1.1$.

Surface roughness is usually expressed in units of μm (micrometer or micron) or μin (microinch). $1\,\mu m = 40\,\mu\text{in}$ and $1\,\mu\text{in} = 0.025\,\mu\text{m} = 25\,\text{nm}$.

There are other important characteristics of a surface besides the roughness. Surfaces usually exhibit a directionality of scratches characteristic of the finishing process. This is called *surface lay.* Surfaces may have a random lay, or an angular or circular pattern of marks. Another characteristic of the surface is its *waviness*, which occurs over a longer distance than the peaks and valleys of roughness. Allowable limits on these surface characteristics are specified on the engineering drawing by the scheme shown in Fig. 13.11.

It is important to realize that specifying a surface by average roughness height is not an ideal approach. Two surfaces can have the same value of R_a and vary considerably in the details of surface profile.

Surface texture does not completely describe a surface. For example, there is an altered layer just below the surface texture layer. This layer is characteristic of the nature and amount of energy that has been put into creating the surface. It can contain small cracks, residual stresses, hardness differences, and other alterations. Control of the surface and subsurface layer as it is influenced by processing is called *surface integrity.*[10]

Table 13.4 gives a description of the various classes of surface finish, and gives some examples of different types of machine elements where each would be specified. The surfaces are defined in words and by the preferred values, N, given by the ISO surface roughness standard.

9. N. Judge, *Manufacturing Engineering,* Oct. 2002, pp. 60–68.

10. A. R. Marder, "Effects of Surface Treatments on Materials Performance," *ASM Handbook*, Vol. 20, pp. 470–90 1997; E. W. Brooman, "Design for Surface Finishing," *ASM Handbook,* Vol. 20, pp. 820–27, ASM International, Materials Park, OH, 1997.

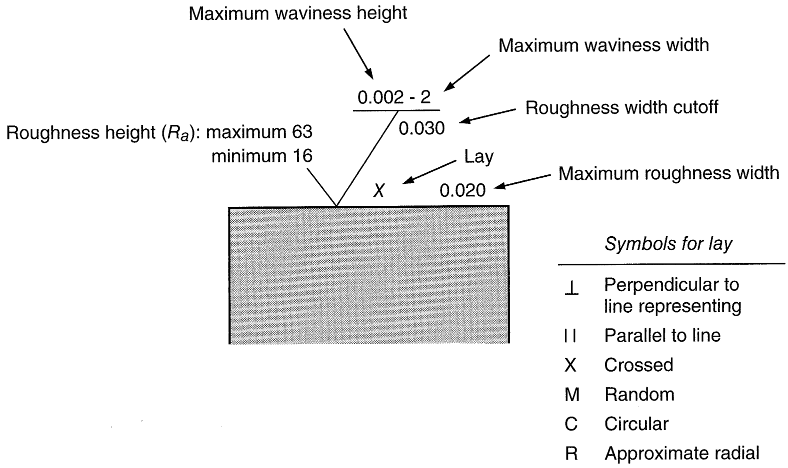

FIGURE 13.11
Symbols used to specify finish characteristics on an engineering drawing. Roughness given in microinches.

TABLE 13.4
Typical Values for Surface Roughness

Description	N-value	R_a, μin	R_a, μm	Typical Application in Design
Very rough	N11	1000	25.0	Nonstressed surface; rough cast surface
Rough	N10	500	12.5	Noncritical components; machined
Medium	N9	250	6.3	Most common surface for components
Average smooth	N8	125	3.2	Suitable for mating surfaces without motion
Better than avg.	N7	63	1.6	Use for close-fitting sliding surfaces an stressed parts except for shafts and vibration conditions.
Fine	N6	32	0.8	Use where stress concentration is high; gears, etc.
Very fine	N5	16	0.4	Use for fatigue-loaded parts; precision shafts
Extremely fine	N4	8	0.2	High-quality bearings; requires honing/polishing
Superfinish	N3	4	0.1	For highest precision parts; requires lapping

Dimensional Accuracy and Tolerances

Processes differ in their ability to meet close tolerances. Generally, materials with good workability can be held to closer tolerances. Achieving dimensional accuracy depends on both the nature of the material and the process. Solidification processes must allow for the shrinkage that occurs when a molten metal solidifies. Polymer processes must allow for the much higher thermal expansion of polymers than metals, and hot working processes for metals must allow for oxidation of the surface.

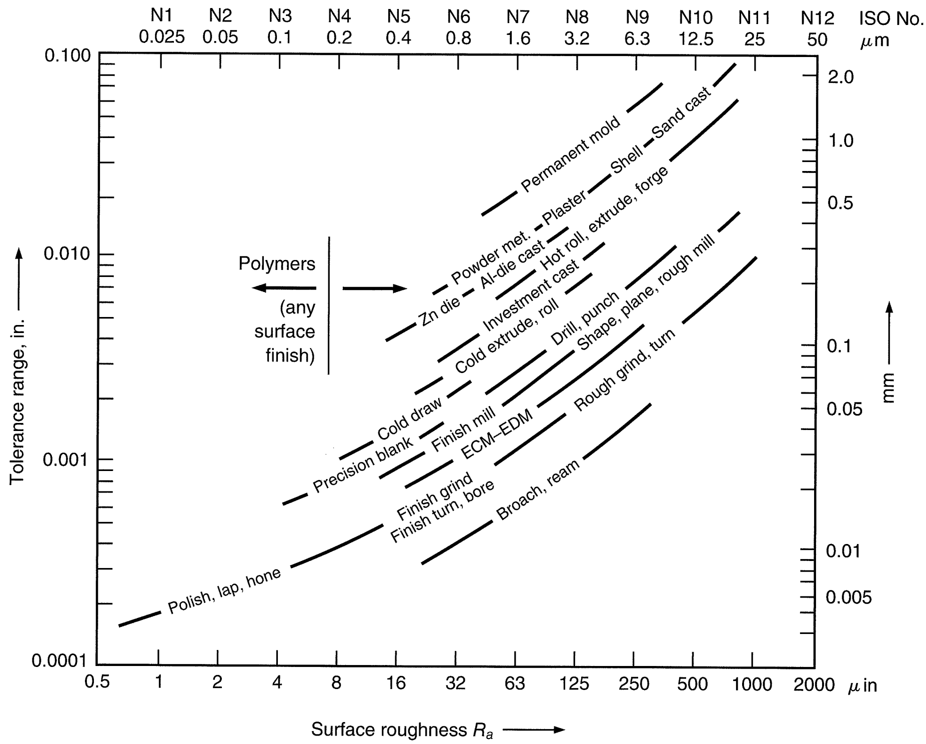

FIGURE 13.12
Approximate values of surface roughness and tolerance on dimensions typically obtained with different manufacturing processes. (J. A. Schey, *Introduction to Manufacturing Processes,* 3d ed. McGraw-Hill, 2000)

Each manufacturing process has the capability of producing a part to a certain surface finish and tolerance range without incurring extra cost. Figure 13.12 shows this general relationship. The tolerances apply to a 1-inch dimension and are not necessarily scalable to larger and smaller dimensions for all processes. For economical design, the loosest possible tolerances and coarsest surface finish that will fulfill the function of the design should be specified. As Fig. 13.13 shows, processing cost increases nearly exponentially as the requirements for tolerances and surface finish are made more stringent.

13.4.6 Cost to Manufacture

The manufacturing cost of the finished product is the most important factor in determining the selection of the manufacturing process and the material.[11] We did not present this topic first in this section because you first needed a better understanding of the other factors that influence process selection. An even more detailed consideration of cost is given in Chapter 16.

11. A. M. K. Esawi and M. F. Ashby, "Cost Estimates to Guide Pre-Selection of Processes," *Materials and Design*, vol. 24, pp. 605–616, 2003.

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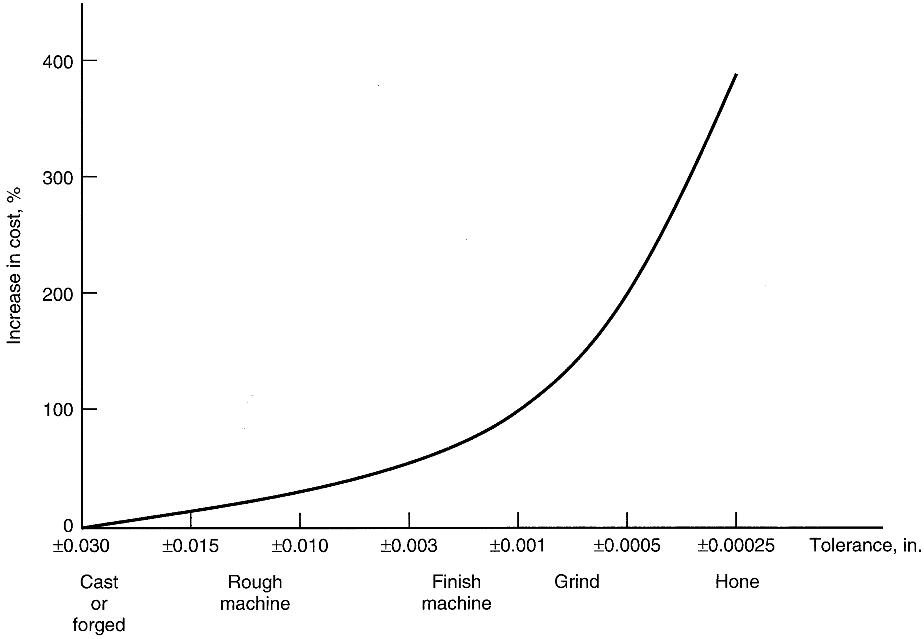

FIGURE 13.13
Influence of tolerance on processing costs (schematic).

The cost to manufacture a part is made up of the cost of the material C_M, the wages of the persons who make the parts and assemble the product, C_L, the capitalized cost of the equipment, C_C, the cost of tooling, C_T, and a cost of overhead, C_{OH}, that lumps together many necessary costs, like plant maintenance, general engineering, and accounting, that cannot be directly associated with each unit of product produced.

The first cost component of the *unit cost*, C_U, of a part is the weight of material m times the cost of material C_M. This must be adjusted by the fraction of material that ends up as scrap, f, due to the sprues and risers that must be cut from castings and molding, or the chips made in machining, or parts that are rejected for defects of some kind.

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$$C_1 = \frac{mC_M}{(1-f)} \tag{13.4}$$

Next we have the labor cost to make the part, expressed as labor cost (wages and benefits) per unit time. If $\dot{n}$ is the production rate, the number of parts produced per unit time, the labor cost, is given by

$$C_2 = \frac{C_L}{\dot{n}} \tag{13.5}$$

The tooling (dies, molds, fixtures, etc.) that is directly involved with the making a particular part has a cost C_T.

$$C_3 = \frac{kC_T}{n} \tag{13.6}$$

where n is the total production run for the part and k is the number of times the tooling must be replaced because of wear, that is, n/n_t raised to the next higher integer (where n_t is the number of parts that can be made before the tools wear out).

While tooling is a direct cost of making the part, the capital cost of equipment is usually not dedicated to a particular part. Instead, many different parts will be made on an injection molding machine by installing different molds. The capital cost of the equipment will be borrowed or charged to a corporate capital equipment account. Either way it must be paid back, little by little as a charge against the parts that are made with this equipment. The easiest way to account for this is to determine the time to pay off the equipment, *capital write-off time* t_{wo}, and divide this into the cost of capital equipment C_C.[12] Two other adjustments are needed. First, it is likely that the equipment will not be used productively 100 percent of the available time, so the cost is divided by a load factor, L, the fractional time the equipment is productive. Also, since the productive equipment time may be shared between several products, the cost assignable to a given product can be obtained by multiplying the total cost by the appropriate fraction q. Finally, the cost in \$/hr is converted to \$/unit by dividing by the production rate n.

$$C_4 = \frac{1}{\dot{n}}\left(\frac{C_C}{Lt_{wo}}\right)q \tag{13.7}$$

There are many costs in manufacturing a product that cannot be charged directly to each part or product because the complexity in breaking down the costs is too laborious. Examples are factory maintenance, operating the tool crib, general supervision, or R&D. These *indirect costs* are added up and then distributed to each part or product as an overhead charge. Often this is done in a fairly arbitrary way, as a cost per production time multiplied by the number of hours or seconds required to make the part. Thus, the total overhead pool is divided by the number of hours of production to give C_{OH}, \$/hr. Once again, to convert this to a unit cost, we divide by the production rate.

$$C_5 = \frac{C_{OH}}{\dot{n}} \tag{13.8}$$

Now, the total unit cost of a part is $C_U = C_1+C_2+C_3+C_4+C_5$.

$$C_U = \frac{mC_M}{(1-f)} + \frac{C_L}{\dot{n}} + \frac{kC_T}{n} + \frac{1}{\dot{n}}\left(\frac{C_C}{Lt_{wo}}\right)q + \frac{C_{OH}}{\dot{n}} \tag{13.9}$$

This equation shows that the total unit cost of a part will depend on:

- material cost, independent of the number of parts, but strongly dependent on its mass.
- tooling cost that varies inversely with the number of parts.
- the labor cost, the capital equipment cost, and overhead cost, that vary inversely with the rate of production.

These dependencies lead to the concept of economic batch size shown in Sec. 12.4.1.

12. This approach does not consider the time value of money. For further details, see Chap. 18. available at www.mhhe.com/dieter.

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13.4.7 Availability, Lead Time, and Delivery

Next to cost, a critical business factor in selecting a manufacturing process is the availability of the production equipment, the lead time to make tooling, and the reliability of the expected delivery date for parts made by outside suppliers. Large structural parts, such as rotors for electrical generators, or the main structural forgings for military aircraft, can be made in only a few factories in the world because of equipment requirements. Careful scheduling with the design cycle may be needed to mesh with the production schedule. Complex forging dies and plastic injection molding dies can have lead times of a year. These kinds of issues clearly affect the choice of the manufacturing process and demand attention during the embodiment design phase.

13.4.8 Further Information for Process Selection

The book by Schey[13] and the handbook chapter by the same author[14] are particularly helpful in the way they compare a wide spectrum of manufacturing processes. A comparison of manufacturing processes is given in Table 13.5. This is based on a series of data cards published by the Open University.[15]

This table is useful in two ways. First, it gives a quick way to screen for some broad process characteristics.

- Shape—the nature of the shapes that can be produced by the process
- Cycle time—time for a machine cycle to produce one part ($1/\dot{n}$)
- Flexibility—time to change tooling to make a different part
- Material utilization—percent of input material that does not end up in finished part
- Quality—level of freedom from defects and ability to hold dimensions to drawing
- Equipment/tooling costs—level of equipment charges and tooling costs.

The rating scale for ranking processes according to these factors is in Table 13.6. (Another rating system using a more detailed listing of process characteristics is given by Schey.[16])

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A second useful feature of Table 13.5 is the references to the extensive series of ASM Handbooks (AHB) and Engineered Materials Handbooks (EMH), which give many practical details on the processes.

The Manufacturing Process Information Maps (PRIMA) give much information that is useful for an initial selection of process.[17] The PRIMA selection matrix

13. J. A. Schey, *Introduction to Manufacturing Processes,* 3d ed., McGraw-Hill, New York, 2000.
14. J. A. Schey, "Manufacturing Processes and Their Selection," *ASM Handbook,* Vol. 20, pp. 687–704, ASM International, Materials Park, OH, 1997.
15. Data cards to accompany L. Edwards and M. Endean, eds., *Manufacturing with Materials,* Butterworth, Boston, 1990.
16. J. A. Schey, "Manufacturing Processes and Their Selection," *ASM Handbook,* Vol. 20, pp. 687–704, ASM International, Materials Park, OH, 1997.
17. K. G. Swift and J. D. Booker, *Process Selection,* 2d ed., Butterworth-Heinemann, Oxford, UK, 2003.

(Fig. 13.9) gives a set of 5 to 10 possible processes for different combinations of material and quantity of parts. Each PRIMA then gives the following information, which is a good summary of the information needed to make an intelligent decision on the manufacturing process:

- Process description
- Materials: materials typically used with the process
- Process variations: common variants of the basic process
- Economic factors: cycle time, minimum production quantity, material utilization, tooling costs, labor costs, lead times, energy costs, equipment costs
- Typical applications: examples of parts commonly made with this process
- Design aspects: general information on shape complexity, size range, minimum thickness, draft angles, undercuts, and limitations on other features
- Quality issues: describes defects to watch out for, expected range of surface finish, and process capability charts showing dimensional tolerances as a function of dimension

The book *Process Selection* is an excellent resource for process selection if the Cambridge Selection software is not available.

EXAMPLE 13.2

The selection of materials for an automobile fan, Example 11.3, was done with the assumption that the manufacturing costs for each material would be approximately equal since they were either casting or molding processes. The top-ranked materials were (1) an aluminum casting alloy, (2) a magnesium casting alloy, and (3) nylon 6/6 with 30 percent chopped glass fiber to increase the fracture toughness of the material. Casting or molding were given high consideration since we expect to be able to manufacture the component with the fan blades integrally attached to the fan hub.

Now we need to think more broadly about possible processes for making 500,000 parts per year. Figure 13.9 and Table 13.5 are used to perform a preliminary screening for potential processes before making a final decision based on costs calculated from Eq. (13.9). Table 13.7 shows the processes suggested in Fig. 13.9 for an aluminum alloy, a magnesium alloy, and the thermoplastic nylon 6/6.

In interpreting Table 13.7, the first consideration was whether Fig. 13.9 indicated that the process was suitable for one of the materials. The matrix of possible processes versus materials shows the greatest number of potential processes for an aluminum alloy, and the fewest for nylon 6/6. The first round of screening is made on the basis of the predominant shapes produced by each process. Thus, blow molding was eliminated because it produces thin, hollow shapes, extrusion and drawing because they produce straight shapes with high length-to-diameter ratios and because the blades must have a slight degree of twist. Sheet metal processes were eliminated because they create only 2-D shapes. Machining was declared too costly by management edict. The preliminary screening left the following processes for further consideration:

Aluminum alloy	Magnesium alloy	Nylon 6/6
Shell molding	Gravity die casting	Injection molding
Gravity die casting	Pressure die casting	
Pressure die casting	Closed die forging	
Squeeze casting	Squeeze casting	
Closed die forging		

Table 13.5
Rating of Characteristics of Common Manufacturing Processes

Process	Shape	Cycle Time	Flexibility	Material Utilization	Quality	Equipment Tooling Costs	Handbook Reference
Casting							
Sand casting	3-D	2	5	2	2	1	AHB, vol. 15
Evaporative foam	3-D	1	5	2	2	4	AHB, vol. 15, p. 230
Investment casting	3-D	2	4	4	4	3	AHB, vol. 15, p. 253
Permanent mold casting	3-D	4	2	2	3	2	AHB, vol. 15, p. 275
Pressure die casting	3-D solid	5	1	4	2	1	AHB, vol. 15, p. 285
Squeeze casting	3-D	3	1	5	4	1	AHB, vol. 15, p. 323
Centrifugal casting	3-D hollow	2	3	5	3	3	AHB, vol. 15, p. 296
Injection molding	3-D	4	1	4	3	1	EMH, vol. 2, p. 308
Reaction injection molding (RIM)	3-D	3	2	4	2	2	EMH, vol. 2, p. 344
Compression molding	3-D	3	4	4	2	3	EMH, vol. 2, p. 324
Rotational molding	3-D hollow	2	4	5	2	4	EMH, vol. 2, p. 360
Monomer casting contact molding	3-D	1	4	4	2	4	EMH, vol. 2, p. 338
Forming							
Forging, open die	3-D solid	2	4	3	2	2	AHB, vol. 14A, p. 99
Forging, hot closed die	3-D solid	4	1	3	3	2	AHB, vol. 14A, p. 111, 193
Sheet metal forming	3-D	3	1	3	4	1	AHB, vol. 14B, p. 293
Rolling	2-D	5	3	4	3	2	AHB, vol. 14A, p. 459
Extrusion	2-D	5	3	4	3	2	AHB, vol. 14A, p. 421
Superplastic forming	3-D	1	1	5	4	1	AHB, vol. 14B, p. 350
Thermoforming	3-D	3	2	3	2	3	EMH, vol. 2, p. 399
Blow molding	3-D hollow	4	2	4	4	2	EMH, vol. 2, p. 352
Pressing and sintering	3-D solid	2	2	5	2	2	AHB, vol. 7, p. 326
Isostatic pressing	3-D	1	3	5	2	1	AHB, vol. 7, p. 605
Slip casting	3-D	1	5	5	2	4	EMH, vol. 14, p. 153
Machining							
Single-point cutting	3-D	2	5	1	5	5	AHB, vol. 16
Multiple-point cutting	3-D	3	5	1	5	4	AHB, vol. 16

Table 13.5
(*continued*)

Process	Shape	Cycle Time	Flexibility	Material Utilization	Quality	Equipment Tooling Costs	Handbook Reference
Grinding	3-D	2	5	1	5	4	AHB, vol. 16, p. 421
Electrical discharge machining	3-D	1	4	1	5	1	AHB, vol. 16, p. 557
Joining							
Fusion welding	All	2	5	5	2	4	AHB, vol. 6, p. 175
Brazing/soldering	All	2	5	5	3	4	AHB, vol. 6, p. 328, 349
Adhesive bonding	All	2	5	5	3	5	EMH, vol. 3
Fasteners	3-D	4	5	4	4	5	. . .
Surface treatment							
Shot peening	All	2	5	5	4	5	AHB, vol. 5, p. 126
Surface hardening	All	2	4	5	4	4	AHB, vol. 5, p. 257
CVD/PVD	All	1	5	5	4	3	AHB, vol. 5, p. 510

Rating scheme: 1, poorest; 5, best. From *ASM Handbook,* Vol. 20, p. 299, ASM International. Used with permission.

TABLE 13.6
Rating Scale for Ranking Manufacturing Processes

Rating	Cycle time	Flexibility	Material Utilization	Quality	Equipment Tooling Costs
1	>15 min	Changeover very difficult	Waste >100% of finished part	Poor quality	High machine and tooling costs
2	5 to 15 min	Slow changeover	Waste 50 t0 100%	Average quality	Tooling and machines costly
3	1 to 5 min	Avg, changeover and setup time	Waste 10 to 50%	Average to good quality	Tooling and machines relatively inexpensive
4	20 s to 1 min	Fast changeover	Waste < 10% finished part	Good to excellent	Tooling costs low
5	<20 s	No setup time	No appreciable waste	Excellent quality	Equip. and tool very low

Rating scale; 1–poorest; 5–best

It is clear that injection molding is the only feasible process for the thermoplastic nylon 6/6. The available processes for aluminum or magnesium alloy come down to several casting processes and closed die forging. These remaining processes are compared using the selection criteria given in Table 13.5 and enumerated at the beginning of Sec.13.4.7. Investment casting is added as an additional process because it is known to make high-quality castings. Data for shell molding is not listed in Table 13.5, but its entry in

TABLE 13.7
Initial Screening of Candidate Processes

Possible Process	Aluminum Alloy Yes or No?	Aluminum Alloy Reject?	Magnesium Alloy Yes or No?	Magnesium Alloy Reject?	Nylon 6/6 Yes or No?	Nylon 6/6 Reject?	Reason for Elimination
1.2 Shell molding	Y		N		N		
1.3 Gravity die casting	Y		Y		N		
1.4 Pressure die casting	Y		Y		N		
1.9 Squeeze casting	Y		Y		N		
2.1 Injection molding	N		N		Y		
2.6 Blow molding	N		N		Y	R	Used for 3-D hollow shapes
2.9 Plastic extrusion	N		N		Y	R	Need to twist the blades
3.1 Closed die forging	Y		Y		N		
3.2 Rolling	Y		N		N		2-D process for making sheet
3.3 Drawing	Y	R	Y	R	N		Makes shapes with high L/D
3.4 Cold forming	Y	R	Y	R	N		Used for hollow 3-D shapes
3.5 Cold heading	Y	R	N	R	N		Used for making bolts
3.8 Sheet shearing	Y	R	Y	R	N		A 2-D forming process
3.12 Metal extrusion	Y	R	Y	R	N		Need to twist the blades
4A Automatic machining	Y	R	Y	R	N		Machining is ruled out by edict.

Table 13.8 was constructed from data given in *Process Selection*. The gravity die casting process is most commonly found under the name of permanent mold casting, and the data for permanent mold casting from Table 13.5 was used in Table 13.8. The rating for each criterion is totaled for each process, as seen in Table 13.8.

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The results of this process ranking are not very discriminating. All casting processes rank 13 or 14, except investment casting. The ranking for hot forging is slightly lower at 12. Moreover, designing a forging die to produce a part with 12 blades integrally attached to the fan hub is more difficult than designing a casting mold for the same shape. For this application there appears to be no advantage of forging over casting, and since the company does not have in-house forging capability, the forged fan component would have to be provided by an outside supplier.

The next step in deciding on the manufacturing process is to compare the estimated cost to manufacture a part using Eq. (13.9). The following processes will be compared: injection molding for nylon 6/6, and low-pressure permanent mold casting, investment casting, and squeeze casting for metal alloys. Squeeze casting is included because it has the potential to produce low-porosity, fine detail castings when compared to shell molding and pressure die casting.

Table 13.8
Second Screening of Possible Manufacturing Processes

Process	Cycle Time	Process Flexibility	Material Utilization	Quality	Equipment & Tooling Costs	Total
Shell molding	5	1	4	3	1	14
Low pressure permanent mold	4	2	2	3	2	13
Pressure die casting	5	1	4	2	1	13
Squeeze casting	3	1	5	4	1	14
Investment casting	2	4	4	4	3	17
Hot closed die forging	4	1	3	3	1	12

EXAMPLE 13.3

Now we use Eq.(13.9) to determine the estimated cost for making 500,000 units of the fan. By using either casting or molding we expect to be able to manufacture a component with the blades cast integral with the hub. This will eliminate assembling the blades into the hub, although there may be a requirement for a balancing step.

The radius of the bladed hub will be 9 in; see Fig. 11.11. The hub is 0.5 in. thick and has a diameter of 4 in. There are 12 blades cast into the hub, each of which is 1 in. wide at the root and 2.3 in. wide at the tip. Each blade is 0.4 in. thick, narrowing down somewhat toward the tip. About 0.7 of the volume envelope is hub and blades. Therefore, the volume of the casting is about 89 cu. in., and if cast in aluminum it would weigh 8.6 lb (3.9 kg).

Only casting or molding processes are considered, since we are interested in an integral hub and blade process. Low-pressure permanent mold casting (gravity die casting) is a variant of die casting in which the molten metal is forced upward into the die by applying low pressure on the liquid metal. Because the die cavity is filled slowly upwards, there is no entrapped air, and the casting has fewer defects. Squeeze casting is a combination of die casting and forming in which metal is introduced into the bottom half of the die and during solidification the top of the die applies high pressure to compress the semisolid material into the final shape.

The surface finish on the blades must be at least N8 (Table 13.4) to minimize fatigue failure. The tolerance on blade width and thickness should be ± 0.020 in. (0.50 mm). Figure 13.12 indicates that these quality conditions can be met by several metal casting processes, including die casting and investment casting. In addition, injection molding is the process of choice for 3-D thermoplastics, and squeeze casting was added as an innovative casting process that produces high-quality castings with high definition of details.

The requirements of the automotive fan are compared with the capabilities of four likely manufacturing processes in Table 13.9. The data for the first three processes were taken from the CES software. The data for squeeze casting was taken from Swift and Booker.[18]

18. K.G. Swift, and J.D. Booker, *Process Selection,* 2d ed., Butterworth-Heinemann, Oxford, UK, 2003.

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TABLE 13.9
Comparison of Characteristics of Each Process with Requirements of the Fan

Process Requirements	Fan Design	Low-Pressure Permanent Mold Casting	Investment Casting	Injection Molding	Squeeze Casting
Size range, max mass (kg) (Fig. 13.7)	3.9	80		30	4.5
Section thickness, max (mm) (Fig. 13.8)	13	120		8	200
Section thickness, min (mm) . . . (Fig. 13.8)	7.5	3		0.6	6
Tolerance (±mm)	0.50	0.5		0.1	0.3
Surface roughness (μm) R_a	3.2	4		0.2	1.6
Economic batch size, units (Fig. 13.5)	5×10^5	$>10^3$	$<10^3$	$>10^5$	$>10^4$

Each of the candidate processes is capable of producing symmetrical 3-D shapes. The screening parameter examined first was the economic batch size. Since it is expected that 500,000 units will be produced per year, investment casting was eliminated as a possibility because the economic batch size is less than 1000 units. Several of the other processes have borderline issues with respect to process capability, but they do not disqualify them from further analysis. For example, it may not be possible to obtain the maximum thickness of 13 mm with injection molding of nylon. This deficiency could be overcome by a different design of the hub using thinner sections and stiffening ribs; see Sec. 12.6.2 There is also a possibility that low-pressure permanent mold casting may not be able to achieve the required tolerance on critical dimensions. Experiments with process variables such as melt temperature and cooling rate will determine whether this proves to be a problem.

Now that we have narrowed the selection of a manufacturing process down to three alternatives, the final selection is based on the estimate of the cost to make one unit of the integral hub–blade fan using the cost model described in Sec. 13.4.6.

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Calculations show that two machines operating three shifts for 50 weeks per year will be required to produce 500,000 units per year. This is reflected in the tooling and capital costs. Labor cost is based on one operator per machine. For the permanent mold casting and squeeze casting processes the material is A357 aluminum alloy. For injection molding the material used is nylon 6/6 reinforced with 30 percent chopped glass fibers.

It is clear from Table 13.10 that the cost of the material is the major cost category. It varies from 54% to 69% of total unit cost for the three processes studied. The production rate is also an important process parameter. It accounts for the higher cost of squeeze casting over permanent mold casting in the categories of labor cost and overhead. Process engineering studies using some of the TQM methods discussed in Chap. 4 might be able to increase the rate of production. However, there are physical limits to increasing this rate very greatly since all three processes are limited by the heat transfer rate that determines the time required to solidify the part sufficiently that it can be ejected from the mold.

TABLE 13.10
Determination of Unit Cost for Three Processes Based on Cost Model in Sec. 13.3.5

Cost Element	Low Pressure Permanent Mold	Injection Molding	Squeeze Casting
Material cost, C_M (\$/lb)	0.60	1.80	0.60
Fraction of process that is scrap, f	0.1	0.05	0.1
Mass of part, m (lb)	8.6	4.1	8.6
C_1 see Eq. (13.4) unit cost	**\$5.73**	**\$7.77**	**\$5.73**
Labor cost, C_L (\$/h)	25.00	25.00	25.00
Production rate, n, (units/h)	38	45	30
C_2 see Eq. (13.5) unit cost	**\$0.66**	**\$0.55**	**\$0.83**
Tooling cost, C_T (\$/set)	80,000	70,000	80,000
Total production run, n (units)	500,000	500,000	500,000
Tooling life, n_t (units)	100,000	200,000	100,000
Sets of tooling required, k	5×2	3×2	5×2
C_3 see Eq. (13.6) unit cost	**\$1.60**	**\$0.84**	**\$1.60**
Capital cost, C_C (\$)	$100{,}000 \times 2$	$500{,}000 \times 2$	200,000
Capital write-off time, t_{wo} (yrs)	5	5	5
Load fraction, L (fraction)	1	1	1
Load sharing fraction, q	1	1	1
C_4 see Eq. (13.7) unit cost	**\$0.17**	**\$0.74**	**\$0.44**
Factory overhead, C_{OH} (\$/h)	60	60	60
Production rate, $\dot{n}$ (units/h)	38	45	30
C_5 see Eq. (13.8) unit cost	**\$1.58**	**\$1.33**	**\$2.00**
Total unit cost = $C_1 + C_2 + C_3 + C_4 + C_5$	**\$9.74**	**\$11.23**	**\$10.60**

Low-pressure permanent mold casting is the obvious choice for producing the fan hub and blades. The only reason for rejecting this process would be if it was not possible to maintain required dimensions or tolerance, or if the castings contained porosity. Squeeze casting would be an attractive alternative, since the addition of mechanically induced compressive stresses would result in less distortion of the metal on cooling, and the ability to hold tighter tolerances for a relatively small increase in unit cost.

13.5
DESIGN FOR MANUFACTURE (DFM)

For the past 20 years engineers have seen a large amount of effort devoted to the integration of design and manufacture, with the goals of reducing manufacturing cost and improving product quality. The processes and procedures that have been developed have become known as *design for manufacture* or design for manufacturability (DFM). Associated with this is the closely related area of *design for assembly* (DFA).

The field is often simply described by the abbreviation DFM/DFA or DFMA. DFMA methods should be applied during the embodiment stage of design.

Design for manufacture represents an awareness of the importance of design as the time for thoughtful consideration of all steps of production. To achieve the goals of DFM requires a concurrent engineering team approach (Sec. 2.4.4) in which appropriate representatives from manufacturing, including outside suppliers, are members of the design team from the start.

13.5.1 DFM Guidelines

DFM guidelines are statements of good design practice that have been empirically derived from years of experience.[19] Using these guidelines helps narrow the range of possibilities so that the mass of detail that must be considered is within the capability of the designer.

1. **Minimize total number of parts:** Eliminating parts results in great savings. A part that is eliminated costs nothing to make, assemble, move, store, clean, inspect, rework, or service. A part is a good candidate for elimination if there is no need for relative motion, no need for subsequent adjustment between parts, and no need for materials to be different. However, part reduction should not go so far that it adds cost because the remaining parts become too heavy or complex.

   The best way to eliminate parts is to make minimum part count a requirement of the design at the conceptual stage of design. Combining two or more parts into an integral design architecture is another approach. Plastic parts are particularly well suited for integral design.[20] Fasteners are often prime targets for part reduction. Another advantage of making parts from plastics is the opportunity to use snap-fits instead of screws, Fig. 13.14a.[21]
2. **Standardize components:** Costs are minimized and quality is enhanced when standard commercially available components are used in design. The benefits also occur when a company standardizes on a minimum number of part designs (sizes, materials, processes) that are produced internally in its factories. The life and reliability of standard components may have already been established, so cost reduction comes through quantity discounts, elimination of design effort, avoidance of equipment and tooling costs, and better inventory control.
3. **Use common parts across product lines:** It is good business sense to use parts in more than one product. Specify the same materials, parts, and subassemblies in each product as much as possible. This provides economies of scale that drive down unit cost and simplify operator training and process control. Product

19. H.W. Stoll, *Appl. Mech. Rev,* Vol. 39, No. 9, pp. 1356–64, 1986; J.R. Bralla, *Design for Manufacturability Handbook,* 2d ed., McGraw-Hill, New York, 1999; D.M. Anderson, *Design for Manufacturability,*, 2d ed., CIM Press, Cambria, CA, 2001.
20. W. Chow, *Cost Reduction in Product Design,* chap. 5, Van Nostrand Reinhold, New York, 1978.
21. P.R. Bonnenberger, *The First Snap-Fit Handbook,* 2d ed., Hanser Gardener Publications Cincinnati, OH, 2005.

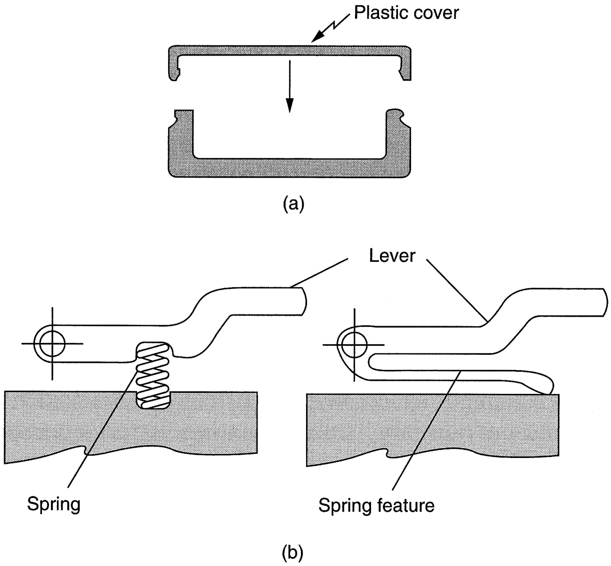

FIGURE 13.14
Some examples of applying DFM. (a) This product utilizes snap-fit principles to attach the cover, eliminating the need for screw fasteners. Since the cover is molded from plastic material and because of the taper of the snap-fit elements, it also illustrates *compliance.* (b) This illustrates a multifunctional part. By incorporating a spring function in the lever, the need for a separate coil spring is eliminated.

data management (PDM) systems can be used to facilitate retrieval of similar designs.

4. **Standardize design features.**Standardizing on design features like drilled hole sizes, screw thread types, and bend radii minimizes the number of tools that must be maintained in the tool room. This reduces manufacturing cost.
5. **Aim to keep designs functional and simple:** Achieving functionality is paramount, but don't specify more performance than is needed. It is not good engineering to specify a heat-treated alloy steel when a plain carbon steel will achieve the performance with a little bit more careful analysis. When adding features to the design of a component, have a firm reason for the need. The product with the fewest parts, the least intricate shapes, the fewer precision adjustments, and the lowest number of manufacturing steps will be the least costly to manufacture. Also, the simplest design will usually be the most reliable and the easiest to maintain.
6. **Design parts to be multifunctional:** A good way to minimize part count is to design such that parts can fulfill more than one function, leading to integral architecture. For example, a part might serve as both a structural member and a spring, Fig. 13.14*b*. The part might be designed to provide a guiding, aligning, or self-fixturing feature in assembly. This rule can cancel out guideline 5 and break guideline 7 if it is carried too far.

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7. **Design parts for ease of fabrication:** As discussed in Chap. 11, the least costly material that satisfies the functional requirements should be chosen. It is often the case that materials with higher strength have poorer workability or fabricability. Thus, one pays more for a higher-strength material, and it also costs more to process it into the required shape. Since machining to shape tends to be costly, manufacturing processes that produce the part to *near net shape* are preferred whenever possible so as to eliminate or minimize machining.

   It is important to be able to visualize the steps that a machine operator will use to make a part so that you can minimize the manufacturing operations needed to make the part. For example, clamping a part before machining is a time-consuming activity, so design to minimize the number of times the operator will be required to reorient the part in the machine to complete the machining task. Reclamping also is a major source of geometric errors. Consider the needs for the use of fixtures and provide large solid mounting surfaces and parallel clamping surfaces.

   Rough evaluations for how easily specific materials can be processed by different manufacturing methods are given in Fig. 13.17. Guidelines for specific processes are given in Secs. 13.11 to 13.19.
8. **Avoid excessively tight tolerances:** Tolerances must be set with great care. Specifying tolerances that are tighter than needed results in increased cost; recall Fig. 13.13. These come about from the need for secondary finishing operations like grinding, honing, and lapping, from the cost of building extra precision into the tooling, from longer operating cycles because the operator is taking finer cuts, and from the need for more skilled workers. Before selecting a manufacturing process, be sure that it is capable of producing the needed tolerance and surface finish.

   As a designer, it is important to maintain your credibility with manufacturing concerning tolerances. If in doubt that a tolerance can be achieved in production, always communicate with manufacturing experts. Never give a verbal agreement to manufacturing that they can loosen a tolerance without documentation and making the change on the part drawing. Also, be careful about how the statement for blanket tolerances on the drawing is worded and might be misinterpreted by manufacturing.
9. **Minimize secondary and finishing operations:** Minimize secondary operations such as heat treatment, machining, and joining and avoid finishing operations such as deburring, painting, plating, and polishing. Use only when there is a functional reason for doing so. Machine a surface only when the functionality requires it or if it is needed for aesthetic purposes.
10. **Utilize the special characteristics of processes:** Be alert to the special design features that many processes provide. For example, molded polymers can be provided with "built-in" color, as opposed to metals that need to be painted or plated. Aluminum extrusions can be made in intricate cross sections that can then be cut to short lengths to provide parts. Powder-metal parts can be made with controlled porosity that provides self-lubricating bearings.

These rules are becoming the norm in every engineering design course and in engineering practice.

13.5.2 Specific Design Rules

A number of DFM rules for design, more specific than the preceding guidelines, have been developed.[22]

1. Space holes in machined, cast, molded, or stamped parts so they can be made in one operation without tooling weakness. This means that there is a limit on how close holes may be spaced due to strength in the thin section between holes.
2. Avoid generalized statements on drawings, like "polish this surface" or "toolmarks not permitted," which are difficult for manufacturing personnel to interpret. Notes on engineering drawings must be specific and unambiguous.
3. Dimensions should be made from specific surfaces or points on the part, not from points in space. This greatly facilitates the making of gages and fixtures. The use of GD&T methods makes this point moot.
4. Dimensions should all be from a single datum surface rather than from a variety of points to avoid overlap of tolerances.
5. The design should aim for minimum weight consistent with strength and stiffness requirements. While material costs are minimized by this criterion, there also will usually be a reduction in labor and tooling costs.
6. Whenever possible, design to use general-purpose tooling rather than special dies, form cutters, and similar tools. An exception is high-volume production where special tooling may be more cost-effective.
7. Use generous fillets and radii on castings and on molded, formed, and machined parts.
8. Parts should be designed so that as many operations as possible can be performed without requiring repositioning. This promotes accuracy and minimizes handling.

It is valuable to have manufacturing engineers and specialists involved in design decision making so that these guidelines and others they bring can inform the process.

13.6
DESIGN FOR ASSEMBLY (DFA)

Once parts are manufactured, they need to be assembled into subassemblies and products. The assembly process consists of two operations, *handling*, which involves grasping, orienting, and positioning, followed by *insertion and fastening*. There are three types of assembly, classified by the level of automation. In *manual assembly* a human operator at a workstation reaches and grasps a part from a tray, and then moves, orients, and pre-positions the part for insertion. The operator then places the parts together and fastens them, often with a power tool. In *automatic assembly,* handling is accomplished with a parts feeder, like a vibratory bowl, that feeds the cor-

22. J. R. Bralla, *Design for Manufacturability Handbook,* 2d ed., McGraw-Hill, New York, 1999.

rectly oriented parts for insertion to an automatic workhead, which in turn inserts the part.[23] In *robotic assembly,* the handling and insertion of the part is done by a robot arm under computer control.

The cost of assembly is determined by the number of parts in the assembly and the ease with which the parts can be handled, inserted, and fastened. Design can have a strong influence in both areas. Reduction in the number of parts can be achieved by elimination of parts (e.g., replacing screws and washers with snap or press fits, and by combining several parts into a single component). Ease of handling and insertion is achieved by designing so that the parts cannot become tangled or nested in each other, and by designing with symmetry in mind. Parts that do not require end-to-end orientation prior to insertion, as a screw does, should be used if possible. Parts with complete rotational symmetry around the axis of insertion, like a washer, are best. When using automatic handling it is better to make a part highly asymmetric if it cannot be made symmetrical.

For ease of insertion, a part should be made with chamfers or recesses for ease of alignment, and clearances should be generous to reduce the resistance to assembly. Self-locating features are important, as is providing unobstructed vision and room for hand access. Figure 13.15 illustrates some of these points.

13.6.1 DFA Guidelines

The guidelines for design for assembly can be grouped into three classes: general, handling, and insertion.

General Guidelines

1. **Minimize the total number of parts:** A part that is not required by the design is a part that does not need to be assembled. Go through the list of parts in the assembly and identify those parts that are essential for the proper functioning of the product. All others are candidates for elimination. The criteria for an *essential part*, also called a theoretical part, are:
   - The part must exhibit motion relative to another part that is declared essential.
   - There is a fundamental reason that the part be made from a material different from all other parts.
   - It would not be possible to assemble or disassemble the other parts unless this part is separate, that is it is an essential connection between parts.
   - Maintenance of the product may require disassembly and replacement of a part.
   - Parts used only for fastening or connecting other parts are prime candidates for elimination.

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23. G. Boothroyd, *Assembly Automation and Product Design,* 2d ed., CRC Press, Boca Raton, FL, 2005; "Quality Control and Assembly," *Tool and Manufacturing Engineers Handbook*, Vol. 4, Society of Manufacturing Engineers, Dearborn, MI 1987.

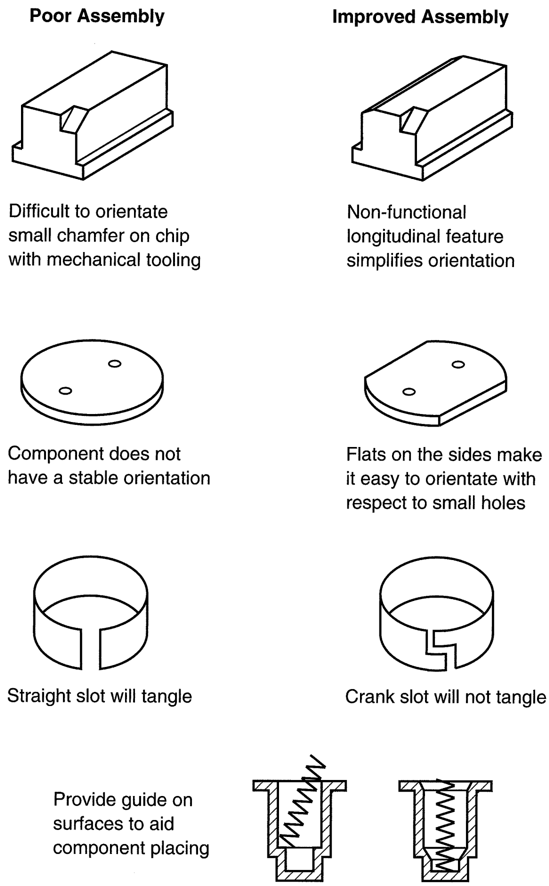

FIGURE 13.15
Some design features that improve assembly.

Designs can be evaluated for efficiency of assembly with Eq. (13.10), where the time taken to assemble a "theoretical" part is taken as 3 seconds.[24]

$$\text{Design assembly efficiency} = \frac{3\times \text{ ``theoretical'' minimum number of parts}}{\text{total assembly time for all parts}} \tag{13.10}$$

A theoretical part is one that cannot be eliminated from the design because it is needed for functionality. Typical first designs have assembly efficiencies of 5 to 10 percent, while after DFA analysis it is typically around 20 to 30 percent.

2. **Minimize the assembly surfaces:** Simplify the design so that fewer surfaces need to be prepared in assembly, and all work on one surface is completed before moving to the next one.

24. For small parts such as those found in household and electronic products, the assembly time runs from 2 to 10 seconds. On an automobile assembly line, times of 45 to 60 seconds are more typical.

3. **Use subassemblies:** Subassemblies can provide economies in assembly since there are fewer interfaces in final assembly. Subassemblies can also be built and tested elsewhere and brought to the final assembly area. When subassemblies are purchased they should be delivered fully assembled and tested. Products made from subassemblies are easier to repair by replacing the defective subassembly.
4. **Mistake-proof the design and assembly:** An important goal in design for assembly is to ensure that the assembly process is unambiguous so that the operators cannot make mistakes in assembling the components. Components should be designed so that they can only be assembled one way. The way to orient the part in grasping it should be obvious. It should not be capable of being assembled in the reverse direction. Orientation notches, asymmetrical holes, and stops in assembly fixtures are common ways to mistake-proof the assembly process. For more on mistake-proofing, see Sec. 13.8.

Guidelines for Handling

5. **Avoid separate fasteners or minimize fastener costs:** Fasteners may amount to only 5 percent of the material cost of a product, but the labor they require for proper handling in assembly can reach 75 percent of the assembly costs. The use of screws in assembly is expensive. Snap fits should be used whenever possible. When the design permits, use fewer large fasteners rather than several small ones. Costs associated with fasteners can be minimized by standardizing on a few types and sizes of fasteners, fastener tools, and fastener torque settings. When a product is assembled with a single type of screw fastener it is possible to use auto-feed power screwdrivers.
6. **Minimize handling in assembly:** Parts should be designed to make the required position for insertion or joining easy to achieve. Since the number of positions required in assembly equates to increased equipment expense and greater risk of defects, quality parts should be made as symmetrical as their function will allow. Orientation can be assisted by design features that help to guide and locate parts in the proper position. Parts that are to be handled by robots should have a flat, smooth top surface for vacuum grippers, or an inner hole for spearing, or a cylindrical outer surface for gripper pickup.

Guidelines for Insertion

7. **Minimize assembly direction:** All products should be designed so that they can be assembled from one direction. Rotation of an assembly requires extra time and motion and may require additional transfer stations and fixtures. The best situation in assembly is when parts are added in a top-down manner to create a z-axis stack.
8. **Provide unobstructed access for parts and tools:** Not only must the part be designed to fit in its prescribed location, but there must be an adequate assembly path for the part to be moved to this location. This also includes room for the operator's arm and tools, which in addition to screwdrivers, could include wrenches or welding torches. If a worker has to go through contortions to perform an assembly operation, productivity and possibly product quality will suffer after a few hours of work.

9. **Maximize compliance in assembly:** Excessive assembly force may be required when parts are not identical or perfectly made. Allowance for this should be made in the product design. Designed-in compliance features include the use of generous tapers, chamfers, and radii. If possible, one of the components of the product can be designed as the part to which other parts are added (part base) and as the assembly fixture. This may require design features that are not needed for the product function.

13.7
ROLE OF STANDARDIZATION IN DFMA

In Section 1.7 the important role of codes and standards in engineering design was introduced. There the emphasis was on the role of standards in protecting public safety and assisting the designer in performing high-quality work. In this section we extend these ideas about standardization to show the important role that part standardization can play in DFMA.

Part proliferation is an endemic problem in manufacturing unless steps are taken to prevent it from happening. One large automotive manufacturer found that in one model line alone it used 110 different radiators, 1200 types of floor carpet, and 5000 different fasteners. Reducing the variety of parts that achieve the same function can have many benefits to the product development enterprise. Firm numbers on the cost of part proliferation are difficult to obtain, but estimates are that about half of manufacturing overhead costs are related to managing too many part numbers.

13.7.1 Benefits of Standardization

The benefits of standardization occur in four areas: cost reduction, quality improvement, production flexibility, and manufacturing responsiveness.[25] The specifics of benefits in each area are outlined here.

Cost Reduction

- **Purchasing costs.** Standardization of parts and the subsequent reduction in part numbers[26] will result in large savings in procurement costs in outsourcing because parts will be bought in larger quantities. This allows for quantity discounts, flexible delivery schedules, and less work for the purchasing department.
- **Reduce costs through raw material standardization.** Cost for in-house production of parts can be reduced if raw materials can be standardized to a single size of bar stock, tubing, and sheet metal. Also, metal casting and plastic molding operations can each be limited to a single material. These standardization efforts allow for increased use of automated equipment with a minimum of cost for tool and fixture changing and setup.

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25. D. M. Anderson, *Design for Manufacturability,* 2d ed., Chap. 5 CIM Press, Cambria, CA, 2001.
26. A part number is the identification for a part (often a drawing number) and is not to be confused with the number of parts.

- **Feature standardization.** Part features such as drilled, reamed, or threaded holes and bend radii in sheet metal all require special tools. Unless there is a dedicated machine for each size, the tools need to be changed for different dimensions, with the corresponding setup charge. Designers often specify an arbitrary hole size, when a standard size would do just as well. If the specification of radii in lathe turning or milling is not standardized it can cause a requirement for the shop to maintain a large inventory of cutting tools.
- **Reduction of inventory and floor space requirements.** The preceding cost reduction tactics assist in decreasing inventory costs either as incoming parts inventory, or the work-in-progress inventory, through fewer machine setups. Standardization makes building-on-demand more of a possibility, which will greatly decrease finished goods inventory. Reducing inventory has the advantage of reducing the required factory floor space. All of these issues, reduction of inventory and floor space, tooling costs, and purchasing and other administrative costs result in a decrease in overhead costs.

Quality Improvement

- **Product quality.** Having fewer parts of a given type greatly reduces the chance of using the wrong part in an assembly.
- **Prequalification of parts.** The use of standard parts means that there is much greater cumulative experience with using the particular part. This means that standard parts can be prequalified for use in a new product without the requirement for extensive testing.
- **Supplier reduction means improved quality.** Standardization of parts means there will be fewer outside suppliers of parts. Those suppliers remaining should be those with a record of producing quality parts. Giving more business to fewer suppliers will be an incentive for developing stronger supplier relationships.

Production Flexibility

- **Material logistics.** The flow of parts within the plant will be easier with fewer parts to order, receive, stock, issue, assemble, test, and reorder.
- **Reliable delivery of standard low-cost parts.** These parts can be restocked directly to points of use in the plant by parts suppliers using long-term purchase agreements, much as food is delivered to a supermarket. This reduces overhead costs for purchasing and materials handling.
- **Flexible manufacturing.** Eliminating setup operations allows products to be made in any batch size. This allows the products to be made to order or to *mass customize* the product. This eliminates finished goods inventory and lets the plant make only the products for which it has an order.

Manufacturing Responsiveness

- **Parts availability.** Fewer part types used in greater volume will mean less chance of running out of parts and delaying production.
- **Quicker supplier deliveries.** Standardization of parts and materials should speed up deliveries. Suppliers will have the standard tools and materials in their inventory.

- **Financially stronger suppliers.** Part suppliers to OEMs have seen their profit margins narrow, and many have gone out of business. With larger volume orders and fewer part types to make, they can rationalize their business model, simplify their supply chain management, and reduce overhead costs. This will give them the resources to improve the quality and efficiency of their operations.

While the benefits from standardization seem very compelling, it may not always be the best course of action. For example, the compromises required by standardization may restrict the design and marketing options in undesirable ways. Stoll[27] presents pros and cons about part standardization.

13.7.2 Achieving Part Standardization

Many engineers do not realize that regardless of the cost of a part, there is real cost in ordering, shipping, receiving, inspecting, warehousing, and delivering the part to where it will be used on the assembly line. Thus, it is just as important to be concerned with standardization of inexpensive parts like fasteners, washers, and resistors as it is with more intricate molded parts. Young engineers need to be made aware of the importance of part standardization, and, they should understand that they are not free to make arbitrary decisions when sizing parts. Early in their careers they should be made aware of the company standard part list, and if one does not exist they should work with their colleagues to develop one.[28]

A common misconception is that the way to achieve a minimum-cost design is to create a minimum-weight design. Certainly this may be true in aircraft and spacecraft design where weight is very important, but for most product design this design philosophy should not be followed if it means using nonstandard parts. The most economical approach is to select the next larger *standard size* of motor, pump, or angle iron to achieve adequate strength or functionality. Special sizes are justified only in very special situations.

A common reason for the existence of part duplication is that the designer is not aware of the existence of an identical part. Even if she knows of its existence, it may be more difficult to find the part number and part drawing than it is to create a new part. This issue is discussed in Sec. 13.7.3.

13.7.3 Group Technology

Group technology (GT) is a methodology in which similar parts are grouped together in order to take advantage of their common characteristics. Parts are grouped into *part families* in terms of commonality of design features (see Fig. 13.6), as well as manufacturing processes and processing steps. Table 13.11 lists typical design and manufacturing characteristics that would be considered.

27. H.W. Stoll, *Product Design Methods and Practices,* Chaps. 9 & 10, Marcel Dekker, New York, 1999.
28. See D.M. Anderson, op. cit, for a detailed description of how to generate a standard part list.

TABLE 13.11
Design and Man ufacturing Characteristics that Are Typically Considered in GT Classification

Design Characteristics of Part		Manufacturing Characteristics of Part	
External shape	Part function	External shape	Annual production
Internal shape	Type of material	Major dimensions	Tooling and fixtures used
Major dimensions	Tolerances	Length/diameter ratio	Sequence of operations
Length/diameter ratio	Surface finish	Primary process used	Tolerances
Shape of raw material	Heat treatment	Secondary processes	Surface finish

Benefits of Group Technology

- GT makes possible standardization of part design and elimination of part duplication. Since only about 20 percent of design is original design, new designs can be developed using previous similar designs, with a great saving in cost and time.
- By being able to access the previous work of the designer and the process planner, new and less experienced engineers can quickly benefit from that experience.
- Process plans for making families of parts can be standardized and retained for future use. Therefore, setup times are reduced and more consistent quality is obtained. Also, since the tools and fixtures are often shared in making a family of parts, unit costs are reduced.
- With production data aggregated in this way, cost estimates based on past experience can be made more easily, and with greater precision.

Another advantage of group technology addresses the trend among consumers for greater variety in products. This has pushed most consumer products from being mass produced products to batch production. Batch manufacturing facilities are typically organized in a *functional layout*, in which processing machines are arranged by common type, that is, lathes are arranged together in a common area, as are milling machines, grinders, and so on. Parts are moved from area to area as the sequence of machining operations dictates. The result is delays because of the need for tooling changes as part types change, or the machine stands idle waiting for a new batch of parts to be delivered. A functional layout is hardly a satisfactory arrangement for batch production.

A much better arrangement is using a *manufacturing cell layout*. This arrangement exploits the similarities provided by a part family. All the equipment necessary to produce a family of parts is grouped into a cell. For example, a cell could be a lineup of a lathe, milling machine, drill press, and cylindrical grinder, or it could be a CNC machining center that is equipped to do all of these machining operations, in turn, on a single computer-controlled machine. Using a cell layout, the part is transferred with minimum movement and delay from one unit of the cell to another. The machines are kept busy because GT analysis has insured that the part mix among the products made in the factory provides an adequate volume of work to make the cell layout economically viable.

Part Classification

Group technology depends on the ability to classify parts into families. At a superficial level this appears relatively easy to do, but to gain the real benefits of GT requires much experience and hard work. Classification of parts can be approached on four levels.

1. **Experience-based judgment.** The easiest approach is to assemble a team of experienced design engineers and process planners to classify parts into families based on part shape and knowledge of the sequence of processing steps used to make the part. This approach is limited in its search capabilities, and it may not assure an optimum processing sequence.
2. **Production flow analysis (PFA).** Production flow analysis uses the sequence of operations to make a part, as obtained from factory routing sheets or computer-aided process planning. Parts that are made by identical operations form a family. This is done by creating a matrix of part numbers (rows) versus machine numbers/operation numbers. The rows and columns are rearranged, often with computer assistance, until parts that use the same process operations are identified by being grouped together in the matrix. These parts are then candidates for being incorporated into a manufacturing cell.

   The PFA method quickly ends up with very large, unwieldy matrices. A practical upper limit is several hundred parts and 20 different machines. Also, the method has difficulty if past process routing has not been done consistently.
3. **Classification and coding.** The previous two methods are chiefly aimed at improving manufacturing operations. Classification and coding is a more formal activity that is aimed at DFMA. The designer assigns a *part code* that includes such factors as basic shape, like in Fig. 13.6, external shape features, internal features, flat surfaces, holes, gear teeth, material, surface properties, manufacturing process, and operation sequences. As of yet, there is no universally applicable or accepted coding system. Some GT systems employ a code of up to 30 digits.
4. **Engineering database.** With the advent of large relational databases, many companies are building their own GT systems directly applicable to their own line of products. All information found on an engineering drawing plus processing information can be archived.

Software on the market does this in one of three ways:

- The designer sketches the shape of the part on the computer screen and the computer searches for all part drawings that resemble this shape.
- The software provides the capability to rapidly browse the library of hundreds of drawings, and the designer flags those that look interesting.
- The designer annotates the part drawing with text descriptors such as the part characteristics shown in Table 13.11. Then the computer can be asked, for example, to retrieve all part drawings with an L/D ratio between certain limits, or retrieve a combination of descriptors.

Determining part classification is an active area of research, stimulated by the widespread use of CAD. The power of computational algorithms combined with the capabilities of CAD systems assure that there will be continual improvement in the automation of part classification.

13.8
MISTAKE-PROOFING

An important element of DFMA is to anticipate and avoid simple human errors that occur in the manufacturing process by taking preventive action early in the product design process. Shigeo Shingo, a Japanese manufacturing engineer, developed this idea in 1961 and called it poka-yoke.[29] In English this is usually referred to as *mistake-proofing* or *error proofing.* A basic tenet of mistake-proofing is that human errors in manufacturing processes should not be blamed on individual operators but should be considered to be system errors due to incomplete engineering design. Mistake-proofing aims at reaching a state of *zero defects,* where a defect is defined as any variation from design or manufacturing specification.

Common mistakes in manufacturing operations are:

- Mistakes setting up workpieces and tools in machines or in fixtures
- Incorrect or missing parts in assemblies
- Processing the wrong workpiece
- Improper operations or adjustment of machines

Note that mistakes can occur not only in manufacturing but in design and purchasing as well. An infamous design mistake occurred with the 1999 orbiter to Mars, when it crashed on entering the Martian atmosphere. The contractor to NASA used conventional U.S. units instead of the specified SI units in designing and building the control rockets, and the error was never detected by those who designed the control system in SI units.

13.8.1 Using Inspection to Find Mistakes

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A natural response to eliminating mistakes is to increase the degree of inspection of parts by machine operators and of products by assembly line workers. However, as shown by Example 13.4, even the most rigorous inspection of the process output cannot eliminate all defects caused by mistakes.

EXAMPLE 13.4 Screening with Self-Checks and Successive Checks

Assume a part is being made with a low average defect rate of 0.25% (0.0025). In an attempt to reduce defects even further, 100 percent inspection is employed. Each operator self-checks each part, and then the operator next in line checks the work of the previous operator.

A defect rate of 0.25% represents 2500 defects in each million parts produced (2500 ppm). If an operator has a 3% error rate in self inspection, and two operators inspect each part in succession, then the number of defective parts that pass through two successive

29. Pronounced POH-kah YOH-kay.

inspections is 2500(0.03)(0.03) = 2.25 ppm. This is a very low level of defective parts. In fact it is below the magic percentage of defects of 3.4 ppm for achieving the Six Sigma level of quality (see Sec. 15.4).

However, the product is an assemblage of many parts. If each product consists of 100 parts, and each part is 999,998 ppm defect free, then a product of 100 parts has $(0.999998)^{100}$ or 999,800 ppm that are defect free. This leaves 200 ppm of assembled products that are defective. If the product has 1000 parts there would be 1999 defective products out of a million made. However, if the product has only 50 parts the defective products would decrease to 100 ppm.

This simple example shows that even with extreme and expensive 100 percent inspection, it is difficult to achieve high levels of defect-free products, even when the product is not very complex. The example also shows that decreasing product complexity (part count) is a major factor in reducing product defects. As Shingo showed,[30] a different approach from inspection is needed to achieve low levels of defects.

13.8.2 Frequent Mistakes

There are four categories of mistakes in part production. They are design mistakes, defective material mistakes, manufacturing mistakes, and human mistakes.

The following are mistakes attributable to the design process:

- Providing ambiguous information on engineering drawings or specifications: Failure to properly use GD&T dimensions and tolerances.
- Incorrect information: Mistake in conversion of units or just plain wrong calculations.
- A poorly developed design concept that does not fully provide the needed functionality. Hastily made design decisions that result in poorly performing products with low reliability, or with dangers to the safety of humans or hazards for the environment.

Defective material is another category of mistakes. These mistakes include:

- Material that is poorly chosen because not all performance requirements have been considered in the selection. Most commonly these involve long-term properties such as corrosion or wear.
- Material that does not meet specifications but gets into production, or purchased components that are not up to quality standards.
- Parts with hard-to-detect flaws such as internal porosity or fine surface cracks because of poorly designed dies or molds, or improper processing conditions (e.g., temperature, rate of deformation, poor lubrication) for the material that is being processed.

The most common mistakes in manufacturing parts or their assembly are listed below, in decreasing order of frequency.[31]

- Omitted operations: Failure to perform a required step in the process plan.
- Omitted part: Forgetting to install a screw, gasket, or washer.

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30. S. Shingo, *Zero Quality Control: Source Inspection and the Poka-yoke System,* Productivity Press, Portland, OR, 1986.
31. C.M. Hinckley, *Make No Mistake,* Productivity Press, Portland, OR, 2000.

Table 13.12
Causes of Human Mistakes and Suggested Safeguards

Human Mistakes	Safeguard
Inattentiveness	Discipline; work standardization; work instructions
Forgetfulness	Checking at regular intervals
Inexperience	Skill enhancement; work standardization
Misunderstanding	Training; checking in advance; standard work practices
Poor identification	Training; attentiveness; vigilance

- Wrong orientation of part: A part is inserted in the proper location but in the wrong orientation.
- Misaligned part: Alignment is not sufficiently accurate to give proper fit or function.
- Wrong location of part: Part is oriented properly but in wrong location. Example: The short bolt is put in the location for the long bolt.
- Selection of wrong parts: Many parts look very much alike. Example: A 1-inch bolt is used instead of 1¼ inch bolt.
- Misadjustments: An operation is incorrectly adjusted.
- Commit a prohibited action: Often this is an accident, like dropping a wrench, or a safety violation, like failure to lock-out a power panel before hooking up a motor.
- Added material or parts: Failure to remove materials. e.g., leaving on protective cover, or cores in a casting. Adding extra parts, e.g., dropping a screw into the assembly.
- Misread, mismeasure, or misinterpret: Error in reading instruments, measuring dimensions, or understanding correct information.

Some generic human mistakes, and safeguards that can be used against committing these mistakes, are given in Table 13.12.

Constructive checking and correction, along with training and work standardization, are the best ways to limit human mistakes. However, the ultimate way to eliminate mistakes is to engineer them out of the system through improved product design and manufacturing. This process is outlined in Sec. 13.8.3.

13.8.3 Mistake-Proofing Process

The steps in a mistake-proofing process follow a general problem-solving process:

- **Identify the problem.** The nature of the mistake is not always obvious. There is a natural human tendency to conceal mistakes. Work hard to develop a culture of openness and quality consciousness. Normal inspection by sampling will not give sufficient sample size of defects in a short time to identify the parts and processes causing the problem. Instead, use 100 percent inspection when looking for the cause of an error.
- **Prioritize.** Once the sources of mistakes have been identified, classify them with a Pareto chart to find the issues with the highest frequency of occurrence and which have the greatest impact on company profits.

- **Use cause finding methods.** To identify the root cause of the mistake use the TQM tools of cause-and-effect diagram, why-why chart, and interrelationship digraph (presented in Sec. 4.7) to identify the root cause of the mistake.
- **Identify and implement solutions.** General approaches for generating mistake-proofing solutions are discussed in Sec.13.8.4. Many solutions will reduce the defect rate in manufacturing parts and reduce the mistake rate in assembling the parts. However, the greatest impact will occur in the initial design of the part if DFMA guidelines are rigorously followed during embodiment design.
- **Evaluate.** Determine if the problem has been solved. If the solution is ineffective, revisit the mistake-proofing process.

13.8.4 Mistake-Proofing Solutions

In the broadest sense, mistake-proofing is about introducing controls to prevent mistakes, detect mistakes, or detect defects arising from mistakes. Clearly it is better to prevent mistakes through appropriate design and operational controls than to only take action once a mistake has occurred.

Mistake-proofing operates in three areas of control.

- **Control of variability,** as when a part diameter varies from piece to piece as parts are made in a manufacturing process. Control of variability is vital to making a quality product. This topic is covered in some detail in Chap. 15 under the topic of robust design.
- **Control of complexity** is addressed chiefly through DFMA guidelines and can often be traced back to issues arising with product architecture decisions in embodiment design.
- **Control of mistakes** is implemented chiefly through the design and use of mistake-proofing devices[32] as were first suggested by the *poka-yoke* methodology.

Mistake-proofing devices can be grouped into five broad classifications:

1. **Checklists.** These are written or computer-based lists of process steps or tasks that need to be done for completeness of operation. The checklist that a commercial aircraft pilot goes through before take-off is a good example. To catch errors in operations, *duplication of actions,* as when you enter a computer password twice, is sometimes used. In manual assembly processes, instructions must be accompanied by clear pictures.
2. **Guide pins, guide ways, and slots.** These design features are used in assembly to ensure that parts are located and oriented properly. It is important that guides should align parts before critical features mate.
3. **Specialized fixtures and jigs.** These devices deal with a broader case of geometries and orientation issues. They typically are intended to catch any errors between steps in the manufacturing process.
4. **Limit switches.** Limit switches or other sensors detect mistakes in location, or the absence of a problem. These sensors trigger warnings, shut down the process,

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32. 200 examples of mistake-proofing devices are described in the Appendix A to C. M. Hinckley, op. cit.

or enable it to continue. Sensors typically are interlocked with other processing equipment.

5. **Counters.** Counters, either mechanical, electrical, or optical are used to verify that the proper number of machine operations or parts have been carried out. Timers are used to verify the duration of a task.

Although the methods and examples of mistake-proofing have been given in the context of manufacturing processes, the methods can be implemented in areas such as sales, order entry, and purchasing, where the cost of mistakes is probably higher than the cost of errors that occur in manufacturing. A very similar, but more formalized process called Failure Modes and Effects Analysis (FMEA) is used to identify and improve upon potential failure modes in design; see Sec. 14.5.

13.9 EARLY ESTIMATION OF MANUFACTURING COST

The decisions about materials, shape, features, and tolerances that are made in the conceptual design and embodiment design phases determine the manufacturing cost of the product. It is not often possible to get large cost reductions once production has begun because of the high cost of change at this stage of the product life cycle. Therefore, we need a way of identifying costly designs as early as possible in the design process.

One way to achieve this goal is to include knowledgeable manufacturing personnel on the product design team. The importance of this is unassailable, but it is not always possible from a practical standpoint due to conflicts in time commitments, or even because the design and manufacturing personnel may not be in the same location.

The method presented in Sec.13.4.6 is useful for selecting between alternative possible processes on the basis of estimated unit part cost. While considerable information is used, the level of detail is not sufficient to do much better than give a relative ranking of competing manufacturing processes.

A system that is useful for cost estimation early in the design process was developed at the University of Hull.[33] It is based on data obtained from British automotive, aerospace, and light manufacturing companies. It allows for the reasonable calculation of part cost as changes are made in design details or for changes in part cost as different processes are used to manufacture the part. An important extension of the method in Sec. 13.4.6 is that the factor of part shape complexity is considered. Sufficient figures are given below so that an example can be followed, but the book by Swift and Booker is required to obtain the full range of needed information.[34]

The process starts with the identification of a small number of materials and processes using Fig. 13.9. Comparison between alternatives is based on estimated unit manufacturing cost, C_u.

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33. K. G. Swift and J. D. Booker, *Process Selection,* 2d ed., Butterworth-Heinemann, Oxford, UK, 2003; also A. J. Allen and K. G. Swift, *Proc. Instn. Mech. Engrs.,* Vol. 204, pp. 143–48, 1990.

34. The figures in this section are from the first edition. They are used because the method can be shown with fewer figures than the more expanded version in the second edition.

$$C_U = VC_{mv} + P_cR_c \tag{13.11}$$

C_{mv} = cost of material per unit volume
V = volume of material input to the process
P_c = basic processing cost of an ideal part shape
R_c = cost coefficient for the part design that takes into account shape complexity, material workability, section thickness, surface finish, and tolerance.

Equation 13.11 shows that unit cost is estimated by first finding the material cost and then adding the cost based on the general relationship between the process cost and the annual production volume, Fig. 13.16, for estimates of an "ideal" part design. This cost is then increased by all of the factors represented by R_c. The basic unit processing cost P_c is a composite cost representing capital equipment costs, operating costs (labor cost, and overhead), tooling cost, and rate of production. When plotted as in Fig. 13.16 it shows the basic relationship between the cost of different processes and the economic batch size for each process. These plots are based on average data for one shift per day and a 2-year payback for equipment and tooling.

The design-dependent factors are included in the R_c term of Eq. (13.11).

$$R_c = C_{mp} \times C_c \times C_s \times C_{ft} \tag{13.12}$$

where

C_{mp} = relative cost associated with material-process suitability (workability or fabricability)
C_c = relative cost associated with shape complexity
C_s = relative cost associated with achieving minimum section thickness
C_{ft} = the higher of the costs to achieve a specified surface finish or tolerance, but not both

For the design of the ideal part, each of the coefficients in Eq. (13.12) is unity. As the design moves away from this situation, one or more of the coefficients will increase in value, thereby increasing the unit manufacturing cost in Eq. (13.11).

Figure 13.17 shows the suitability rating of the material-process combinations that result in C_{mp}. Note that many of the combinations are inadmissible for technical or economic reasons.

The shape complexity factor C_c is based on the classification system shown in Fig. 13.18. This system divides shapes into three basic categories: (A) solids of revolution, (B) prismatic solids, and (C) flat or thin-wall section components. Within each category the complexity increases from 1 to 5. Shape classification is based on the finished shape of the part. C_c is the most important coefficient in Eq. (13.12). Therefore, careful study of the category definitions is important. Once the shape subcategory has been established, a set of curves for the process is entered (Fig. 13.19) and the coefficient is picked off. Figure 13.20 shows the curves for obtaining the section coefficient C_s. If the required section thickness falls to the left of the black vertical line, additional secondary processing (machining or grinding) is likely to be necessary. This cost is included in the value of the coefficient.

Curves for tolerances C_t and surface finish C_f are given in Fig. 13.21. In using these charts, identify the most severe tolerance requirement in the part, and note

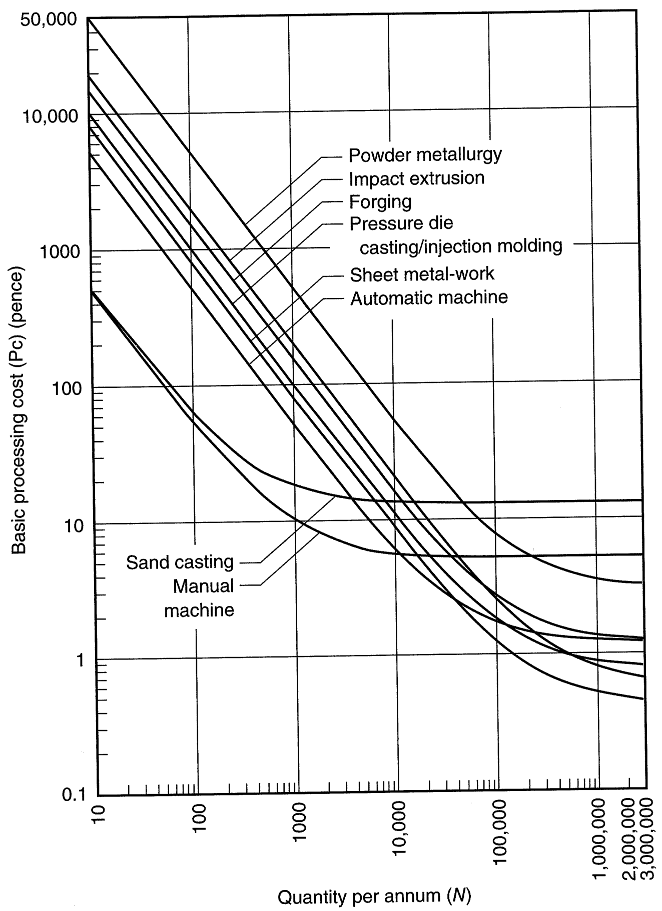

FIGURE 13.16
Average curves of P versus N for selected manufacturing processes. (From K. G. Swift and J. D. Booker, *Process Selection*, p. 175 Arnold, London. Used with permission.)

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whether it applies on one or more than one plane. The same applies for the surface finish requirements. Note that the value for either C_t or C_f is used, depending on which coefficient is larger. Costs estimated this way have been shown to be within at least 15 percent of the actual cost. Note that the Swift and Booker method uses a factor to account for shape complexity, which is not considered at all in determining an estimate of manufacturing cost discussed in Sec.13.4.6.

EXAMPLE 13.5
We wish to estimate the cost of manufacturing the part shown at the top of A3 in Fig. 13.18. Its dimensions are as follows: large diameter 1 in. small diameter 0.25 in. length of long cylinder 2 in. length of short cylinder 1 in. The diameter of the cross-bore is such that the wall thickness is 5 mm. The tolerance on this bore diameter is 0.005 in. The surface finish is 5 μm. We expect to need 10,000 parts per year. For strength reasons the part will be made from a quenched and tempered medium alloy steel.

Material \ Process	Impact extrusion	Sand casting	Pressure die casting	Forging	Sheet metal-working	Machining	Powder metallurgy	Injection molding
Cast iron		1				1.2	1.6	
Low carbon steel	1.3	1.2		1	1.2	1.4	1.2	
Alloy steel	2	1.3		2	1.5	2.5	1.1	
Stainless steel	2	1.5		2	1.5	4	1.1	
Copper alloy	1	1	3	1	1	1.1	1	
Aluminum alloy	1	1	1.5	1	1	1	1	
Zinc alloy	1	1	1.2	1	1	1.1	1	
Thermoplastic						1.1		1
Thermoset						1.2		1
Elastomers						1.1		1.5

FIGURE 13.17
Relative cost of material-process suitability, C_{mp}. (From K. G. Swift, and J. D. Booker, *Process Selection*, p. 178, Arnold, London. Used with permission.)

Figure 13.9 suggests we look at whether the part should be made by sand casting, machining, or powder metallurgy. Using the charts reproduced in this section we estimate the coefficients for Eq. (13.12) to be:

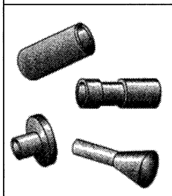
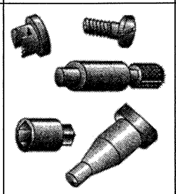
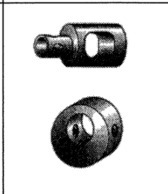
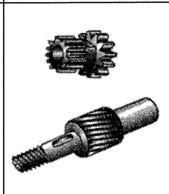
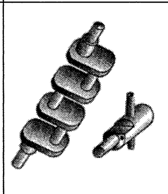
Process	C_{mp}	C_c	C_s	C_t	C_f	R_c	P_c	P_cR_c
Sand casting	1.3	1.3	1.2	1.9	1.9	3.85	10.5*p*	40*p*
Machining	2.5	3.0	1.0	1.0	1.0	7.50	5*p*	38*p*
Powder metallurgy	1.1	2.4	1.0	1.0	1.0	2.64	60*p*	158*p*

Multiplying coefficients according to Eq. (13.12) gives R_c. Note how machining carries the greatest penalty because of the poor machinability of alloy steel and the geometry complexity. However, the basic processing cost P_c is relatively low. The required number of parts is not sufficient to pay back the tooling costs of powder metallurgy processing.

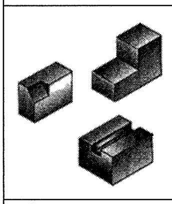
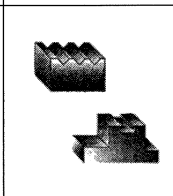
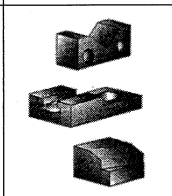
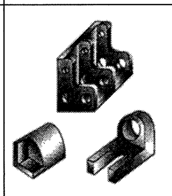
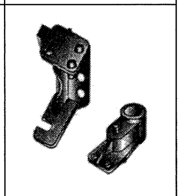
Turning now to Eq. (13.11), the volume of the part is 0.834 in^3. The cost of alloy steel is about \$1.25 per lb. Since the density of steel is 0.283 lb/in.^{3}, C_{mv} is \$0.354 per in^3 and VC_{mv} is \$0.30. The rest of Eq. (13.11) is in pence (*p*). There are 100 pence to the pound (£), and 1£ $\approx$ \$1.65. Therefore, VC_{mv} = \$0.30 /1.65 (\$/£) = £0.182 = 18 *p*. The estimated unit manufacturing cost is: sand casting = 58 *p*; machining = 56 *p*, and powder metallurgy = 176 *p*.

For this batch size machining is the preferred process over sand casting because the surface finish and tolerances will be better. At 10,000 parts per year powder metallurgy is ruled out because of high tooling costs. However, experienced designers would have recognized that molding in a cross-bore is not good practice in powder metallurgy. The design guidelines in Table 13.3 should have warned us that a shape like A3 is not easily obtainable with powder metallurgy.

A — Part Envelope is Largely a Solid of Revolution

Single/Primary Axis		Secondary Axes: Straight line features parallel and/or perpendicular to primary axis		Complex Forms
Basic rotational features only	Regular secondary/ repetitive features	Internal	Internal and/or external features	Irregular and/or complex forms.
A 1	**A 2**	**A 3**	**A 4**	**A 5**
				
Category includes: Rotationally symmetrical/ grooves, undercuts, steps, chamfers, tapers and holes along the primary axis/centre line	Internal/external threads, knurling and simple contours through flats/splines/keyways on/around the primary axis/centre line	Holes/threads/ counterbores and other internal features not on the primary axis	Projections, complex features, blind flats, splines, keyways on secondary axes	Complex contoured surfaces, and/or series of features which are not represented in previous categories

B — Part Envelope is Largely a Rectangular or Cubic Prism

Single Axis/Plane		Multiple Axes		Complex Forms
Basic features only	Regular secondary/ repetitive features	Orthogonal/straight line based features	Simple curved features on a single plane	Irregular and/or contoured forms
B 1	**B 2**	**B 3**	**B 4**	**B 5**
				
Category includes: Through steps, chamfers and grooves/channels/slots and holes/threads on a single axis	Regular through features, T-slots and racks/plain gear sections etc. Repetitive holes/threads/counter bores on a single plane	Regular orthogonal/straight line based pockets and/or projections on one or more axis. Angled holes/threads/ counter bores	Curves on internal and/or external surfaces	Complex 3-D contoured surfaces/geometries which cannot be assigned to previous categories

C — Flat Or Thin Wall Section Components

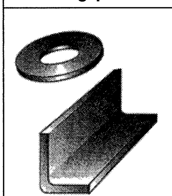
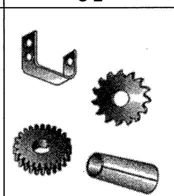
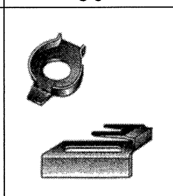
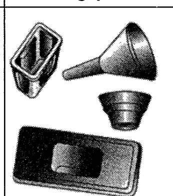
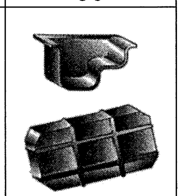
Single Axis	Secondary/Repetitive Regular Features		Regular Forms	Complex Forms
Basic features only	Uniform section/ wall thickness	Non-uniform section/ wall thickness	Cup, cone and box-type parts	Non-uniform and/or contoured forms
C 1	**C 2**	**C 3**	**C 4**	**C 5**
				
Category includes: Blanks, washers, simple bends, forms and through features on or parallel to primary axis	Plain cogs/gears, multiple or continuous bends and forms	Component section changes not made up of multiple bends or forms. Steps, tapers and blind features	Components may involve changes in section thickness	Complex or irregular features or series of features which are not represented in previous categories

FIGURE 13.18
The shape classification system used to determine C_c. (From K. G. Swift, and J. D. Booker, *Process Selection*, p. 180, Arnold, London, 1997. Used with permission.)

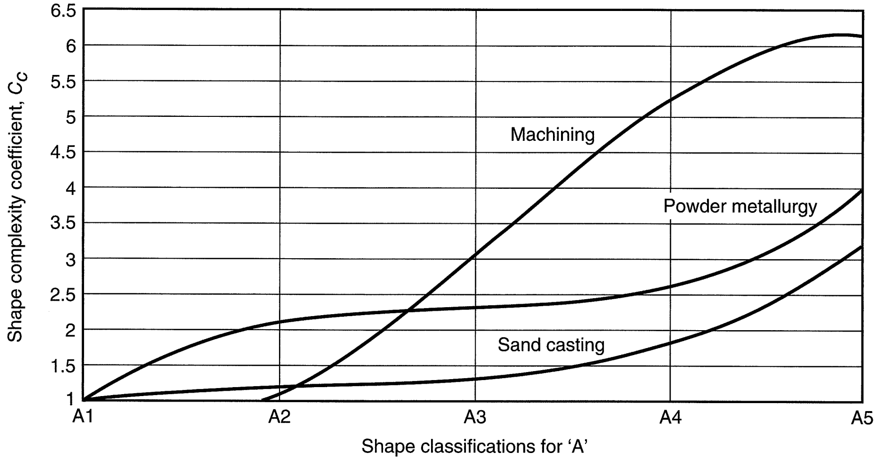


FIGURE 13.19

Curves for determining C_c, for shape classification A. (From K. G. Swift,and J. D. Booker, *Process Selection*, p. 181, Arnold, London, 1997. Used with permission.)

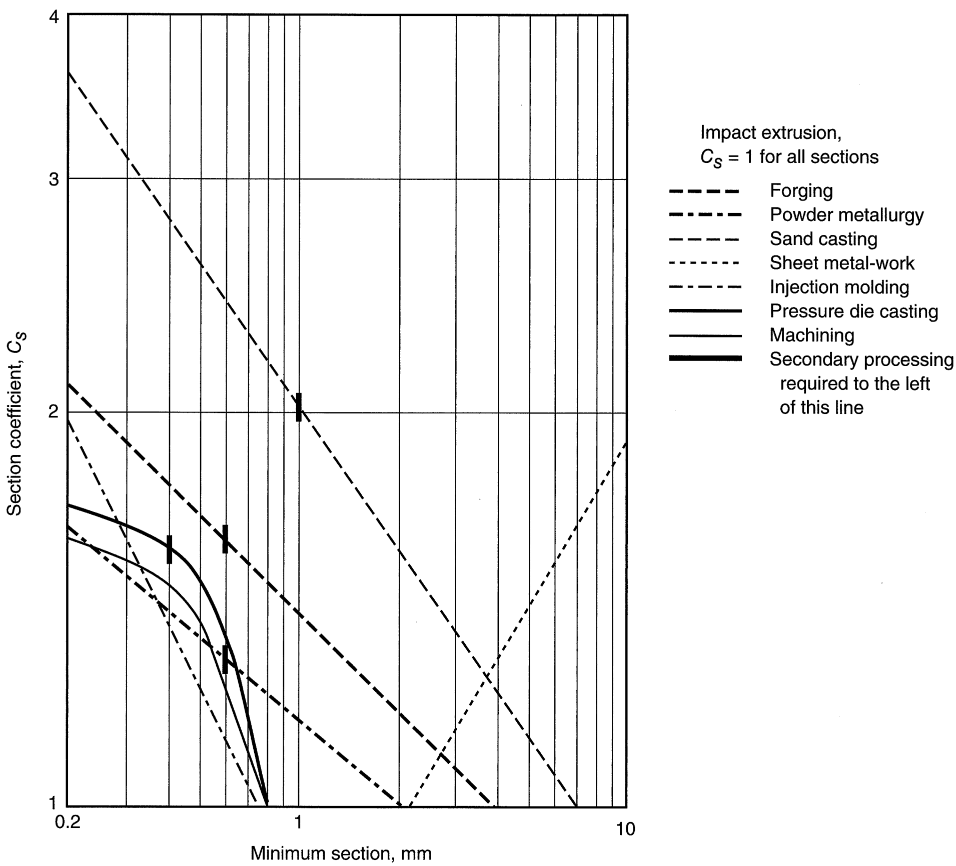


FIGURE 13.20

Chart used for determining the section coefficient C_s. (From K. G. Swift, and J. D. Booker, *Process Selection*, p. 184, Arnold, London, 1987. Used with permission.)

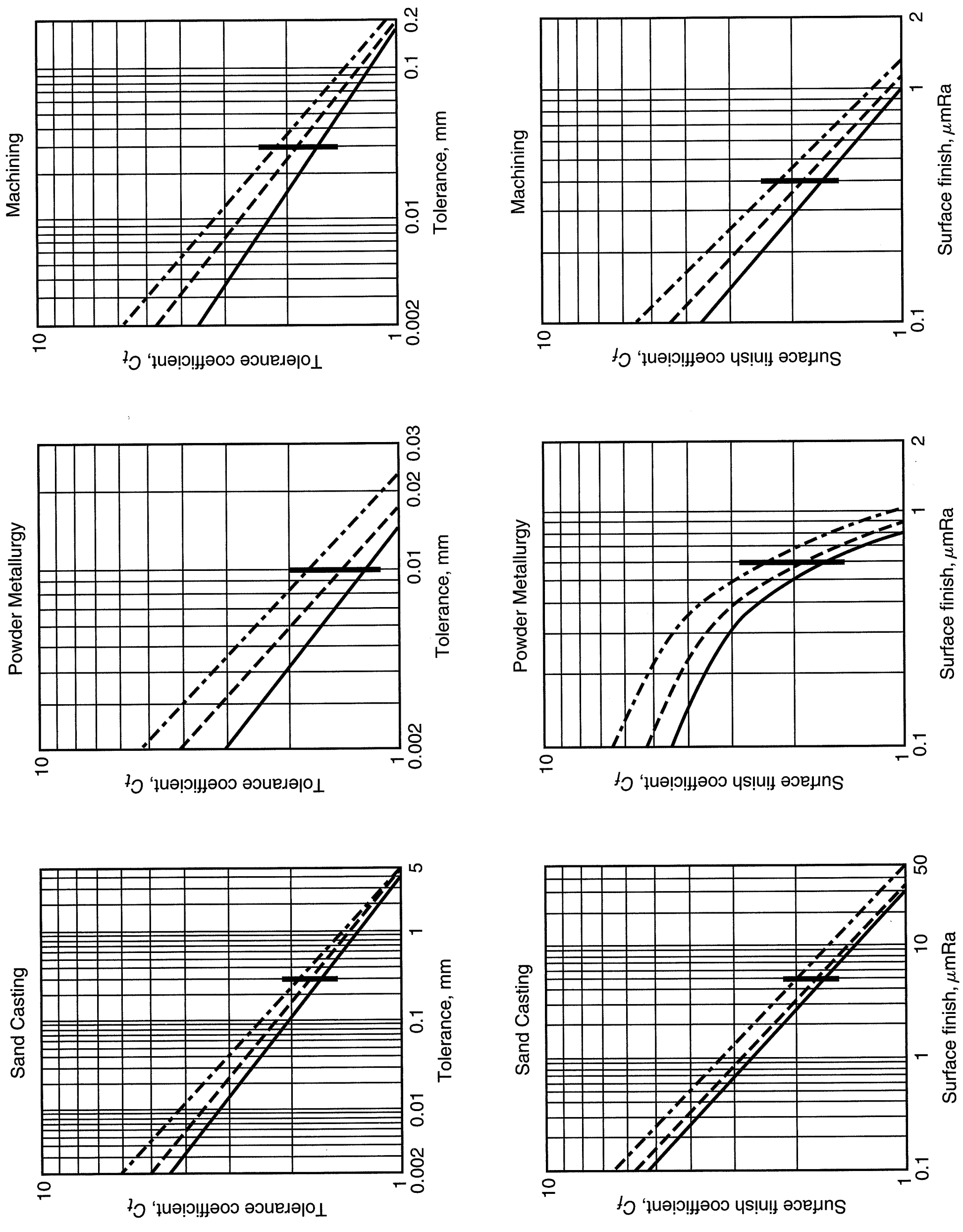


FIGURE 13.21
Charts used to determine C_t (top row) and C_f (bottom row). — 1 plane, —— 2 planes, ——— 3 planes (From K. G. Swift, and J. D. Booker, *Process Selection*, Arnold, London, 1997. Used with permission.)

13.10 COMPUTER METHODS FOR DFMA

The design for assembly methodology (DFA) was developed prior to formal DFM methodology, although DFM guidelines as "rules of thumb" have existed for centuries. DFA on the entire product assembly and its emphasis on reducing part count serves as a driver for DFM. DFM focuses more on the individual part and how to reduce the cost of manufacture. The objective is to quickly provide information on costs while the design is still fluid. While DFM and DFA methods can be done manually on paper, the use of computerized methods greatly aids the designer by providing prompts and help screens, providing access to data that is often scattered in the literature, and making it easy to quickly see the effect of design changes. The use of DFMA software also teaches good design practice. Whatever the method, a major benefit from performing a DFMA analysis is that the rigor of using a formal analysis scheme invariably leads to asking better questions, and therefore to better solutions.

13.10.1 DFA Analysis

The most widely used design for assembly methodology is the Boothroyd-Dewhurst DFA method.[35] The method uses a step-by-step application of the DFA guidelines, like those given in Sec.13.6.1, to reduce the cost of manual assembly. The method is divided into an analysis phase and a redesign phase. In the first phase, the time required to handle and insert each part in the assembly is found from data tables based on time and motion study experiments. These values are derived from a part's size, weight, and geometric characteristics. If the part requires reorienting after being handled, that time is also included. Also, each part is identified as being essential or "theoretical," (whether it is a candidate for elimination in a redesign phase). The decision on the minimum number of theoretical parts is determined by applying the criteria listed under Guideline 1 in Sec.13.6.1. Then the estimated total minutes to put together the assembly is determined. With this information the Design Assembly Efficiency can be determined using Eq. (13.10). This gives the designer an indication of how easily the design can be assembled, and how far the redesign phase should progress to increase assembly efficiency.

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EXAMPLE 13.6

A design is needed for a motor-drive assembly that moves vertically on two steel guide rails.[36] The motor must be fully enclosed and have a removable cover for access to the position sensor. The chief functional requirement is that there be a rigid base that supports the motor and the sensor and moves up and down on the rails. The motor must be fully enclosed and have a removable cover so the position detection sensor can be adjusted.

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35. G. Boothroyd, P. Dewhurst and W. Knight, *Product Design for Manufacture and Assembly,* 2d ed., Marcel Dekker, New York, 2002. DFA and DFM software is available from Boothroyd-Dewhurst, Inc. www.dfma.com.

36. G. Boothroyd, "Design for Manufacture and Assembly," *ASM Handbook,* Vol. 20, p. 676, ASM International, Materials Park, OH, 1997.

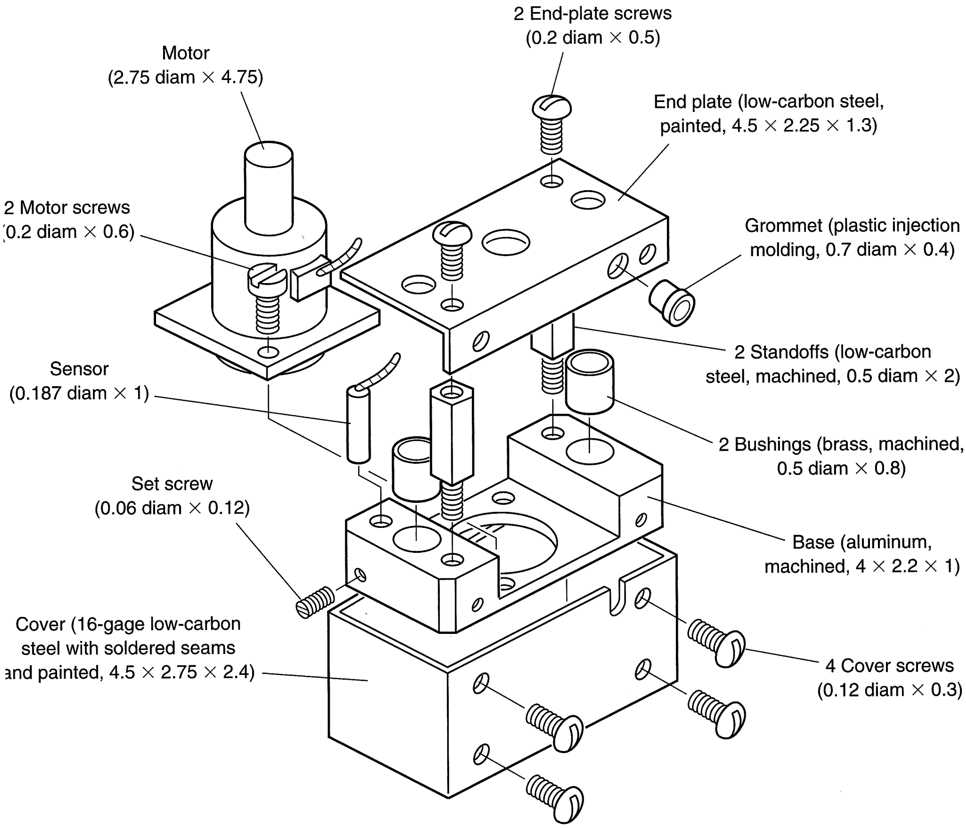

FIGURE 13.22
Initial design of the motor-drive assembly. (*ASM Handbook,* Vol. 20, p. 680, ASM International, Materials Park, OH, 1997. Used with permission.)

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Figure 13.22 shows the initial design of the motor-drive assembly. The rigid base is designed to slide up and down the steel guide rails (not shown). It also supports the linear motor and the position sensor. Two brass bushings are pressed into the base to provide suitable friction and wear characteristics for sliding on the steel rails. The end plate is fitted with a plastic grommet through which pass the connecting wires to the motor and the sensor. The box-shaped cover slides over the whole assembly from below the base and is held in place by four cover screws, two attached to the base and two passing into the end plate. In addition there are two stand-off rods that support the end plate and assorted screws to make a total of eight main parts and nine screws, for a total of 17 parts. The motor and sensor are outsourced subassemblies. The two guide rails are made from 0.5 in. diameter cold drawn steel bar stock. Because they are clearly essential components of the design, and there is no apparent substitute, they are not involved in the analysis.

We now use the DFA criteria to identify the theoretical parts, those that cannot be eliminated, and the parts that are candidates for replacement, Sec. 13.6.1.

- The base is clearly an essential part. It must move along the guide rails, which is a "given" for any redesign. However, by changing the material for the base from aluminum to some other material there could be a savings in part count. Aluminum sliding on steel is not a good combination. The bushings are part of the base and are included in the design to provide the function of low sliding friction. However, it is known that nylon (a thermoplastic polymer) has a much lower sliding coefficient of friction against steel than aluminum. Using nylon for the base would permit the elimination of the two brass bushings.
- Now we consider the stand-off rods. We ask the question, "are they only there to connect two parts?" Since the answer is yes, they are candidates for elimination. However, if eliminated the end plate would have to be redesigned.
- The end plate functions to protect the motor and sensor. This is a vital function, so the redesigned end plate is a cover and is a theoretical part. It must also be removable to allow access for servicing. This suggests that the cover could be a plastic molded part that would snap onto the base. This will eliminate the four cover screws. Since it will be made from a plastic, there is no longer a need for the grommet that is in the design to prevent fraying of the electrical leads entering the cover.
- Both the motor and the sensor are outside of the part elimination process. They are clearly essential parts of the assembly, and their assembly time and cost of assembly will be included in the DFA analysis. However, their purchase cost will not be considered because they are purchased from outside vendors. These costs are part of the material costs for the product.
- Finally, the set screw to hold the sensor in place and the two screws to secure the motor to the base are not theoretically required.

The time for manual assembly is determined by using lookup tables or charts[37] to estimate (1) the handling time, which includes grasping and orienting, and (2) the time for insertion and fastening. For example, the tables for handling time list different values depending on the symmetry, thickness, size, and weight of the part, and whether it requires one hand or two to grasp and manipulate the part. Extra time is added for parts with handling difficulties such as tangling, flexibility, or slipperiness, the need for optical magnification, or the need to use tools. For a product with many parts this can be a laborious procedure. The use of DFA software can be a substantial aid not only in reducing the time for this task, but in providing prompts and questions that assist in the decision process.

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Tables for insertion time differentiate whether the part is secured immediately or whether other operations must take place before it can be secured. In the latter case it differentiates whether or not the part requires holding down, and how easy it is to align the part.

Table 13.13 shows the results of the DFA analysis of the initial design. As discussed previously, the base, motor, sensor, and end plate are found to be essential parts, so the theoretical part count is 4 out of a total of 19 parts. Therefore, according to Eq. (13.10), the design efficiency for the assembly is quite low, 7.5 percent, indicating that there should be ample opportunity for part elimination.

37. G. Boothroyd, et. al., op. cit., Chap. 3.

TABLE 13.13
Results of DFA Analysis for the Motor-Drive Assembly (Initial Design)

Part	No.	Theoretical Part Count	Assembly Time, s	Assembly Cost, ¢
Base	1	1	3.5	2.9
Bushing	2	0	12.3	10.2
Motor subassembly	1	1	9.5	7.9
Motor screw	2	0	21.0	17.5
Sensor subassembly	1	1	8.5	7.1
Setscrew	1	0	10.6	8.8
Stand-off	2	0	16.0	13.3
End plate	1	1	8.4	7.0
End-plate screw	2	0	16.6	13.8
Plastic bushing	1	0	3.5	2.9
Thread leads	...	...	5.0	4.2
Reorient	...	...	4.5	3.8
Cover	1	0	9.4	7.9
Cover screw	4	0	31.2	26.0
Total	19	4	160.0	133.0

Design efficiency for assembly = $(4 \times 3)/160 = 7.5\%$

In Table 13.13 the cost of assembly is determined by multiplying the total assembly time by the hourly cost of assembly. In this example it is \$30/h.

The results of the DFA analysis for the redesigned motor-drive assembly, Fig. 13.23, are given in Table 13.14. Note that the part count has been reduced from 19 to 7, with an increase in the assembly efficiency from 7.5% to 26%. There is a commensurate reduction in the cost of assembly from \$1.33 to \$0.384. The three nonessential parts are all screws that theoretically could be eliminated but have been retained for reliability and quality reasons. The next step is to do a design for manufacture analysis to determine whether the changes made in material and design have carried over to reduced part costs.

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This example shows the importance of DFA in design. Even though assembly follows part manufacturing, the DFA analysis contributes much more than reducing the cost of assembly, which rarely exceeds 20 percent of the product cost. A major contribution of DFA is that it forces the design team to think critically about part elimination through redesign. A part eliminated is a part that does not require manufacturing.

13.10.2 Concurrent Costing with DFM

The DFM Concurrent Costing software[38] allows the real-time cost estimation of parts using much more detail than the methods discussed previously in Sec. 13.4.6 and 13.9. Typically the program starts by downloading a CAD file for the part that is to be

38. Boothroyd-Dewhurst, Inc., www.dfma.com.

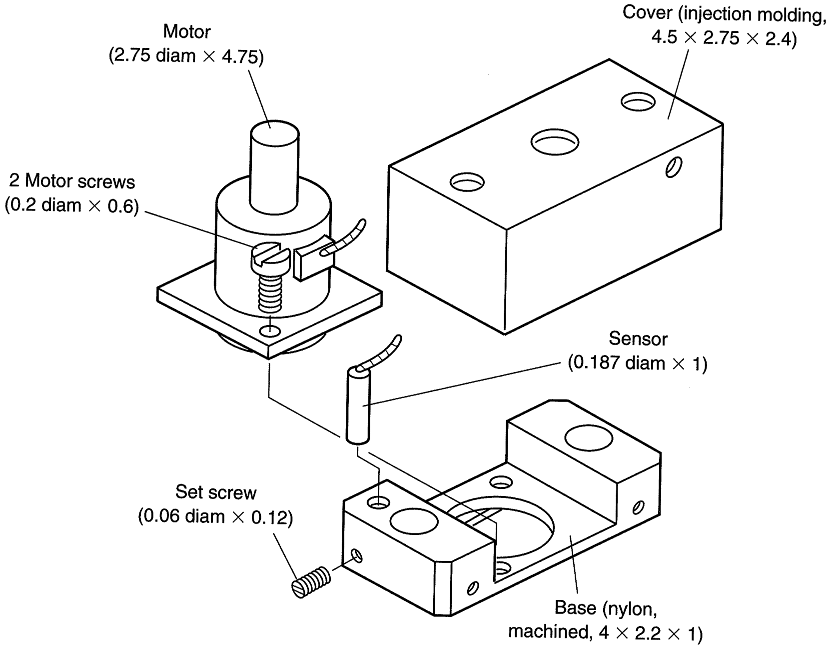

FIGURE 13.23
Redesign of motor-drive assembly based on DFA analysis. (*ASM Handbook,* Vol. 20, p. 68, ASM International, Materials Park, OH, 1997. Used with permission.)

TABLE 13.14
Results of DFA Analysis for Motor-Drive Assembly After Redesign

Part	No.	Theoretical Part Count	Assembly Time, s	Assembly Cost, ¢
Base	1	1	3.5	2.9
Motor subassembly	1	1	4.5	3.8
Motor screw	2	0	12.0	10.0
Sensor subassembly	1	1	8.5	7.1
Setscrew	1	0	8.5	7.1
Thread leads	. . .	. . .	5.0	4.2
Plastic Cover	1	1	4.0	3.3
Total	7	4	46.0	38.0

Design efficiency for assembly = (4 × 3)/46 = 26%

redesigned. However, if the design is not yet at a stage where a CAD drawing has been made, it is possible to input a shape envelope (cylinder, hollow cylinder, rectangular block, hollow block, irregular cross section) and dimensions of the part.

EXAMPLE 13.7
We will describe the use of the software in the costing and design of a plastic cover similar to but with more details than the one shown in Fig. 13.23. The material and process

are selected from drop-down menus. Generally this starts with a menu of materials and processes, and selection of a class of materials gives the designer the option of selecting a specific material. Selecting the material greatly limits the choice of processes. Injection molding is the obvious choice for the hollow rectangle made from the thermoplastic ABS.

Figure 13.24 shows the computer screen after the material and process have been selected. The values are determined by the part geometry that is entered as a drawing, and default values for the injection molding process. Because this is a molding process, much of the cost is determined by the cost of the mold. The DFM input will be concerned chiefly with how decisions on design details are reflected in the cost to make the tooling.

Following down the list of design parameters we come to part complexity. Part complexity is measured by the number of *surface patches* needed to describe both the inner and outer surface of the part. The inner surface of the cover is ribbed and contains bosses used for making screw connections, so the patches add up to a considerable value. The next two sections ask for input that further defines the mold cost.

- Tolerances: The tightness of the tolerance determines the care needed in machining the mold cavity.
- Appearance: If the part is transparent, the mold surface will need to be polished to a high degree.
- Texture: If the surface needs to have a grain or leather appearance, this will require fine engraving of the mold surface.
- Parting line: The parting line refers to the shape of the surface across which the mold separates to eject the part. A straight parting plane is the least costly, but if the part design requires a stepped or curved surface, the mold cost will be significantly increased.
- Mold construction: A two-plate mold, a stationary cavity plate, and a moving core plate is the least complex mold system.
- Runner system: For high rates of production a heated runner is designed into the fixed plate. This also eliminates the need to separate the runners and sprues from the part. This mold feature adds cost to the mold.
- Mold material: This choice will determine the life of the mold.
- Number of cavities: Depending on the size of the part, it is possible to make more than one part per shot. This requires several cavities, which increases the productivity, $\dot{n}$, but also increases the machining time and the mold cost.
- Devices in one cavity: If it is necessary to mold depressions or undercuts on the *inside* of the part, it requires building the core pin retraction device inside the core plate. This is difficult and very expensive.

Users of the software need some knowledge of the construction and operation of injection molds to go beyond the basic default values and link the part design with mold construction costs.[39]

Note that the preliminary piece part cost and the tooling cost allocated to each part are given at the bottom left in Fig. 13.24. Any of the parameters in this table can be changed, and the costs will be recalculated quickly to show the effect of the change. For example, we might decide that using 30 percent of recycled (regrind) plastic resin would degrade the properties of the part, so this value is set at 10 percent. This change increases the material cost. Next, we decide that the part size is small enough that two parts can be made in a single mold. The number of cavities is changed from 1 to 2. This increases the

39. G. Boothroyd, et. al., op. cit., Chap. 8; H. Rees and B. Catoen, *Selecting Injection Molds,* Hanser Gardner Publications, Cincinnati, OH, 2005.

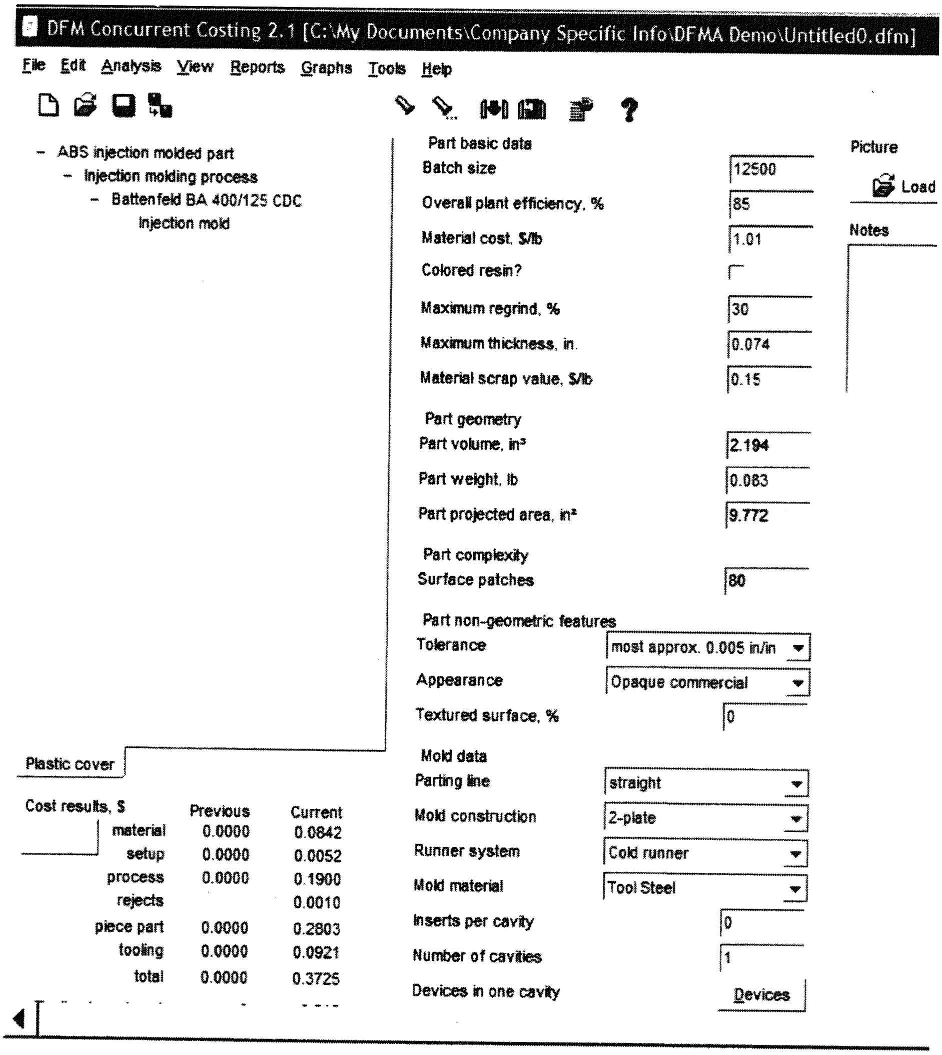

FIGURE 13.24
Design parameters used to determine cost of an injection-molded cover. (Used with permission of Boothroyd-Dewhurst, Inc.)

tooling cost but it reduces the piece part cost because the number of parts made per unit time is doubled.

Another level of detail that can be changed is the specification of the injection molding machine (clamping force, shot capacity horsepower), the process operation costs (number of operators, operator hourly rate, machine rate), part reject rate, machine and mold setup cost, mold process data (cavity life, fill time, cooling time, mold reset time), and the cost to make the mold broken down into the cost of prefabricated plates, pillars, bushings, etc. and the cost of machining the mold cavity and cores. A review of Sec. 13.4.6 will show where these factors fit into the overall cost equation.

This example shows the level of detail that is needed for a reliable determination of part cost, especially the cost of tooling and process operations. The degree of design complexity and interaction with process parameters is such that a computer-based cost model is the only way to do this quickly and consistently. Design details made at the configuration design step can be explored in a "what-if" mode for their impact on tooling costs before an actual commitment to purchase tooling is made. The sections that follow give more information on design details pertinent to particular processes.

13.10.3 Process Modeling and Simulation

Advances in computer technology and finite element analysis have led to industry's widespread adoption of computer process models. Just as finite element and finite difference analyses and CFD have made possible refined design for performance of components that have reduced the cost of prototype testing, so have computer process models[40] reduced the development time and cost of tooling. The greatest application of process models has been with casting, injection molding, closed-die forging, and sheet metal forming processes.

Since most manufacturing processes use large equipment and expensive tooling, it is costly and time consuming to do process improvement development. A typical type of problem is making refinements to the mold to achieve complete material flow in all regions of a component made by casting or injection molding. In deformation processes like forging or extrusion, a typical problem is to modify the dies to prevent cracking in regions of high stress in the part. Today, these types of problems and many others can be solved quickly using commercially available simulation software. The results of the analysis can be seen as a series of color maps of a process parameter, such as temperature. Animations showing the actual solidification of the metal over time are commonplace. References to common process modeling software will be given as we describe the DFM guidelines for several processes in subsequent sections of this chapter.

13.11
DESIGN OF CASTINGS

One of the shortest routes from raw material to finished part is a casting process. In casting, a molten metal is poured into a mold or cavity that approximates the shape of the finished part (Fig. 13.25). Heat is extracted through the mold (in this case a sand mold), and the molten metal solidifies into the final solid shape. The chief design issues for the mold are (1) to provide an entry for the molten metal into the mold that creates laminar flow through the sprue and runner, (2) to provide a source of molten metal, suitably located in the mold so that it stays molten until all of the casting has been filled, and (3) that *cores* are suitably placed to provide hollow features for the part.

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40. J. A. Dantzig, and C. T. Tucker III, *Modeling in Materials Processing,* Cambridge University Press, Cambridge, UK, 2001.

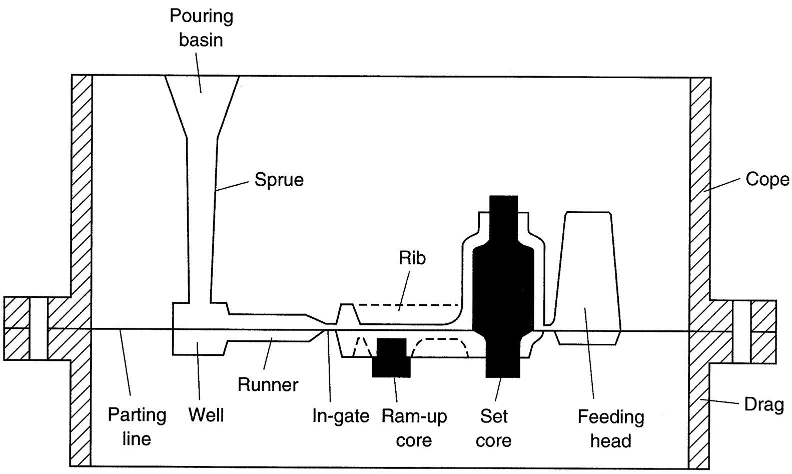

FIGURE 13.25
Parts of a conventional sand casting process.

This seemingly simple process can be quite complex metallurgically, since the metal undergoes a complete transition from the superheated molten state to the solid state.[41] Liquid metal shrinks on solidification. Thus, the casting and mold must be designed so that a supply of molten metal is available to compensate for the shrinkage. The supply is furnished by introducing feeder heads (risers) that supply molten metal but must be removed from the final casting (Fig. 13.25). Allowance for shrinkage and thermal contraction after the metal has solidified must also be provided in the design. Since the solubility of dissolved gases in the liquid decreases suddenly as the metal solidifies, castings are subject to the formation of gas bubbles and porosity.

The mechanical properties of a casting are determined during solidification and subsequent heat treatment. The grain structure of the casting, and thus its properties, are determined by how fast each part of the casting freezes. This cooling rate is roughly proportional to the ratio of the square of the surface area of the casting to the square of its volume. Thus, bulky castings freeze much more slowly than thin section castings and have lower properties. A sphere of a given volume will freeze more slowly than a thin plate of the same volume because the plate has much more surface area to transfer heat into the mold.

The casting must be designed so that the flow of molten metal is not impeded by solidified metal before the entire mold cavity fills with molten metal. The casting should freeze progressively, with the region farthest from the source of molten metal freezing first so that the risers can supply liquid metal to feed shrinkage that occurs during solidification. Designing the needed solidification pattern can be achieved with finite element modeling to construct temperature distributions as a function of time.[42]

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41. H. Fredriksson and U. Åkerlind, *Materials Processing During Casting,* John Wiley & Sons, Ltd., Chichester, UK, 2006.
42. Commercially available software includes PAM-QUICKCAST and ProCast from ESI Group (www.esigroup.com).

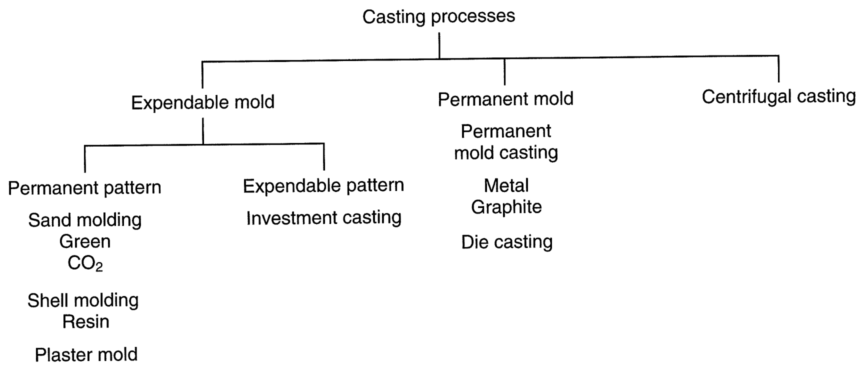

FIGURE 13.26
Classification of casting processes.

The FEA can predict shrinkage regions due to lack of feeding and grain size (property) distribution in the casting.

There are a large number of casting processes, which can be classified best with respect to the type of mold that is employed (Fig. 13.26). The two broad categories are *expendable mold* casting, in which the mold is destroyed after making each part, and *permanent mold casting*, for which many parts are made in each mold. A brief description of each process is given at www.mhhe.com/dieter.

13.11.1 Guidelines for the Design of Castings

Proper attention to design details can minimize casting problems and lead to lower costs.[43] Therefore, close collaboration between the designer and the foundry engineer is important. The use of computer-based solidification modeling in this design collaboration is recommended.

The chief consideration is that the shape of the casting should allow for orderly solidification by which the solidification front progresses from the remotest parts toward the points where molten metal is fed in. Whenever possible, section thickness should be uniform. Large masses of metal lead to hot spots, where freezing is delayed, and a *shrinkage cavity* is produced when the surrounding metal freezes first.

Figure 13.27 illustrates some design features that can eliminate the shrinkage cavity problem. A transition between two sections of different thicknesses should be made gradually (a). As a rule of thumb, the difference in thickness of adjoining sections should not exceed 2 to 1. Wedge-shaped changes in wall thickness should not have a taper exceeding 1 to 4. The thickness of a boss or pad (b) should be less than the thickness of the section the boss adjoins, and the transition should be gradual. The local heavy section caused by omitting the outer radius at a corner (c) should be eliminated. The radius for good shrinkage control should be from one-half to one-third of

43. *Casting Design Handbook,* American Society for Metals, 1962; *ASM Handbook*, Vol. 15, American Society for Metals, Materials Park, OH, 1988; T. S. Piwonka, "Design for Casting," *ASM Handbook*, Vol. 20, pp. 723–29, ASM International, Materials Park, OH, 1997.

the section thickness. A strong hot spot is produced when two ribs cross each other (d). These areas solidify after the thinner sections surrounding the junction so that the shrinkage cannot be fed with liquid metal, resulting in a shrinkage cavity. This problem can be eliminated by offsetting the ribs as shown in (d). A good way to evaluate where hot spots brought about by a large mass of molten metal, occur is to inscribe a circle in the cross section of the part. The larger the diameter of the circle, the greater the thermal mass effect, and the more the concern with shrinkage cavity formation.

Castings must be designed to ensure that the pattern can be removed from the mold and the casting from a permanent mold. A *draft*, or taper, of from 6 to 3 degrees is required on vertical surfaces so the pattern can be removed from the mold. Projecting details or undercuts should be avoided, as these require extra cores. Molds made with extensive use of cores cost more money, so castings should be designed to minimize the use of cores. Also, provisions must be made for placing cores in the mold cavity and holding them in place when the metal flows into the mold.

Solidification stresses can occur when different sections of the casting solidify at different times and rates. If this happens while the alloy is cooling through the temperature range where both liquid and solids coexist, it can result in internal fracture called *hot tearing*. Uneven cooling as the temperature continues to drop can result in severe distortion or warping of the casting.

Some casting processes like die casting, permanent mold casting and investment casting produce parts with excellent dimensional accuracy and smooth surfaces. Parts made with these processes are *net shape parts* that require no machining before using. Sand-cast parts always require machining after casting in order to attain the required dimensions and surface finish. Therefore, it is necessary to provide extra material in the casting as a *machining allowance*.

13.11.2 Producing Quality Castings

Casting offers exceptional design flexibility of shape at reasonable cost. It is an ancient metalworking process that has not always enjoyed a reputation for producing high-quality parts. A point not always understood by designers is that in a part made by casting, its mechanical properties depend on the design of the part because the properties depend on the size and shape of the grains. This depends on the solidification rate, which in turn depends on the thickness of different sections of the part. Furthermore, most casting processes are carried out in the atmosphere so that hot liquid metal can react with air to form oxide films and inclusions. Inclusions are nonmetallic particles formed by interaction with the mold or from chemical reactions among the constituents of the molten metal. These can serve as sites for crack initiation, and oxide films themselves can act like cracks.

Porosity of various origins can be present in a cast part. We have already discussed the macroporosity[44] produced by inadequate feeding of liquid while the casting is cooling. This is solved by modifications to the part geometry combined with better placement of risers in the casting. The use of solidification computer models is

44. Macroporosity is large enough to be seen with the unaided eye on radiographic inspection. Microporosity refers to pores that are not visible without magnification.

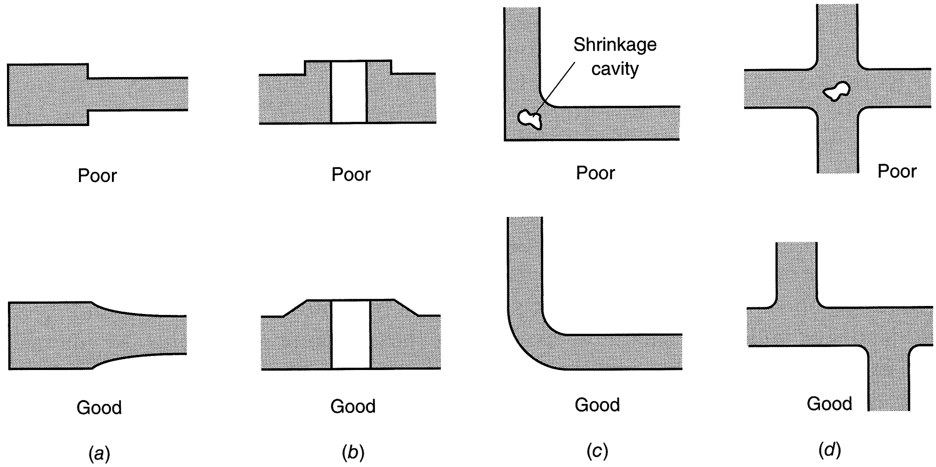

FIGURE 13.27
Some design details to minimize shrinkage cavity formation.

highly effective in identifying possible sites for macroporosity. The second type of porosity, microporosity, is more difficult to eliminate. As the metal solidifies it tends to form small, interlocking, tree-like structures called dendrites. When these approach 40 percent solid material by volume, the passages for further fluid inflow become blocked, leaving a fine porosity network. A second mechanism for pore formation arises from the fact that the solubility of gases in liquid metal decreases strongly with falling temperature. Thus, the dissolved gases are expelled from the liquid metal, and they form bubbles that grow into sizeable pores.

Microporosity can be minimized by the choice of alloy, but it is not something the designer can affect by the part design. It can be nearly eliminated by melting and pouring in the absence of air (vacuum melting), as is done for aircraft turbine blades, but this is very expensive. Another possibility is to use hot isostatic pressing (HIP) to close up any residual porosity. This process consists of enclosing the parts in a pressure vessel and subjecting them to a hydrostatic pressure of argon at 15 to 25 ksi at an elevated temperature for several hours. This will eliminate nearly all vestiges of microporosity, but again it is not an inexpensive secondary process.

The complexity of successfully casting parts with high-quality metallurgical properties requires the designer to be able to predict the solidification of the part and the metallurgical structure of the final part. At a minimum this means being able to determine how the part will solidify before a casting is poured, and to make design alterations until a casting is obtained without macroporosity. It would be highly desirable to be able to map the temperature-time curve at critical points in the casting. To do this requires teaming up with a progressive foundry with an experienced foundry engineer who is skilled in using solidification software. The most advanced software is capable of predicting grain size and structure, and therefore being able to infer mechanical properties. This software is also capable of predicting the distortions that occur during casting.

Obtaining quality castings requires working with a foundry that is up-to-date on the latest casting technology.[45] Much of this newer technology deals with minimizing defects in castings. A high-tech foundry will be knowledgeable about and practicing such things as:

- The proper way to prepare the melt to minimize the level of inclusions and level of dissolved gas
- Design of sprue, runner, and ingate so as to minimize the distance the liquid metal falls or prevent molten metal from spilling into unfilled regions of the casting
- Mold design to keep the liquid metal front moving at all times
- Design to eliminate bubbles of entrained air in the liquid metal
- Design to avoid the need to feed metal uphill against gravity
- Finding out whether feeding requirements are established by calculation or guesswork
- Design to prevent convection problems by ensuring that thermal gradients act with rather than against gravity
- The use of filters to reduce inclusions in the casting

This knowledge area is not that of the part designer, but he should at least be aware of the issues so as to be able to evaluate the technical capability of his casting supplier.

Using casting simulation software to design the part and mold, and using a part supplier that employs modern casting operations concepts, will produce parts that perform admirably in many applications. Reducing the level of defects will result in parts with more reproducible mechanical properties than are usually expected from castings. This is important in allowing designers to gain confidence that castings can be used in applications where forgings were previously the process of choice. This has happened in aircraft engine applications like jet turbine blades, where the highly alloyed metals needed to resist creep at high temperatures are very difficult to shape by deformation processes like forging. The quality casting technology that has been developed for these types of applications is finding its way into less demanding applications.

13.12
DESIGN OF FORGINGS

Forging processes are among the most important means of producing parts for high-performance applications. Forging is typical of a group of bulk deformation processes in which a solid billet is forced under high pressure by the use of a press to undergo extensive plastic deformation into a final near-to-finished shape.[46] Other examples of deformation processes are *extrusion*, in which a long object with a high L/D ratio is produced by pushing a metal billet through a die, *drawing*, in which a billet is pulled through a die, and *rolling,* in which a slab is passed through rolls to make a thin sheet.

45. M. Jolly, "Professor John Campbell's Ten Rules for Making Reliable Castings," *JOM*, May 2005, pp. 19–28; J. Campbell, *Castings Practice: The Ten Rules of Castings,* 2d ed., Butterworth-Heinemann, Oxford, UK, 2004.

46. B. L. Ferguson, "Design for Deformation Processes," *ASM Handbook,*Vol. 20, pp. 730–44, ASM International, Materials Park, OH, 1997. To see animations of various types of forging processes, go to www.deform.com and click on Applications.

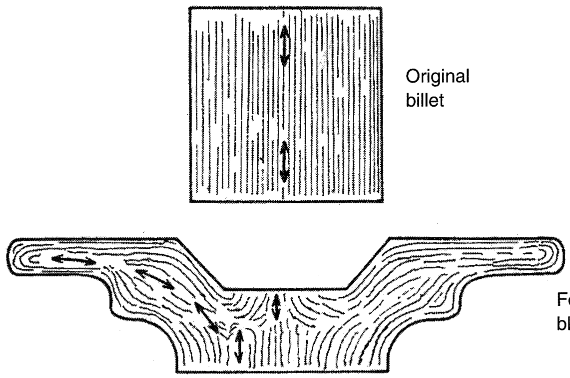

FIGURE 13.28
The redistribution of the fiber structure direction during the forging of a part.

Forging usually is carried out on a hot workpiece, but other deformation processes such as cold extrusion or impact extrusion may be conducted cold, depending upon the material. Because of the extensive plastic deformation that occurs in forging, the metal undergoes metallurgical changes. Any porosity is closed up, and the grain structure and second phases are deformed and elongated in the principal directions of working, creating a "fiber structure." The forging billet has an axial fiber structure due to hot working, but this is redistributed depending upon the geometry of the forging (Fig. 13.28).

The mechanical fibering due to the preferred alignment of inclusions, voids, segregation, and second-phase particles in the direction of working introduces a directionality (anisotropy) to structure-sensitive properties such as ductility, fatigue strength, and fracture toughness. The principal direction of working (such as the long axis of a bar) is defined as the longitudinal direction. The long-transverse direction is perpendicular to the longitudinal direction. The variation of reduction of area in the tensile test (the most sensitive measure of ductility) with the angle that the specimen axis makes with the forging axis is shown in Fig. 13.29. This shows that structure-sensitive mechanical properties like reduction of area, fatigue limit, and fracture toughness exhibit anisotropy as a result of closing up of porosity and alignment of second-phase particles produced by the plastic deformation. The designer needs to realize that some properties may not be the same in all directions of the forging. Therefore, in designing a forging, the direction of maximum plastic deformation (longitudinal) should be aligned with the direction of the part that needs to carry the maximum stress.

Forgings are classified into open- or closed-die forgings. Open dies, usually flat dies, are used to impose localized forces for deforming billets progressively into simple shapes, much as the blacksmith does with his hammer and anvil. *Closed-die forging* or impression die forging uses mechanical presses or hammers to force the metal to flow into a *closed cavity* to produce complex shapes to close dimensional tolerances. A wide variety of shapes, sizes, and materials can be made in forging. Table describing the advantages of the common forging processes can be found at www.mhhe.com/dieter. With proper forging die design, grain flow is controlled to give the best properties at the critically stressed regions.

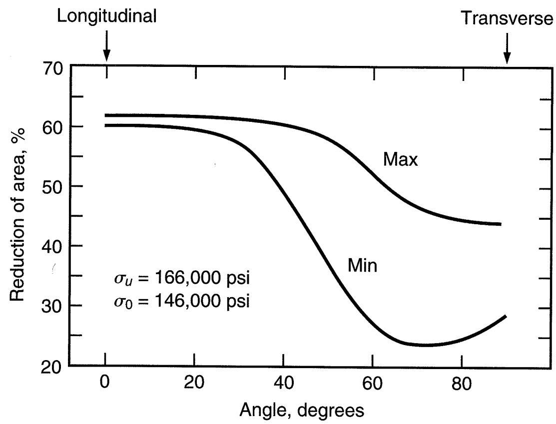

FIGURE 13.29
Relation between reduction of area and orientation within the forging.

Closed-die forgings rarely are done in a single step. The billet, often a piece of a bar stock, is first shaped in blocker dies (Fig. 13.30*a*) to shape the material properly so it will flow to fill the cavity of the finishing die completely (Fig. 13.30*b*). To ensure complete filling of the die cavity, a slight excess of material is used. It escapes into the flash surrounding the part, where it is "trapped" from further deformation. This causes the pressure over the rest of the workpiece to build up, forcing the workpiece material into the farthest recesses of the die. In this way, the details of the forging are achieved. Then the flash is trimmed off from the finished forging and recycled.

13.12.1 DFM Guidelines for Closed-Die Forging

Forging is essentially a molding process like casting, only now the material is a plastically deforming solid instead of a very low-viscosity fluid. Thus the DFM guidelines for forging are very similar to casting.[47] Detailed rules for designing forgings are given in *ASM Handbook,* Vol. 14A, pp. 701–823.

- As with a casting, vertical surfaces of a forging must be tapered to permit removal of the forging from the die cavity. The normal draft angle on external surfaces is 5 to 7°, and for internal surfaces it is 7 to 10°.
- The maximum flash thickness should not be greater than ¼ in. or less than 1/32 in. on average.
- Webs are the sections of a forging normal to the motion of the moving die, and ribs are the relatively thin sections parallel to the die motion, Fig. 13.30*b*. These features are easiest to form by the deforming metal when ribs are not too high and narrow and the web is relatively thick and uniform.
- The parting line, where the die halves meet, is an important design consideration because its location helps to influence grain flow, die costs, and die wear. For optimum economy it should be kept to a single plane if at all possible, since that

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47. J. G. Bralla, *Handbook of Product Design for Manufacturing,* Chap. 3.13, McGraw-Hill, New York, 1986; www.forging.org\Design\pg3_5_4_1.html

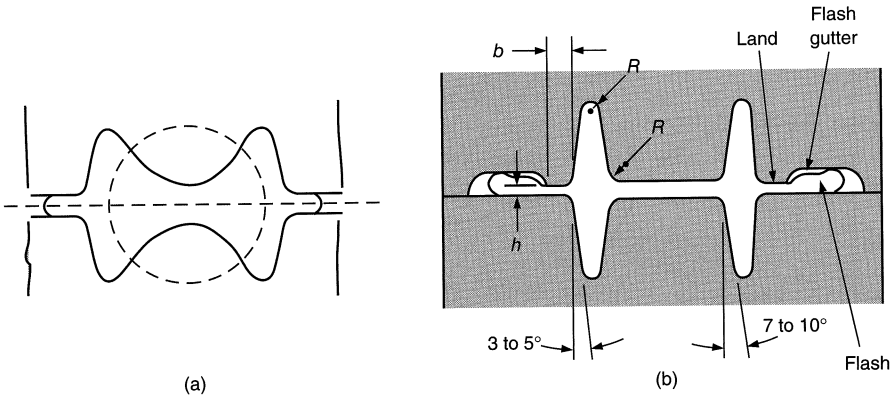

FIGURE 13.30
Schematic of closed-die forging. (a) Blocker die; (b) finishing die. (After J.A. Schey.)

will make die sinking, forging, and trimming less costly. Figure 13.30 shows that the flash occurs at the parting line. Because the forging fiber structure is unavoidably cut through when the flash is trimmed, the parting line is best placed where the minimum stresses arise in the service of the forging.

- Whenever possible in the design of forgings, as in the design of castings, it is desirable to keep the thickness of adjacent sections as uniform as possible. Rapid changes in section thickness should be avoided. Laps[48] and cracks are most likely to occur where metal flow changes because of large differences in the bulk of the sections. To prevent these defects, generous radii must be provided at those locations.

- Most forging is done at elevated temperature where the flow (yield) stress of the material is much lower than at room temperature. This significantly reduces the pressure that must be produced in the dies, but it also causes oxidation of the surface. The *machining envelope* is the excess metal that must be removed to bring the forging to the finished size and surface finish. The ultimate in precision forging is the *net-shape forging*, in which the machining allowance is zero. Generally, however, allowance must be made for removing surface scale (oxide), correcting for warpage and mismatch (where the upper and lower dies shift parallel to the parting plane), and for dimensional mistakes due to thermal contraction or die wear.

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13.12.2 Computer-Aided Forging Design

To predict the sequence of shapes to go from a piece of bar stock to a complex, defect-free forged shape requires great skill on the part of the die designer. This complex engineering task has been greatly aided by 30 years of research in applying FEA to

48. A lap is a surface defect caused by metal being folded over and then forged into the surface without being welded. Laps often cause fatigue cracks.

the analysis of deformation processes. Currently, software is available for the desktop computer[49] that allows the designer to accurately determine not only press loads and die stresses but also such significant parameters as stress, strain, and temperature distribution throughout the deforming workpiece and free surface profile. An important feature of the software is the ability to visualize the geometrical changes in the workpiece as the dies close in each step of the process. The designer can make changes in the tooling design and observe on subsequent simulations whether these led to improvement in the material flow and eliminated flow defects like laps or incomplete die fill. The savings in the cost of reworking dies and trying out reworked dies have led to broad industry adoption of deformation processing simulation software. Complementary software models the change in grain size as the part undergoes forging at elevated temperature.

13.13 DESIGN FOR SHEET-METAL FORMING

Sheet metal is widely used for industrial and consumer parts because of its capacity for being bent and formed into intricate shapes. Sheet-metal parts comprise a large fraction of automotive, agricultural, and aircraft components. Successful sheet-metal forming depends on the selection of a material with adequate formability, the proper design of the part and the tooling, the surface condition of the sheet, the selection and application of lubricants, and the speed of the forming press.

13.13.1 Sheet Metal Stamping

The cold stamping of a strip or sheet of metal with dies can be classified as either a cutting or a forming operation.[50] Cutting operations are designed to punch holes in sheets or to separate entire parts from sheets by *blanking.* A blanked shape may be either a finished part or the first stage in a forming operation in which the final shape is created by plastic deformation.

The sheared edge that is produced when sheet metal is punched or blanked is neither perfectly smooth nor perpendicular to the sheet surface. Simple blank contours should be used whenever possible since the die cost depends upon the length and the intricacy of the contour of the blank. It may be less expensive to construct a component from several simple parts than to make an intricate blanked part. Blanks with sharp corners are expensive to produce. The layout of the blanks on the sheet should be such as to minimize scrap loss.

Notching a blank along one edge results in an unbalanced force that makes it difficult to control dimensions as accurately as with blanking around the entire contour. The usual tolerances on blanked parts are ± 0.003 in.

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49. DEFORM® from Scientific Forming Technologies, Columbus, OH.

50. *ASM Handbook,* Vol.14B, *Metalworking: Sheet Forming,* ASM International, Materials Park, OH, 2006; J. A. Schey, *Introduction to Manufacturing Processes,* 3d ed., Chap. 10, McGraw-Hill, New York, 2000.

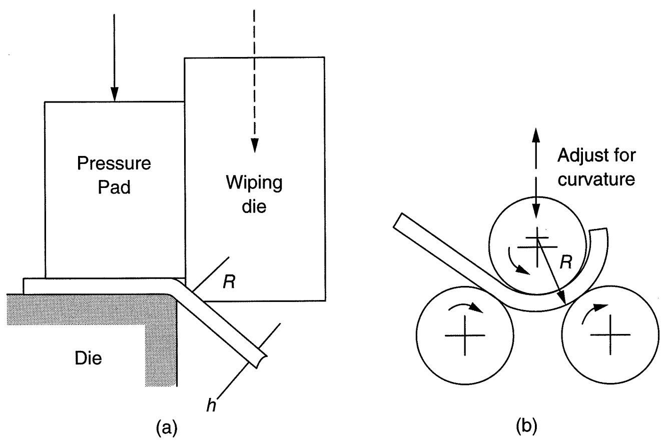

FIGURE 13.31
Sheet bending with a (a) wiping die, and (b) bending rolls.

When holes are punched in metal sheet, only part of the metal thickness is sheared cleanly; that is, a hole with partially tapered sides is created. If the hole is to be used as a bearing surface, then a subsequent operation will be required to obtain parallel walls. Diameters of punched holes should not be less than the thickness of the sheet or a minimum of 0.025 in. Smaller holes result in excessive punch breakage and should be drilled. The minimum distance between holes, or between a hole and the edge of the sheet, should be at least equal to the sheet thickness. If holes are to be threaded, the sheet thickness must be at least one-half the thread diameter.

13.13.2 Sheet Bending

Bending is a common sheet-forming operation. Bending along a straight line is done by *wiping*, Fig. 13.31*a*. The sheet is held down with a pressure pad and is wiped over the die radius with a wiping die. Long, straight bends are made in a press-brake, which is a type of press in which the sheet is placed between two dies. Thick sheet and plate are bent using a three-roll bender, Fig. 13.31*b*. The radius of curvature of the bend can be changed by varying the distance between the rolls. Long shapes like garage door channels are made by roll forming.

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A sheet metal part that is bent must undergo plastic deformation if it is to retain its bent shape. When this happens the bend region elongates a small amount and the sheet thins slightly to maintain a constant volume. The *bend allowance*, L_{BA}, the length of the neutral axis in the bend, is given by

$$L_{BA} = \alpha\left(R_b + kt\right) \tag{13.13}$$

where α is the bend angle in radians, R_b is the bend radius (measured to the inside of the bend), and t is the thickness of the sheet. If $R_b > 2t$ the neutral axis is in the center of the sheet thickness and $k = 0.5$. However, if $R_b < 2t$ (a sharp bend) the neutral axis is located about one-third of the distance from the inner bend surface, $k = 0.33$.

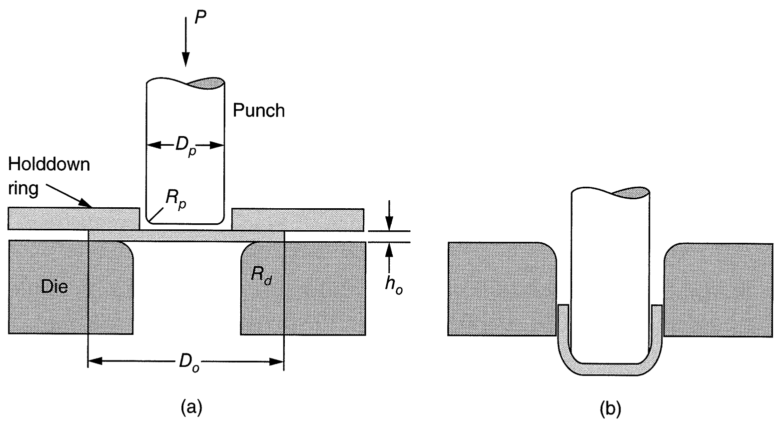

FIGURE 13.32
Deep drawing of a cylindrical cup (a) before drawing; (b) after drawing.

During bending, the contour of the part matches that of the dies; but upon release of the load, the elastic forces are released. Consequently, the bent material springs back, and both the angle of the bend and the bend radius increase. Therefore, to compensate for *springback*, the metal must be bent to a smaller angle and sharper radius so that when the metal springs back, it is at the desired values. Another way to deal with springback is to advance the punch beyond what is required to bend the radius. This compresses the metal and plastically deforms it in the bend region. Springback becomes more severe with increasing yield strength and section thickness.

The ability to bend a metal without cracking at the bend improves when the bend is made across the "metal grain" (i.e., the line of the bend is perpendicular to the rolling direction of the sheet). The largest possible bend radius should be used in design to prevent cracking, and the bend radius should not be less than the sheet thickness t. The formability of sheet in bending is expressed in multiples of the sheet thickness; thus a $2t$ material has a greater formability than a sheet metal whose minimum bend radius is $4t$.

13.13.3 Stretching and Deep Drawing

Metal sheets are often formed into large contoured shapes such as the roof or fender of an automobile. To form such shapes requires a combination of stretching and deep drawing. In *stretching,* the sheet is clamped around its periphery and subjected to tension forces that elongate it and thin the sheet at the same time. The limit of deformation is the formation of a localized region of thinning (necking) in the sheet. This behavior is governed by the uniform elongation of the material in a tension test. The greater the capacity of the material to undergo strain hardening, the greater its resistance to necking in stretching.

The classic example of sheet drawing is *deep drawing*, as in the formation of a cup.[51] In deep drawing, the blank is "drawn" with a punch into a die, Fig. 13.32. In

51. J. A. Schey, op. cit., pp. 408–19.

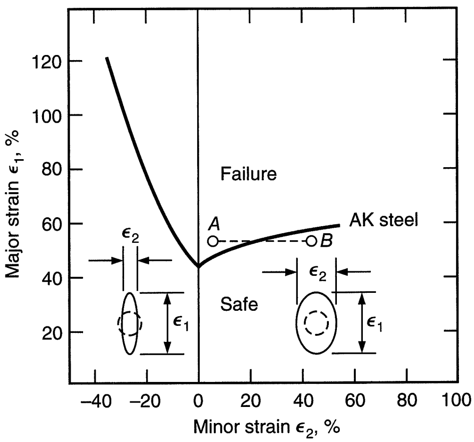

FIGURE 13.33
Example of the use of the Keeler-Goodwin forming limit diagram.

deep drawing the circumference of the blank is decreased when the blank is forced to conform to the smaller diameter of the punch. The resulting circumferential compressive stresses cause the blank to thicken and also to wrinkle at its outer circumference unless sufficient pressure is provided by the holddown ring or binder. However, as the metal is drawn into the die over the die radius, it is bent and then straightened while being subjected to tension. That results in substantial thinning of the sheet in the region between the punch and the die wall. The deformation conditions in deep drawing are substantially different from those in stretching. Success in deep drawing is enhanced by factors that restrict sheet thinning: a die radius about 10 times the sheet thickness, a liberal punch radius, and adequate clearance between the punch and die. Of considerable importance is the crystallographic texture of the sheet. If the texture is such that the slip mechanisms favor deformation in the width direction over slip in the thickness direction of the sheet, then deep drawing is facilitated. This property of the material can be measured in tension test on the sheet from the *plastic strain ratio r.*

$$r = \frac{\text{strain in width direction of tension specimen}}{\text{strain in thickness direction}} = \frac{\varepsilon_w}{\varepsilon_t} \tag{13.14}$$

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The best deep-drawing sheet steels have an r of about 2.0.

An important tool in developing sheet-forming operations is the Keeler-Goodman forming limit diagram (Fig. 13.33). It is experimentally determined for each sheet material by placing a grid of circles on the sheet before deformation. When the sheet is deformed, the circles distort into ellipses. The major and minor axes of an ellipse represent the two principal strain directions in the stamping. Strains at points where the sheet just begins to crack are measured. The largest strain, ε_1, is plotted on the y-axis and the smaller strain, ε_2, is plotted along the x-axis. The strains are measured at points of failure for different stampings with different geometries to fill out the diagram. Strain states above the curve cause failure, and those below do not cause failure. The tension-tension sector is essentially stretching, whereas the tension-compression sector is closer to deep drawing. As an example of how to use the diagram, suppose point *A* represents the critical strains in a particular sheet metal stamping. This failure could be eliminated by changing the metal flow by either design changes to the die or the part to move the strain state to *B*. Alternatively, a material of greater formability in which the forming limit diagram was at higher values could be substituted.

13.13.4 Computer-Aided Sheet Metal Design

Several computer-aided design tools for designing dies for parts to be made by sheet metal forming[52] are used extensively by the automotive industry.[53] Another software,[54] PAM-STAMP 2G, provides a completely integrated sheet metal forming simulation for a wide range of applications. The CAD model for the part is imported into the Diemaker Module where a parametric geometric model, of a die is created in a matter of minutes. Next the Quikstamp Module takes the geometric model, and using elastic-plastic models of different steel and aluminum sheet materials it determines the feasibility of the formability of the design. This is done using forming limit diagrams similar to Fig. 13.33. After possibly several die design changes or changes of sheet material, the ability to make the part is verified. Then the design passes to the Autostamp Module, where a virtual die tryout is conducted in detail. The simulation can show the location of defects like splits and wrinkles and shows where drawbeads should be placed to alter metal deformation flow. Operating parameters such as the die cushion force and sheet lubrication can be changed to observe their effects on formability. Built-in springback prediction enables the designer to make changes in tooling geometry before any expensive tooling has been built. This software, and the others mentioned previously, allow the development of tooling in a few days, whereas with conventional "cut and try" methods it may take several months.

13.14 DESIGN OF MACHINING

Machining operations represent the most versatile of common manufacturing processes. Practically every part undergoes some kind of machining operation in its final stages of manufacture. Parts that are machined may have started out as castings or forgings and require only a few drilled holes and finishing, or they may be machined completely from bar stock or plate when only a small number of parts are needed.

There is a wide variety of machining processes with which the design engineer should be familiar.[55] Machining processes can be categorized by whether the tool

52. C-Y. Sa, "Computer-Aided Engineering in Sheet Metal Forming," *ASM Handbook,*, Vol. 14B, pp. 766–90.
53. www.autoform.com; www.dynaform.com
54. www.csi-group.com
55. For examples see *ASM Handbook,* Vol. 16, ASM International, Materials Park, OH, 1989; E.P. DeGarmo, J. T. Black, and R. Kohser, *Materials and Processes in Manufacturing,* 9th ed., Chaps. 21–30, John Wiley & Sons, New York, 2003.

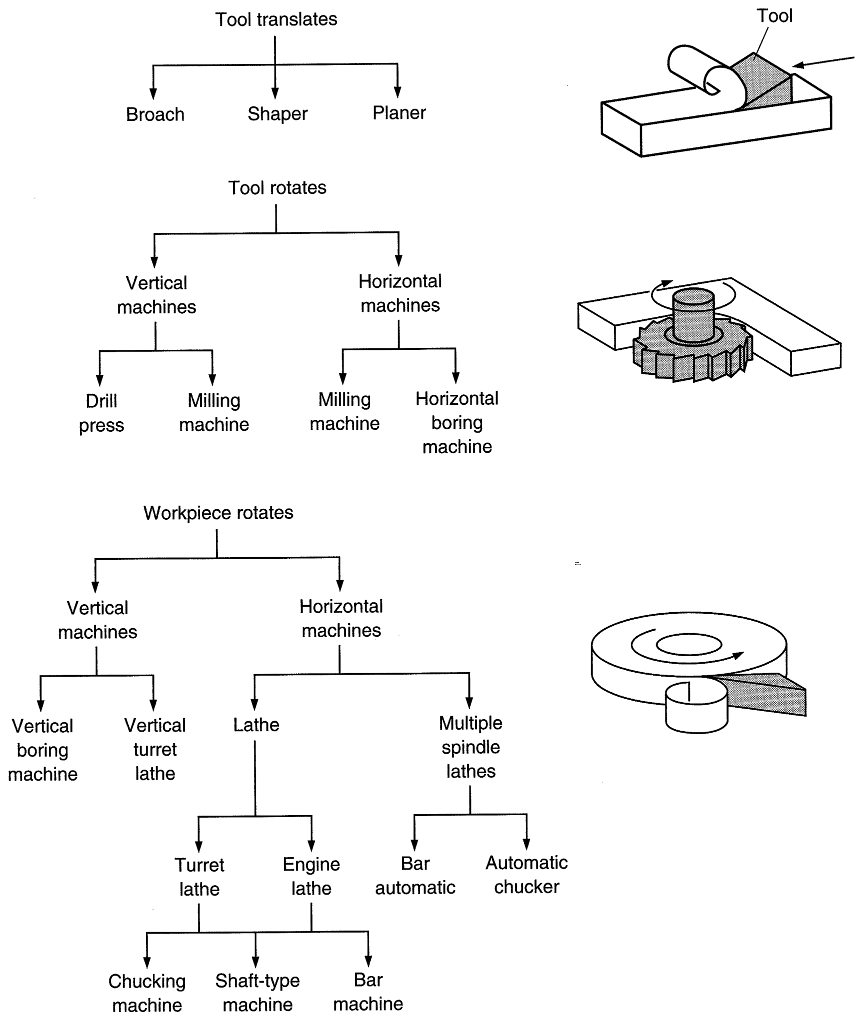

FIGURE 13.34
Classification of metal-cutting processes.

translates or rotates or is stationary while the workpiece rotates. The classification of machining processes based on this system is shown in Fig. 13.34.

All machining operations produce a shape by cutting a succession of small chips from the workpiece with a hard, sharp cutting tool. There are many ways of removing material by chip formation. Some processes use a tool with a single cutting edge (e.g., lathe, shaper, planer), but most use a multipoint tool (milling, drilling, sawing, grinding). Two very different approaches to machining are forming and generating. A shape is *formed* when a cutting tool possessing the finished contour of the shape is fed (plunged) directly into the workpiece. The workpiece may be moving or stationary, as in drilling a hole.

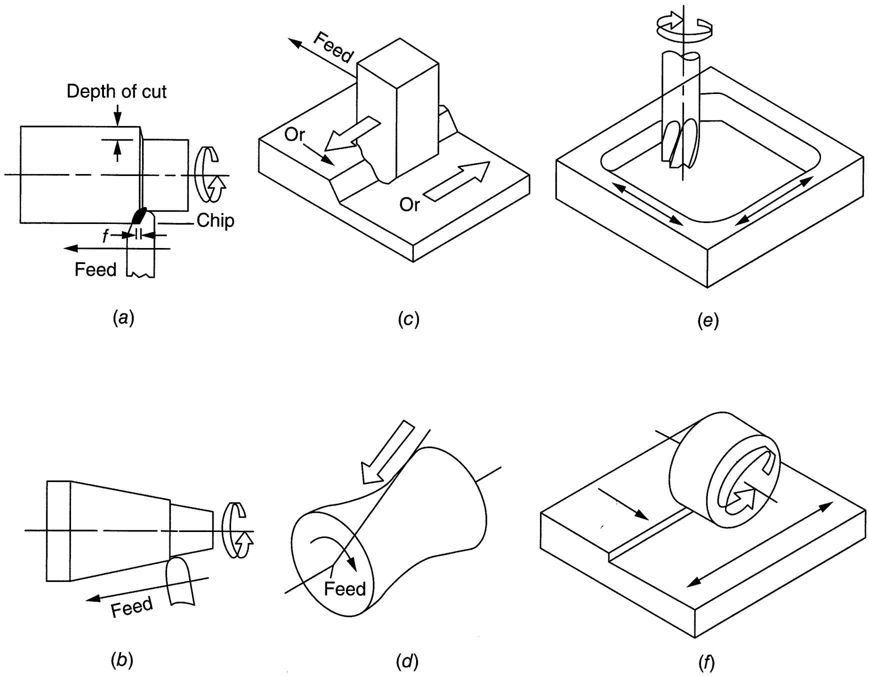

FIGURE 13.35
Programmed tool motion (feed) is necessary in generating a shape: (a) turning a cylinder and (b) a cone; (c) shaping (planing) a flat and (d) a hyperboloid; (e) milling a pocket; and (f) grinding a flat (principal motions are marked with hollow arrows, feed motions with solid arrows).

Most machining processes *generate* a shape by relative motion between the tool and the workpiece. The *primary motion* moves the cutting tool into the workpiece, and the *feed motion* moves the point of engagement of the tool along the workpiece. Fig. 13.35 shows some examples.

In Fig. 13.35*a,* the workpiece is a cylinder rotating in a lathe. The tool is set to a depth of cut and the primary turning motion produces the chip. At the same time the feed motion parallel to the longitudinal axis of the cylinder generates a cylinder of smaller diameter in this lathe turning process. If the workpiece axis and the feed motion are at an angle, a cone (tapered cylinder) is generated, Fig. 13.35*b.*

If the tool moves relative to a stationary workpiece (shaping) or the workpiece relative to a stationary tool (planing), with feed normal to the primary motion, a flat surface is generated, Fig. 13.35*c*. If the workpiece were given a feed motion by rotating it around its axis parallel to the tool motion, a cylinder would be produced. If the workpiece axis could be set at an angle, then a hyperboloid with cylindrical symmetry would be generated, Fig. 13.35*d*.

Figure 13.35*e* shows the common process of cutting a pocket with an end mill. Primary motion comes from the rotating end mill, while the feed motion can be any-

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where in the x-y plane. In Fig. 13.35*f* the primary motion comes from a rotating grinding wheel to produce a flat-ground surface.

13.14.1 Machinability

Most metals and plastics can be machined, but they vary a great deal in the ease with which they can be machined, that is, their *machinability*. Machinability is a complex technological property that is difficult to define precisely. The machinability of a material is usually measured relative to a standard material in a particular machining process. A material has good machinability if the tool wear is low, the cutting forces are low, the chips break into small pieces instead of forming long snarls, and the surface finish is acceptable.

Machinability is a system property that depends on the workpiece material, the cutting tool material and its geometry, the type of machining operation, and its operating conditions.[56] Table 13.15 lists metallic alloys by decreasing order of machinability. The right column in this table lists various machining processes in decreasing order of machinability. For example, for any material, grinding is generally possible when other machining processes give poor results, and milling is easier to accomplish than generation of gear teeth.

Nothing has greater impact on machining costs and quality of machined parts than the machinability of the work material. Therefore, choose the material of highest machinability for the machining process you need to make the part. The one generalization that can be applied to machinability is that the higher the hardness of the workpiece material, the poorer the machinability. Therefore, steel parts are usually machined in the annealed condition and then heat-treated and finished by grinding. It is necessary to leave a grinding allowance to remove any distortion from heat treatment

13.14.2 DFM Guidelines for Machining

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The following are general guidelines for designing parts that will be made by machining.[57]

- An important factor for economy in machining is to specify a machined surface only when it is needed for the functioning of the part. Two design examples for reducing the amount of machined area are shown in Fig. 13.36.
- In designing a part, the sequence by which the part would be machined must be kept in mind so the design details that make machining easy are incorporated.[58]

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56. D. A. Stephenson and J. S. Agapiou, *Metal Cutting Theory and Practice,* 2d ed., Chaps. 2, 11, and 13, CRC Press, Boca Raton, FL, 2006.
57. G. Boothroyd, and W. A. Knight, *Fundamentals of Machining and Machine Tools,* 2d ed., Chap. 13, Marcel Dekker, New York, 1989; "Simplifying Machining in the Design Stage," *Tool and Manufacturing Engineers Handbook* Vol. 6, *Design for Manufacturability* SME, Dearborn, MI, 1992.
58. See the virtual machine shop, http://jjjtrain.kanabco.com/vms/library.html

TABLE 13.15
Classes of Metals and Machining Processes, Listed in Decreasing Order of Machinability

Classes of Metals	Machining Processes
Magnesium alloys	Grinding
Aluminum alloys	Sawing
Copper alloys	Turning with single-point tools
Gray cast iron	Drilling
Nodular cast iron	Milling
Carbon steels	High-speed, light feed, screw machine work
Low-alloy steels	Screw machining with form tools
Stainless steels	Boring
Hardened and high-alloy steels	Generation of gear teeth
Nickel-base superalloys	Tapping
Titanium alloys	Broaching

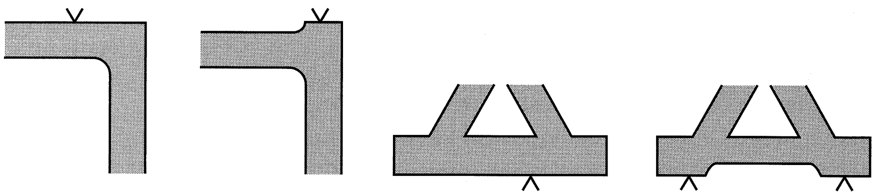

FIGURE 13.36
Examples of design details in castings that minimize the area of the machined surface.

Software exists to assist in selecting the steps for machining a part. The software simulates the cutter paths on the computer screen.

- The workpiece must have a reference surface that is suitable for holding it on the machine tool or in a fixture. A surface with three-point support is better than a large, flat surface because the workpiece is less likely to rock. Sometimes a supporting foot or tab must be added to a rough casting for support purposes. It will be removed from the final machined part.
- When possible, the design should permit all the machining to be done without reclamping the workpiece. If the part needs to be clamped in a second, different position, one of the already machined surfaces should be used as the reference surface.
- Whenever possible, the design should be such that existing tools can be used in production. When possible, the radius of the feature should be the same as the radius of the cutting tool, Fig. 13.37*a*.
- Design parts so that machining is not needed on the unexposed surfaces of the workpiece when the part is gripped in the work-holding device.

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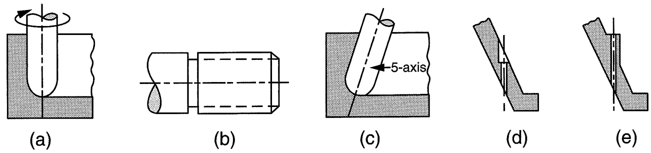

FIGURE 13.37
Some design details that affect machining operations.

- Make sure that when the part is machined, the tool, tool holder, work-piece, and work-holding device do not interfere with one another.
- Remember that a cutting tool often requires a runout space because the tool cannot be retracted instantaneously, see Fig. 13.37*b*.
- Adjust the cutting conditions to minimize the formation of sharp burrs. A burr is a small projection of metal that adheres at the edges of the cut workpiece. If thicker than 0.4 mm, burrs cannot be removed by blast grit or tumbling methods and must be machined away.

The following guidelines pertain to drilling holes:

- The cost of a hole increases proportionately with depth; but when the depth exceeds three times the diameter, the cost increases more rapidly.
- When a drill is cutting, it should meet equal resistance on all cutting edges. It will if the entry and exit surfaces it encounters are perpendicular to its axis.
- Holes should not be placed too near the edge of the workpiece. If the workpiece material is weak and brittle, like cast iron, it will break away. Steel, on the other hand, will deflect at the thin section and will spring back afterward to produce a hole that is out of round.
- When there is a choice, design a through hole rather than a blind hole.

The following guidelines pertain to turning or milling operations.

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- To avoid tool changing, radii should be designed to be the same as the edge of a milling cutter (Fig. 13.37*a*) or the nose radius of a lathe cutting tool. Of course, this rule should not supersede the need to have the appropriate radius for stress concentration considerations.
- The deflection of tools when boring or milling internal holes sets limits on the depth-to-diameter ratio.
- Undercuts can be machined if they are not too deep. It is essential to use an undercut if the design requires either external or internal threads, Fig. 13.37*b*.
- Designing features at an angle to the main tool movement direction call for special machines or attachments, Fig. 13.37*c*. They will be costly to make because of the need to interrupt operations and transfer to another machine.
- Placing features at an angle to the workplace surface will deflect the tool and prevent it from holding close tolerances, Fig. 13.37*d*. Fig. 13.37*e* shows an appropriate design to avoid this problem.

13.15 DESIGN OF WELDING

Welding is the most prominent process for joining large components into complex assemblies or structures. It is an important area of the wider topic of joining parts into assemblies.

13.15.1 Joining Processes

Technology has created a myriad of joining processes, Fig. 13.38. They can be conveniently divided into permanent and nonpermanent joints. Nonpermanent joints are used when the assembly must be taken apart for maintenance, repair, or recycling.

Bolts and screws[59] and snap fits[60] (especially in plastic parts) are most common. Other nonpermanent joining methods are shrink and press fits, snap rings, pins, and various types of mechanical quick-release mechanisms like clamps and clips.

Permanent mechanical joining methods include riveting, stitching, and stapling of thin materials, and seams produced in sheet metal by making tight bends. Sometimes a sealer such as polymer or solder is used to make the seam impermeable.

The majority of processes for making permanent joints involve melting, either the melting (fusion) of two metals at a joint (welding) or the addition of a molten material at a temperature where the metals at the joint have not melted (brazing. soldering, and adhesive bonding).

An extensive PRIMA selection matrix and data sheets have been developed for joining processes.[61]

13.15.2 Welding Processes

Brief descriptions of the most common welding processes[62] follow, starting with the left side of Fig. 13.38.

Solid-State Welding

In solid-state welding, welding is carried out without melting either of the materials to be joined. The oldest welding process is the solid-state method called *forge welding*. It is the technique used by the blacksmith in which two pieces of steel or iron are heated and forged together under point contact. Slag and oxides are squeezed out, and interatomic bonding of the metal results. In the modern version of forge welding,

59. The design of bolts and screws is typically covered in machine design texts; see R. G. Budynas and J. K. Nisbet *Shigley's Mechanical Engineering Design,* 8th ed., Chap. 8, McGraw-Hill, New York, 2008.
60. P. R. Bonenberger, *The First Snap-Fit Handbook,* 2d ed., Hanser Gardner Publications, Cincinnati, OH, 2005.
61. K.G. Swift and J. D. Booker, *Process Selection,* 2d ed., pp. 31–34 and pp. 190–239, Butterworth-Heinemann, Oxford, UK, 2003.
62. *ASM Handbook,* Vol. 6, *Welding, Brazing, and Soldering,* ASM International, Materials Park, OH, 1993.

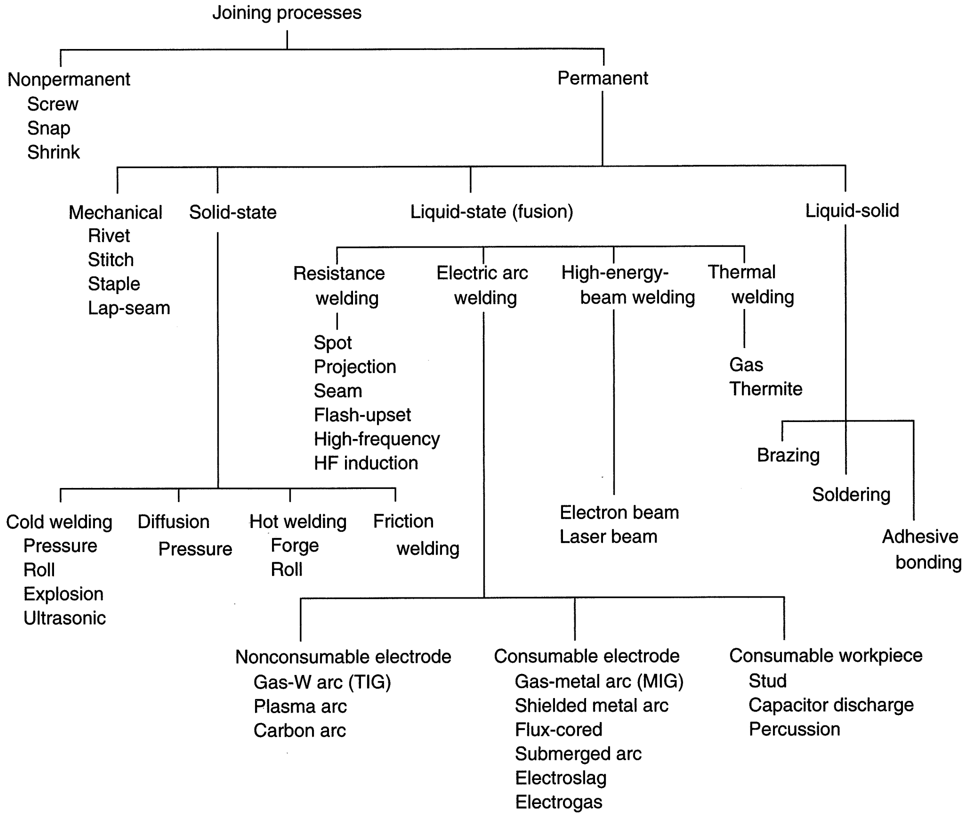

FIGURE 13.38
Classification of joining processes.

steel pipe is produced by forming sheet into a cylinder and welding the edges together by forge-seam welding in which either the sheet is pulled through a conical die or the hot strip is passed between shaped rolls.

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As the name implies, cold-welding processes are carried out at room temperature without any external heating of the metal. The surfaces must be very clean, and the local pressure must be high enough to produce substantial cold-working. The harmful effect of interface films is minimized when there is considerable relative movement of the surfaces to be joined. The movement is achieved by passing the metal through a rolling mill or subjecting the interface to tangential ultrasonic vibration. In explosive bonding there is very high pressure and extensive vorticity at the interfaces. Diffusion bonding takes place at a temperature high enough for diffusion to occur readily across the bond zone. Hot roll bonding is a combination of diffusion bonding and roll bonding.

Friction welding (inertia welding) utilizes the frictional heat generated when two bodies slide over each other. In the usual way of doing friction welding, one part is held fixed and the other part (usually a shaft or cylinder) is rotated rapidly and, at the same time, forced axially against the stationary part. The friction quickly heats the abutting surfaces and, as soon as the proper temperature is reached, the rotation is stopped and the pressure is maintained until the weld is complete. The impurities are squeezed out into a flash, but essentially no melting takes place. The heated zone is very narrow, and therefore dissimilar metals are easily joined.

Liquid-State Welding (Fusion Welding)

In the majority of welding processes a bond between the two materials is produced by melting, usually with the addition of a filler metal. In welding, the workpiece materials and the filler material in the joint have similar compositions and melting points. By contrast, in soldering and brazing, the filler material has a much different composition that is selected to have a lower melting point than the workpiece materials.

Resistance welding utilizes the heat generated at the interface between two metal parts when a high current is passed through the parts. Spot welding is used extensively to join metal sheets by melting them at discrete points (spots) under pressure from the electrodes. Rather than produce a series of spots, an electrode in the form of a roller often is used to produce a seam weld. If the part to be welded contains small embossed projections, they are easily softened under the electrode and pushed back to produce the weld nugget.

Heat for welding comes from chemical sources or high-energy beams. Gas welding, especially the reaction between oxygen and acetylene to produce an intense flame, has been used for many years. Thermite welding uses the reaction between Fe_2O_3 and Al, which produces Fe and an intense heat. The process is used to weld heavy sections such as rails. Energy from a laser beam is used to produce welds in sheet metal. Its advantage over an electron beam is that a vacuum is not required. Each form of energy is limited in power, but it can be carefully controlled. Laser beam and electron beam welding lend themselves to welding thin gauges of hardened or high-temperature materials.

The thermal energy produced from an electric arc has been utilized extensively in welding. Most *electric arc welding* is done with an arc struck between a consumable electrode (the filler or weld rod) and the workpiece. A coating is applied to the outside surface of the metal electrode to provide a protective atmosphere around the weld pool. The electrode coating also acts as a flux to remove impurities from the molten metal and as an ionizing agent to help stabilize the arc. This is the commonly used *shielded metal arc process.* Since the electrode coating is brittle, only straight stick electrodes can be used. That restricts the process to a slow hand operation. If the flux coating is placed inside a long tube, the electrode can be coiled, and then the shielded arc process can be made continuous and automatic. In the *submerged arc process* the consumable electrode is a bare filler wire, and the flux is supplied from a separate hopper in a thick layer that covers the arc and the weld pool. In the *electroslag process* the electrode wire is fed into a pool of molten slag that sits on top of the molten weld pool. Metal transfer is from the electrode to the weld pool through the molten slag. This process is used for welding thick plates and can be automated. In the *gas metal arc* (MIG) process the consumable metal electrode is shielded by an inert gas such as argon or helium. Because there is no flux coating, there is no need to remove the slag deposit from the weld bead after each pass.

In *nonconsumable electrode welding* an inert tungsten electrode is used. Depending on the weld design, a filler rod may be required. In gas tungsten arc welding (TIG welding), argon or helium is used. The process produces high-quality welds in almost any material, especially in thinner-gauge sheet. The two most common welding methods are the metal arc process for welding large structures like ships, pipelines, and bridges, and TIG welding for smaller machine structures and thin sheet.

Liquid-Solid-State Welding

In this class of welding processes the temperature generated is not high enough to melt the metals to be joined. Brazing uses low-melting-point alloys of copper, gold, or silver to bond steel, cast iron, and aluminum alloys. Low-melting-point solders are used in joining copper and aluminum wires and in joining electronic components in printed circuit boards. To create a good bond in either brazing or soldering, a flux must be added to clean oxide films from the metal surfaces, prevent further oxidation during heating, and assist in the wetting of the metal surfaces. The materials used in brazing and soldering are much weaker than the base metals they join. They can only create a strong bond if there is excellent bonding of the filler metal with the base metal, and if the joint thickness is the proper amount. To achieve good bonding, the base metal must be free of oxides and organics, and the filler metal must completely wet the base metal surfaces. Since filler metal is inherently weaker than the base metal, it gets its strength from the constraint imposed by the thicker and stronger base metal plates. If the filler layer is too thick, the filler metal properties will control and the joint strength will be weak. If the filler layer is too thin, then there may be difficulty drawing in the liquid by capillary action. Typically the optimum joint thickness is about 5 to 10 μm.

Adhesive bonding uses a liquid polymer as the filler material. It can be used to join plastics, metals, or ceramics in applications where the stresses are rather low. Adhesive bonding depends solely on adhesion forces to provide the bond. Thus, the surfaces must be very clean, although some surface roughness can be advantageous to increase the surface area. The adhesive must completely wet the surface to give complete coverage, and as with soldering and brazing, the joint gap must be small and well controlled. The technology of adhesive bonding has advanced rapidly and today is used to bond surfaces in aircraft and automotive products.

13.15.3 Welding Design

To design a weldment, consideration must be given to the selection of materials, the joint design, the selection of the welding process, and the stresses that must be resisted by the design. The welding process subjects the workpiece at the joint to a temperature that exceeds the melting point of the material. Heat is applied locally and rapidly to create a miniature casting in the weld pool. Often successive weld passes are laid down. The base metal next to the weld bead, the *heat-affected zone* (HAZ), is subjected to rapid heating and cooling, so the original microstructure and properties of the base metal are changed, Fig. 13.39. The figure shows coarse columnar grains characteristic of a casting in the weld joint. Into the base metal the elongated

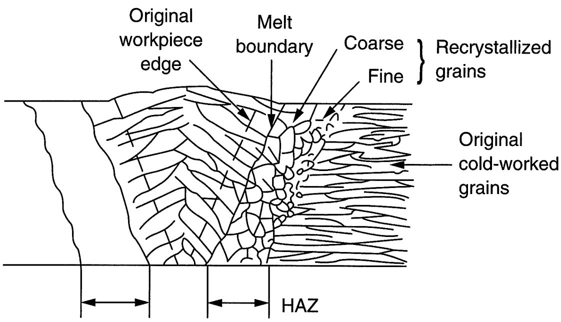

FIGURE 13.39
Sketch showing the grain structure in a section through an electric arc weld in two rolled metal plates.

cold-worked grains have recrystallized and formed a large grain size near the original joint boundary, falling off in grain size throughout the region of the HAZ because of the difference in temperature and time that they have seen. Considerable opportunity for defects exists unless the welding process is properly carried out.

Material Behavior and Selection

Since fusion welding is a melting process, controls appropriate to producing quality castings must be applied. Reactions with the atmosphere are prevented by sealing off the molten pool with an inert gas or a slag or by carrying out the welding in a vacuum chamber. The surfaces of the weld joint should be cleaned of scale or grease before welding is undertaken. The thermal expansion of the weld structure upon heating, followed by solidification shrinkage, can lead to high internal tensile stresses that can produce cracking and/or distortion. Rapid cooling of alloy steels in welding can result in brittle martensite formation and consequent crack problems: see Fig. 13.43*a*. As a result, it is common to limit welding to carbon steels with less than 0.3 percent carbon or to alloy steels in which the carbon equivalent[63] is less than 0.3 percent carbon. When steels with 0.3 to 0.6 percent carbon must be used because their high strength is required, welding without martensite cracking can be performed if the weld joint is preheated before welding and postheated after the weld bead has been deposited. These thermal treatments decrease the rate of cooling of the weld and heat-affected zone, and they reduce the likelihood of martensite formation.

Material selection for welding involves choosing a material with high weldability. Weldability, like machinability, is a complex technological property that combines many more basic properties. The melting point of the material, together with the specific heat and latent heat of fusion, will determine the heat input necessary to produce fusion. A high thermal conductivity allows the heat to dissipate and therefore requires a higher rate of heat input. Metals with higher thermal conductivity result in more rapid cooling and more problems with weld cracking. Greater distortion results from a high thermal expansion, with higher residual stresses and greater danger of weld cracking. There is no absolute rating of weldability of metals because different

63. $C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

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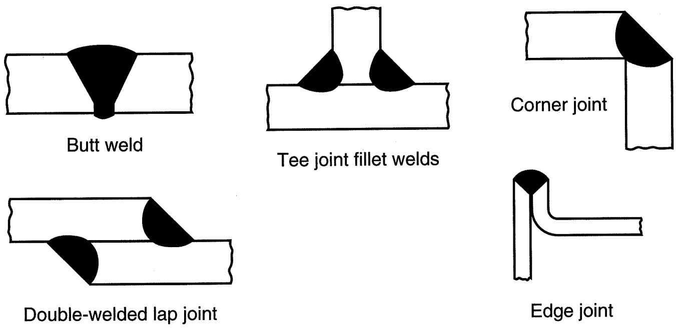

FIGURE 13.40
Basic types of welded joints.

welding processes impose a variety of conditions that can affect the way a material responds.

Weld Joint Design

The basic types of welded joints are shown in Fig. 13.40. Many variations of these basic designs are possible, depending on the type of edge preparation that is used. A square-edged butt joint requires a minimum of edge preparation. However, an important parameter in controlling weld cracking is the ratio of the width of the weld bead to the depth of the weld. It should be close to unity. Since narrow joints with deep weld pools are susceptible to cracking, the most economical solution is to spend money shaping the edges of the plate to produce a joint design with a more acceptable width-to-depth ratio. Ideally, a butt weld should be a full-penetration weld that fills the joint completely throughout its depth. When the gap in a butt joint is wide, a backing strip is used at the bottom of the joint. Fillet welds (center, top row in Fig. 13.40) are the welds most commonly used in structural design. They are inherently weaker than full-penetration butt welds. A fillet weld fails in shear. The design of welded structures calls for specialized expertise that is discussed in machine design texts and books on welding design.[64]

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Distortion in Welding

Distortion is ever-present in welding since it involves the rapid application of heat to a localized area, followed by the rapid removal of the heat. One of the best ways to eliminate welding distortion is to design the welding sequence with thermal distortion in mind. If, because of the geometry, distortion cannot be avoided, then the forces that produce the shrinkage distortion should be balanced with other forces provided by fixtures and clamps. Shrinkage forces can also be removed after welding by postwelding

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64. R.G. Budynas and J.K. Nisbet, op. cit, Chap. 9; *Design of Weldments,* O. W. Blodgett, *Design of Welded Structures,* The James F. Lincoln Arc Welding Foundation, Cleveland, OH, 1963; T. G. F. Gray and J. Spencer, *Rational Welding Design,* 2d ed., Butterworths, London, 1982; www.engineersedge.com/weld_design_menu.shtml.

annealing and stress-relief operations. Distortion can be minimized by specifying in the design only the amount of weld metal that is absolutely required. Overwelding adds not only to the shrinkage forces but also to the costs.

DFM Guidelines for Welding

The following are some general considerations applicable in designing a welded part.

- Welded designs should reflect the flexibility and economy inherent in the welding process. Do not copy designs based on casting or forging.
- In the design of welded joints, provide for straight force flowlines. Avoid the use of welded straps, laps, and stiffeners except as required for strength. Use the minimum number of welds.
- Weld together parts of equal thickness whenever possible.
- Locate the welds at areas in the design where stresses and/or deflections are least critical.
- Carefully consider the sequence with which parts should be welded together and include that information as part of the engineering drawing.
- Make sure that the welder or welding machine (for automatic welding) has unobstructed access to the joint so that a quality weld can be produced. Whenever possible, the design should provide for welding in the flat or horizontal position, not overhead.

13.15.4 Cost of Joining

We can adapt the cost of manufacture model presented in Sec.13.4.6 to cover the cost of joining parts. This supplements the method of estimating assembly costs that was outlined in Sec. 13.10.1. The cost of joining *per unit* assembly or subassembly, C_{join}, is given by[65]

$$C_{\text{join}} = \sum_{\text{all joints}}^{n} \left\{ C_{\text{com}} + C_L \times t_{process} + \frac{C_t}{n} \left(\frac{C_o}{Lt_{\text{wo}}} + C_{\text{OH}} \right) \left(t_{process} + \frac{t_{setup}}{n_{batch}} \right) \right\} \quad (13.15)$$

where C_{com} is the cost of consumable materials such as weld rod, flux, adhesives, or fasteners
C_t is the cost of dedicated jigs and fixtures
n is the number of joints to be made in the entire production run
t_{process} is the time to create a single weld or adhesive joint, or to insert and torque a single fastener

The other symbols in Eq. (13.15) have the same meaning as given in Sec. 13.3.

65. A. M. K. Esawi and M. F. Ashby, *Materials and Design,* Vol. 24, pp. 605–16, 2003.

13.16
RESIDUAL STRESSES IN DESIGN

Residual stresses are the system of stresses that can exist in a part when the part is free from external forces. They are sometimes referred to as internal stresses or locked-in stresses.[66] They arise from nonuniform plastic deformation of a solid, chiefly as a result of inhomogeneous changes in volume or shape that occur during manufacturing processes.

13.16.1 Origin of Residual Stresses

Residual stresses are developed due to nonuniform deformation. To understand how, consider an assembly that is made by joining a core and a tight-fitting tube[67] (Fig. 13.41*a*). Both components are made from the same material and have equal cross-sectional areas. The core was longer than the tube, so before they were joined by welding the core was compressed by a fixture to the same length as the tube, (Fig. 13.41*b*). After making the weld, the fixture compressing the core was removed and the assembly assumed a new length somewhere between the original lengths of

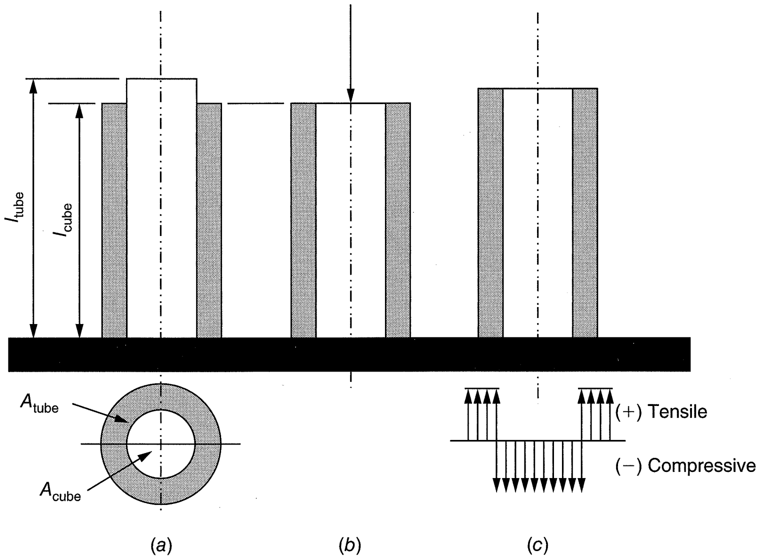

FIGURE 13.41
Example of the formation of residual stresses due to inhomogeneous deformation.

66. W. B. Young, ed., *Residual Stresses in Design, Process and Materials Selection,* ASM International, Materials Park, OH, 1987; U. Chandra, "Control of Residual Stresses," *ASM Handbook,* Vol. 20, pp. 811–19, ASM International, Materials Park, OH, 1997.
67. J. A. Schey, *Introduction to Manufacturing Processes,* 3d ed., pp. 105–6, McGraw-Hill, New York, 2000.

the two components. Now the core wants to expand to its original length, and the tube wants to return to its original length, but they are now joined as a single assembly and the individual components cannot move. The tube has extended relative to its original length so it is subjected to tensile residual stresses. The core has been compressed relative to its original length so it is subjected to compressive residual stresses. Even though there is no external load on the assembly it has a tensile stress at its surface and a compressive stress in its core (Fig. 13.41*c*). Because the areas of tube and core are equal, the stresses are equal and uniform in each region. The residual stress system existing in the assembly after reaching its final state (c) must be in static equilibrium. Thus, the total force acting on any plane through the body and the total moment of forces on any plane must be zero. For the longitudinal stress pattern in Fig. 13.41 this means that the area subjected to compressive residual stresses must balance the area subjected to tensile residual stresses.

The situation regarding residual stress generation is not quite so simple as is pictured in Fig. 13.41. Often residual stresses in deformation processes arise from having regions of heavy plastic deformation contiguous to regions of light deformation. The boundaries between these regions are not as simple nor are the volumes of the regions the same as in the previous example, but the results are the same. Regions of the part that have been required to deform in tension will upon unloading develop compressive residual stresses, and vice versa. In some cases the residual stresses acting in the three principal directions need to be known. The state of residual stress at any point is a combined stress derived from the residual stresses in the three principal directions. Frequently, because of symmetry, only the residual stress in one direction need be considered. A complete determination of the state of residual stress in three dimensions is a considerable undertaking.

Residual stresses cannot exceed the value of the yield stress of the material. A stress in excess of that value, with no external force to oppose it, will relieve itself by plastic deformation until it reaches the value of the yield stress. Residual stress and stresses from applied forces add algebraically, so long as their sum does not exceed the yield stress of the material. For example, if the maximum applied stress due to applied loads is 60,000 psi tension and the part already contains a tensile residual stress of 40,000 psi, the total stress at the critically stressed region is 100,000 psi. However if the residual stress is a compressive 40,000 psi produced by shot peening, then the actual stress is 20,000 psi.

In Fig. 13.41, if the weld holding together the two components was machined away, each component would be free to assume its original length. The assembly would undergo distortion from its intended shape. The same thing happens in parts with more complex residual stress distributions. If they are machined, removing material alters the residual stress distribution and the new balance of forces may cause distortion of the part.

Any process, whether mechanical, thermal, or chemical, that produces a permanent nonuniform change in shape or volume creates a residual stress pattern. Practically, all cold-working operations develop residual stresses because of nonuniform plastic flow. In surface-working operations, such as shot peening, surface rolling, or polishing, the penetration of the deformation is very shallow. The distended surface layer is held in compression by the less-worked interior.

A surface compressive residual stress pattern is highly effective in reducing the incidence of fatigue failure.

Residual stresses arising from thermal processes may be classified as those due to a thermal gradient alone or to a thermal gradient in conjunction with a phase transformation, as in heat-treating steel. These stresses arise most frequently in quenching during heat treatment, or in heating and cooling experienced in casting and welding.

The control of residual stresses starts with understanding the fundamental source of the stress and identifying the parameters in the manufacturing process that influence the stress. Then, experiments are performed in varying the process parameters to produce the desired level of stress. FEA modeling has been used effectively in predicting how residual stresses can be reduced.[68]

13.16.2 Residual Stress Created by Quenching

The case of greatest practical interest involves the residual stresses developed during the quenching of steel for hardening. The residual stress pattern created is due to thermal volume changes plus volume changes resulting from the transformation of austenite to martensite. The simpler situation, in which the stresses are due only to thermal volume changes, will be considered first. This is the situation encountered in the quenching of a metal that does not undergo a phase change on cooling, like copper. This condition is also present when steel is quenched from a tempering temperature below the A_1 critical temperature.

The distribution of residual stress over the diameter of a quenched bar in the longitudinal, tangential, and radial directions is shown in Fig. 13.42*a* for the most common situation of a metal that contracts on cooling. Figure 13.42*c* shows that the opposite residual stress distribution is obtained if the metal expands on cooling (this occurs for only a few materials). The sequence of events producing the stress pattern shown in Fig. 13.42*a* is as follows: The relatively cool surface of the bar tends to contract into a ring that is both shorter and smaller in diameter than it was originally. This tends to extrude the hotter, more plastic center into a cylinder that is longer and thinner than it was originally. If the inner core were free to change shape independently of the outer region of the bar, it would change dimensions to a shorter and thinner cylinder on cooling. Mechanics of materials principles require that continuity must be maintained throughout the bar. Thus, the outer ring is drawn in (compressed) in the longitudinal, tangential, and radial directions at the same time the inner core is extended in the same directions. The stress pattern shown in Fig. 13.42*a* results.

The magnitude of the residual stresses produced by quenching depends on the stress-strain relationship for the metal and the degree of strain mismatch produced by the quenching operation. For a given strain mismatch, the higher the elastic modulus of the metal the higher the residual stress. Further, since the residual stress cannot exceed the yield stress, the higher the yield stress the higher the possible residual stress. The yield stress–temperature curve for the metal also is important. If the yield stress

68. U. Chandra, op. cit.

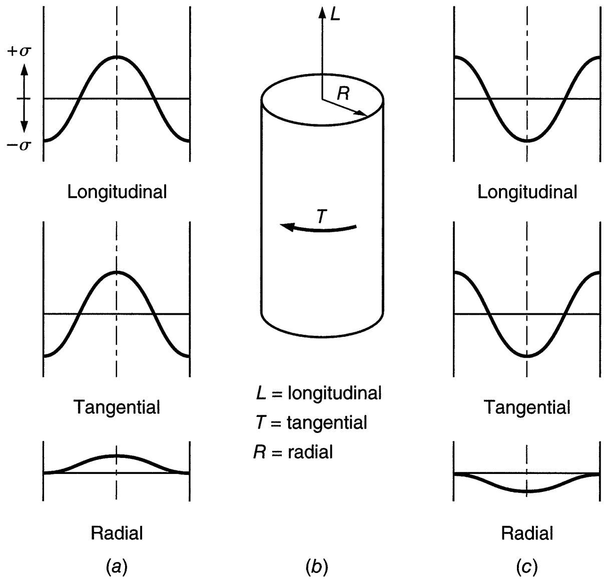

FIGURE 13.42
Residual stress patterns found in quenched bars and due to thermal strains (schematic). (a) For metal that contracts on cooling; (b) orientation of directions; (c) for metal that expands on cooling.

decreases rapidly with increasing temperature, the strain mismatch will be small at high temperatures because the metal can accommodate to thermally produced volume changes by plastic flow. Metals that have a high yield strength at elevated temperatures, like nickel base superalloys, will develop strain mismatches in quenching, leading to high residual stresses.

The following physical properties will lead to high mismatch strains on quenching:

- Low thermal conductivity, k
- High specific heat, c
- High density, ρ
- High coefficient of thermal expansion, α

The first three factors can be combined into the thermal diffusivity $D = k/\rho c$. Low values of thermal diffusivity lead to high strain mismatch. Other process conditions that produce an increase in the temperature difference between the surface and center of the bar promote high quenching stresses. They are (1) a large diameter of the cylinder, (2) a large temperature difference between the initial temperature and the temperature of the quenching bath, and (3) rapid heat transfer at the metal-liquid interface.

In the quenching of steels, austenite (the high-temperature form of steel) begins to transform to martensite whenever the local temperature of the bar reaches the M_s temperature. Since an increase in volume accompanies the phase transformation,

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the metal expands as the martensite reaction proceeds on cooling from the M_s to M_f temperature.[69] This produces a residual stress distribution of the type shown in Fig. 13.42*c*. The residual stress distribution in a quenched steel bar is the resultant of the competing processes of thermal contraction and volume expansion due to martensite formation. The resulting stress pattern depends upon the transformation characteristics of the steel, as determined chiefly by composition and hardenability,[70] the heat-transfer characteristics of the system, and the severity of the quench.

Figure 13.43 illustrates some of the possible residual stress patterns that can be produced by quenching steel bars. On the left side of the figure is an isothermal transformation diagram for the decomposition of austenite. To form martensite the bar must cool fast enough to avoid entering the area where soft pearlite forms. The cooling rates of the outside, midradius, and center of the bar are indicated on the diagram by the curves marked *o*, *m*, and *c*. In Fig. 13.43*a* the quenching rate is rapid enough to convert the entire bar to martensite. By the time the center of the bar reaches the M_s temperature, the transformation has been essentially completed at the surface. The surface layers try to contract against the expanding central core, and the result is tensile residual stresses at the surface and compressive stresses at the center of the bar (Fig. 13.43*b*). However, if the bar diameter is rather small and the bar has been drastically quenched in brine so that the surface and center transform at about the same time, the surface will arrive at room temperature with compressive residual stresses. If the bar is slack-quenched so that the outside transforms to martensite while the middle and center transform to pearlite (Fig. 13.43*c*), there is little restraint offered by the hot, soft core during the time when martensite is forming on the surface, and the core readily accommodates to the expansion of the outer layers. The middle and center pearlite regions then contract on cooling in the usual manner and produce a residual stress pattern consisting of compression on the surface and tension at the center (Fig. 13.43*d*).

13.16.3 Other Issues Regarding Residual Stresses

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The two previous sections were concerned with residual stresses produced by inhomogeneous plastic deformation due to mechanical forces or constraints, due to thermal expansion, or due to volume changes as a result of solid-state transformations. In this section we briefly discuss several additional important issues about residual stresses.

- The residual stresses in castings are often modeled by a quenched cylinder. However, the situation in castings is made more complicated by the fact that the mold acts as a mechanical restraint to the shrinking casting. Moreover, the casting design may produce greatly different cooling rates at different locations that are due to variations in section size and the introduction of chills. Chills are metal plates added to a sand mold to produce an artificially rapid cooling rate.

69. M_s and M_f are the temperatures at which martensite starts to form and finishes forming, respectively, on quenching.
70. Hardenability is an engineering measurement of the depth of hardening in a steel as a result of quenching into a specific medium.

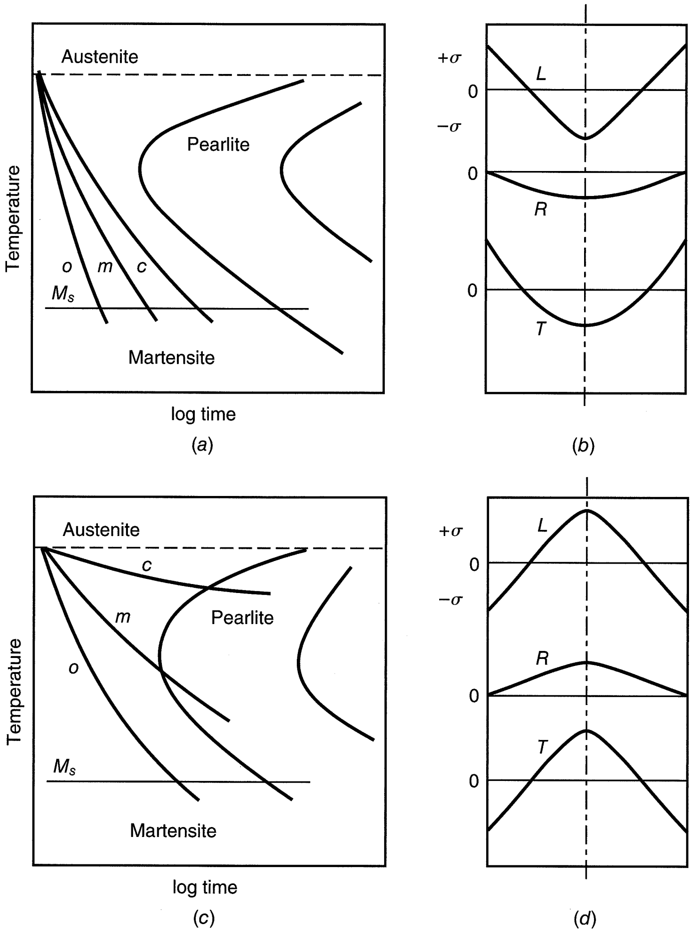

FIGURE 13.43
Transformation characteristics of a steel (a and c), and resulting residual stress distributions (b and d).

- Appreciable residual stresses are developed in welding, even in the absence of a phase transformation. As the weld metal and heat-affected zone shrink on cooling, they are restricted by the cooler surrounding plate. The result is that the weld region contains tensile residual stresses, which are balanced by compressive stresses in a region of the plate outside of the heat-affected zone. Because thermal gradients tend to be high in welding, the residual stress gradients also tend to be high. Residual stresses in welds are often involved in weld cracking.
- Chemical processes such as oxidation, corrosion, and electroplating can generate large surface residual stresses if the new surface material retains coherency with the underlying metal surface. Other surface chemical treatments such as carburizing and nitriding cause local volume changes by the diffusion of an atomic species into the surface, and this can result in residual stresses.

Residual stresses are measured by either destructive or nondestructive testing methods.[71] The destructive methods relax the locked-in stress by removing a layer from the body. The stress existing before the cut was made is calculated from the deformation produced by relaxing the stress. The nondestructive method depends on the fact that the spacing of atomic planes in a crystalline material is altered by stress. This change can be measured very precisely with a diffracted x-ray beam. The x-ray method is nondestructive, but it gives only the value of residual surface stress.

13.16.4 Relief of Residual Stresses

The removal or reduction in the intensity of residual stress is known as *stress relief.* Stress relief may be accomplished either by heating or by mechanical working operations. Although residual stresses will disappear slowly at room temperature, the process is very greatly accelerated by heating to an elevated temperature. The stress relief that comes from a stress-relief anneal is due to two effects. First, since the residual stress cannot exceed the yield stress, plastic flow will reduce the residual stress to the value of the yield stress at the stress-relief temperature. Only the residual stress in excess of the yield stress at the stress-relief temperature can be eliminated by immediate plastic flow. Generally, most of the residual stress will be relieved by time-dependent creep or stress relaxation. Since the process is extremely temperature-dependent, the time for nearly complete elimination of stress can be greatly reduced by increasing the temperature. Often a compromise must be made between the use of a temperature high enough for the relief of stress in a reasonable length of time and annealing the effects of cold-working.

The differential strains that produce high residual stresses also can be eliminated by plastic deformation at room temperature., Products such as sheet, plate, and extrusions are often stretched several percent beyond their yield stress to relieve differential strains by yielding. In other cases the residual stress distribution that is characteristic of a particular working operation may be superimposed on the residual stress pattern initially present in the material. A surface that contains tensile residual stresses may have the stress distribution converted into beneficial compressive stresses by a surface-working process like rolling or shot peening. However, it is important in using this method of stress relief to select surface-working conditions that will completely cancel the initial stress distribution. If only very light surface rolling were used on a surface that initially contained tensile stresses, only the tensile stresses at the surface would be reduced. Dangerously high tensile stresses could still exist below the surface.

13.17 DESIGN FOR HEAT TREATMENT

Heat treatment is widely used to change the metallurgical structure of a part and by this process improve its mechanical properties. Common heat treatment processes are described here.

71. A. A. Denton, *Met. Rev.,* Vol. 11, pp. 1–22, 1966; C. O. Ruud, *J. Metals,* pp. 35–40, July 1981.

- Annealing is heating a metal or alloy to an elevated temperature, holding at temperature for enough time to allow a desired metallurgical change to occur, and then cooling slowly to room temperature. It is used to relieve residual stresses, to homogenize a cast structure so that chemical segregation is minimized, or to remove the hardening effects of cold working and through the generation of new strain-free grains (recrystallization) create a structure that has adequate ductility to allow additional working.
- Quenching of steels to produce hard but brittle martensite has been described in the previous section. Quenching must be followed by heating below the transformation temperature (A_1) to temper the martensite into a precipitation of fine carbides. Quenched and tempered (Q&T) steels are the engineering materials with the best combination of readily achievable strength and toughness.
- Many nonferrous alloys, especially aluminum alloys, are strengthened by first heating to solution treatment temperature to put the alloying elements into solid solution, and then cooling rapidly to an aging temperature. The alloy is held (aged) for a sufficient time to allow the formation of a fine precipitate that hardens the alloy.

13.17.1 Issues with Heat Treatment

Processing by heat treatment requires energy. It also requires a protective atmosphere or surface coating on the metal to prevent the part from oxidizing or otherwise reacting with the furnace atmosphere. During long exposure at elevated temperatures, metal parts soften, creep, and eventually sag. Therefore, parts may require special fixtures to support them during heat treatment. Since heat treatment is a secondary processing step, it would be advantageous to eliminate the need whenever possible. Sometimes a part made from a cold-worked sheet or bar can be substituted for a heat-treated part to achieve the needed strength properties. Usually the flexibility and/or superior properties that result from heat treatment make it the preferred choice in manufacturing.

The best combination of high strength and high toughness is produced in a steel by first heating within the austenite temperature region (1400 to 1650°F) and then quenching rapidly enough that hard and brittle martensite is formed (see Fig. 13.43). The part is then reheated below the austenite region to allow the martensite to break down (temper) into a fine precipitation of carbides in a soft ferrite (iron) matrix. Achieving a proper quenched and tempered microstructure depends on cooling fast enough that pearlite or other nonmartensitic phases are not formed. This requires a balance between the heat transfer from the part (as determined chiefly by geometry), the cooling power of the quenching medium (brine, water, oil, or air), and the transformation kinetics of the steel (as controlled by the alloy chemistry). These factors are interrelated by the property called hardenability.[72]

In heating for austenitization, care should be taken to subject the parts to uniform temperature in the furnace. Long, thin parts are especially prone to distortion from

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72. *ASM Handbook,* Vol. 4, *Heat Treating,* ASM International, Materials Park, OH, 1991; C. A. Siebert, D. V. Doane, and D. H. Breen, *The Hardenability of Steels,* ASM International, Materials Park, OH, 1977.

nonuniform temperature. Parts containing residual stress from previous processing operations may distort on heating as the residual stresses are partially relieved.

Quenching is a severe treatment to impose upon a piece of steel.[73] In quenching, the part is suddenly cooled at the surface. The part must shrink rapidly because of thermal contraction (steel is at least 0.125 in. per ft larger before quenching from the austenitizing temperature), but it also undergoes a volume increase when it transforms to martensite at a comparatively low temperature. As discussed in Sec. 13.16.2 and shown in Fig. 13.43, this heat treatment can produce high residual stresses on the surface. Locally concentrated tensile stresses may be high enough to produce fractures called *quench cracks*. Local plastic deformation can occur in quenching even if cracks do not form, and that causes warping and distortion.

Problems with quench cracks and distortion are chiefly caused by nonuniformity of temperature distribution that result from part geometry as influenced by the design. Thus, many heat-treatment problems can be prevented by proper design. The most important guideline is to make the cross sections of the part as uniform as possible. In the ideal design for heat treatment, all sections should have equal ability to absorb or give up heat. Unfortunately, designing for uniform thickness or sectional area usually interferes with the functions of the design. A sphere is the ideal geometry for uniform heat transmission, but obviously only a limited number of parts can utilize this shape.

13.17.2 DFM for Heat Treatment

Design details that minimize stress concentrations to prevent fatigue also are good design practices to minimize quench cracking. Distortion in heat treatment is minimized by designs that are symmetrical. A single keyway in a shaft is a particularly difficult design feature to deal with in quenching. A part with a special distortion problem may have to be quenched in a special fixture that restrains it from distorting beyond the tolerance limits. Another guideline is to so design the part that the quenching fluid has access to all critical regions that must be hardened. Since the quenching fluid produces a vapor blanket when it hits the hot steel surface, it may be necessary to design for special venting or access holes for the quenching fluid.

SYSWELD is a design simulation software for heat treatment and welding.[74] This software assists with the steel selection and choice of the quenching media. It uses hardenability calculations to determine what the hardness distribution will be in the part. The software will also determine whether the risk of cracking is acceptable and whether distortion is within acceptable limits. It also evaluates whether compressive residual stresses are high enough and properly located in the part.

The welding simulator, which is part of the SYSWELD suite of software, uses the same FEA methods to analyze the part design for residual stresses. The simulation software provides visualization of distortion as determined by joint design, welding conditions, and the metallurgical transformations of the particular steel.

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73. A. J. Fletcher, *Thermal Stress and Strain Generation in Heat Treatment,* Elsevier Applied Science, New York, 1989.
74. See esi-group.com.

13.18
DESIGN FOR PLASTICS PROCESSING

The manufacturing processes used with plastics must accommodate to the unique flow properties of polymers. Compared to metals, the flow stress of a plastic part is much lower and highly strain rate dependent, the viscosity is much higher than liquid metal, and the formability is much greater. See Sec. 12.6 for a discussion of how the properties of plastics affect their use in design. Plastics divide broadly into (1) thermoplastic polymers (TP) that soften on heating and harden when cooled and can be remelted repeatedly; (2) thermosetting polymers (TS) that set or cross-link upon heating in an irreversible way; and (3) polymer composites that have either a TS or TP matrix reinforced with fibers of glass or graphite. TP polymers are polymerized in their primary manufacturing step and enter plastics processing as a granule or pellet resin. TS polymers are polymerized during the processing step, usually by the addition of a catalyst or simply by the addition of heat.

The plastic manufacturing processes considered in this section are:

- Injection molding (mostly TP)
- Extrusion (TP)
- Blow molding (TP)
- Rotational molding (TP)
- Thermoforming (TP)
- Compression molding (mostly TS)
- Casting (mostly TS)
- Composite processing (mostly TS)

Plastic manufacturing processes excel in producing parts with good surface finish and fine detail.[75] By adding dyes and colorants, the part can be given a color that eliminates a secondary painting operation. However, the cycle time is usually longer than for metal-working processes. Depending on the plastic process, the cycle time can vary from 10 s to 10 h. Generally plastics manufacturing is the preferred method for producing small- to medium-sized parts for consumer and electronic products where mechanical stresses in parts are not too high.

13.18.1 Injection Molding

Injection molding is a process in which plastic granules are heated and forced under pressure into a die cavity (see Fig. 13.3). It is a fast process (10 to 60 s cycle time) that is economical for production runs in excess of 10,000 parts. It is well suited for

75. *Tool and Manufacturing Engineers Handbook,* Vol. 8, *Plastic Part Manufacturing,* Society of Manufacturing Engineers, Dearborn, MI, 1996; "Engineering Plastics," *Engineered Materials Handbook* Vol. 2, Sec. 3, ASM International, Materials Park, OH, 1988; E. A. Muccio, "Design for Plastics Processing," *ASM Handbook,* Vol. 20, pp. 793–803, 1997.

producing three-dimensional shapes that require fine details like holes, snaps, and surface details. It is the plastics analog to pressure die casting in metals.

Design of the gating and feed system for the die is crucial to ensure complete die fill.[76] As in design for casting, it is important to design the molding so that solidification does not prevent complete mold fill. The design and location of the gates for entry of polymer into the die is a crucial design detail. In large parts there may need to be more than one gate through which resin will flow in two or more streams into the mold. These will meet inside of the mold to create a fusion line. This may be a source of weakness or a surface blemish.

The mold must be designed so that the solid part can be ejected without distortion. Thus, the direction of mold closure, the parting surface between the two halves of the mold, and the part design must be considered concurrently. By proper consideration of part orientation in the mold it may be possible to avoid expensive mold costs like side cores. If at all possible, design the part so that it can be ejected in the direction of mold closure.

In addition to the economics of the process, the main DFM concerns involve the ability to achieve the required dimensional tolerances.[77] Mostly this deals with shrinkage, which is much larger in plastics than in metals As the polymer cools from a plastic melt to a solid, the volume decreases (the density increases). Different plastics show different amounts of shrinkage. To minimize shrinkage, fillers, like glass fiber, wood flour, or natural fibers, are added during molding. Shrinkage can also be influenced by the rate and direction of injecting the melt into the mold. It is best to have any shrinkage occur while the part is confined by the mold. However, with some plastics and part geometries, postmold shrinkage can occur. This is related to the generation of high residual stresses during the molding process and their gradual relief over hours, days, or weeks at room temperature. The creation of these residual stresses is a function of the mold design and the operating conditions of temperature and cooling rate during the process.

13.18.2 Extrusion

Extrusion is one of the few continuous plastic processes. It is carried out in a machine similar to an injection molding mahine. It is used to produce sheet (>0.010 in. thick), film, long lengths with a profiled cross section, and fiber. The chief DFM issues with the process are die swell and molecular orientation. In die swell the extrudate swells to a size greater than the die from which it just exited. Thus, the design must compensate for the swell. During extrusion, polymer molecules become highly oriented in one or two directions as a result of the strongly oriented flow inherent in the extrusion

76. Software to aid in mold design and provide practical advice on manufacturing constraints is available as an add-on module with most 3-D CAD software. The most common software is Moldflow (www.moldflow.com).
77. R. A. Malloy, *Plastic Part Design for Injection Molding,* Hanser Publishers, New York, 1994.

process. When molecular orientation is controlled, it can improve the properties of the material.

13.18.3 Blow Molding

Blow molding produces hollow products. A heated thermoplastic tube (called a parison) is held inside a mold and is expanded under air pressure to match the inner contour of the mold. The part cools, hardens, and is ejected from the mold. The process produces a part that is dimensionally defined on its external dimensions, but the interior surfaces are not controlled. Examples are milk bottles and automotive fuel tanks. The process does not lend itself to incorporating design details such as holes, sharp corners, or narrow ribs.

13.18.4 Rotational Molding

Like blow molding, rotational molding produces a hollow part. Rotational molding uses a fine TP powder that is placed inside a hollow, heated metal mold. The mold is slowly rotated about two perpendicular axes. Gravity rather than centrifugal force causes even coating of the mold surface. While still rotating, the mold is cooled and the part solidifies and hardens. Rotational molding can produce large parts, like tanks up to 500 gal capacity. Since it is a low-pressure process and the plastic is not forced through narrow channels, rotational molding does not induce a significant amount of residual stress. Therefore, parts made by rotational molding exhibit a high degree of dimensional stability.

13.18.5 Thermoforming

Thermoforming, or vacuum forming, is a sheet forming process in which a TP sheet is clamped to a mold and heated to soften it, and a vacuum is applied to draw the sheet into the contour of the mold. When the sheet cools, it will retain the shape of the mold. Traditionally, thermoforming is done with only a single mold, but for more precise control of dimensions, two matching mold halves are used, as is done in sheet metal forming.

13.18.6 Compression Molding

The oldest plastics process is compression molding. It is similar to powder metallurgy. A preform of polymer, usually TS, is placed in a heated mold cavity and a plunger applies pressure to force the polymer to fill the mold cavity. The plastic is allowed to cure and is then ejected from the mold. Because the amount of flow is much less than in injection molding or extrusion, the level of residual stress in the part is low.

A variation of compression molding is *transfer molding*. In this process the plastic is preheated in a transfer mold and then "shot" into the mold as a viscous liquid with a transfer ram. The ram holds the plastic under pressure until it begins to cure. Then the ram retracts, and the part completes its cure cycle and is ejected. Compression molding has a cycle time of 40 to 300 s, while for transfer molding the cycle time is 30 to 150 s. Also, because a liquid plastic enters the mold in transfer molding it is possible to mold in inserts or to encapsulate parts. However, parts made this way have sprues and runners which must be trimmed and which result in lower yield of material.

13.18.7 Casting

Plastics are cast much less frequently than metals. The oldest applications are the casting of sheets and rods of acrylics and the "potting" of electrical components in epoxy. The development of a wider range of casting resins has led to consideration of casting as a way to make prototypes and low-volume production parts. Casting produces parts with low residual stress and a high degree of dimensional stability. Because of the high viscosity (low fluidity) of polymers it is difficult to fill molds by gravity alone and get fine detail without applying pressure, as in injection molding.

13.18.8 Composite Processing

The most common composite materials are plastics reinforced with glass, metal, or carbon fibers.[78] The reinforcement may be in the form of long, continuous filaments, short fibers, or flakes. TS polymers are the most common matrix materials. Except for filament winding, as in making a rocket motor case, the fiber and the matrix are combined in some preliminary form prior to processing. Molding compounds consist of TS resin with short, randomly dispersed fibers. Sheet molding compound (SMC) is a combination of TS resin and chopped fibers rolled into a sheet about 1/4 in. thick. Bulk molding compound (BMC) consists of the same ingredients made in billet form instead of sheet. SMC is used in the lay up of large structures. BMC is used in compression molding. Prepreg consists of long fibers in partially cured TS resin. Prepregs are available as tape or cross-plied sheets or fabrics.

Composites are made by either open-mold or closed-mold processes. In hand layups, successive layers of resin and fiber are applied to the mold by hand, with the resin being rolled into the fiber. An alternative is an open-mold process in which the liquid resin and chopped glass fibers are sprayed into the surface of the mold. In bag molding, a plastic sheet or elastomer bag is clamped over the mold and pressure is applied either by drawing a vacuum or with compressed air.

Closed-mold composite processing closely follows the compression molding process. Variations have evolved to better place and orient the fibers in the composite. In

78. *ASM Handbook,* Vol. 21, *Composites,* ASM International, Materials Park, OH, 2001.

resin transfer molding (RTM) a glass preform or mat is placed in the mold and a TS resin is transferred into the cavity under moderate pressure to impregnate the mat.

13.18.9 DFM Guidelines for Plastics Processing

The issues of designing with plastics have been discussed in Sec. 12.6. These issues chiefly result from the lower strength and stiffness of polymers compared with metals. This limits plastic parts to applications where stresses are low, and to parts designed with many internal stiffening features. In considering DFM it must be recognized that (1) polymers have much higher coefficients of thermal expansion and (2) much lower thermal conductivity than metals. The first issue means that molds must be carefully designed to achieve tight tolerances. The second issue means that because of slower heat conduction, the time for the part to cool from the melt to a solid object that can be ejected from the mold is too long to result in a desirably short cycle time. This drives the design for many plastic parts to have thin walls, usually less than 10 mm.

Since many of the design for manufacturing guidelines are common to all plastics processes, we have consolidated them here.

- The wall is the most important design feature of the plastic part. The wall thickness should not vary greatly within the part. The nominal wall thickness will vary from about 4 to 30 mm depending on the process and the plastic. The rate of change of the thickness of the nominal wall should be gradual to ensure mold filling. Avoid thick walls. They require more plastic, but more importantly, they reduce the cycle time by requiring longer time until the part is rigid enough to be ejected from the mold.
- The typical projections from the inside surface of a molded wall are ribs, webs, and bosses. Ribs and webs are used to increase stiffness rather than increasing wall thickness. A *rib* is a piece of reinforcing material between two other features that are more or less perpendicular. A *web* is a piece of bracing material between two features that are more or less parallel. A *boss* is a short block of material protruding from a wall which is used to drive a screw through or to support something in the design. Ribs should be made slightly thinner than the walls they reinforce in order to avoid sink marks (depressions) on the outside wall.
- It is important to design into a part as many features (e.g., holes, countersinks to receive fasteners, snap fits, and living hinges) as are needed rather than adding them as secondary operations. A big part of the attractiveness of plastic manufacture is that it minimizes the need for secondary operations.
- Part design and process selection affect the residual stresses formed in the part. These stresses arise from inhomogeneous flow as the polymer molecules flow through the passages of the mold. Generous radii, higher melt temperatures (which result in longer cycle time), and processes which minimize polymer flow result in lower residual stresses. Lower residual stresses lead to better dimensional stability.
- Plastic parts are often used in consumer products where appearance is of great importance. An attractive feature of plastics is that they can be colored by adding color concentrates when compounding the polymer resin. The surface roughness of a molded part will reproduce the surface finish of the mold. By etching the surface

of the mold, letters or logos that protrude about 0.01 mm above the surface of the part can be produced. It is much more expensive to mold depressed letters on the part, and this should be avoided if possible.

- As in forging and casting, the parting line should be chosen to avoid unnecessary complexity of the mold. Perfect mating of the parting surfaces is difficult to achieve when they are not flat. This results in a small flash all of the way around the perimeter of the part. If the flash is small due to good placement of the parting line it may be removed by tumbling, rather than a more expensive machining process. Avoid undercuts since they will require expensive movable inserts and cores.
- Tight radii can be molded but generous radii allow for better polymer flow, longer mold life, and lower stress concentrations. The minimum radii should be 1 to 1.5 mm. However, large radii lead to hot spots and sinks.
- Molded parts require a taper (draft angle) to remove the parts. The draft on exterior surfaces is a modest 0.5 to 2 degrees, with larger allowance on ribs and bosses.
- Metal inserts are often molded in plastic parts to provide functions such as screw attachments or electrical binding posts. The flow in these regions of the mold must be carefully designed to prevent weld lines. A *weld line* is formed when the fronts of two or more melt streams meet each other and fail to achieve complete intermolecular penetration. Often there is air trapped by the meeting of the flow streams. This reduces the mechanical properties in the region and affects the appearance of the surface of the part. Since there is no adhesion between the surface of metals and plastics, it is important to provide mechanical locking features, like knurling, for metal inserts in plastics.

13.19 SUMMARY

This chapter completes the core theme of the book that design, materials selection, and processing are inseparable. Decisions concerning the manufacturing of parts should be made as early as possible in the design process-certainly in embodiment design. We recognize that there is a great deal of information that the designer needs to intelligently make these decisions. To aid in this the chapter provides:

- An overview of the most commonly used manufacturing processes, with emphasis on the factors that need to be considered in design for manufacture
- References to a carefully selected set of books and handbooks that will provide both in-depth understanding of how the processes work and detailed data needed for design
- An introduction to several simple methodologies for ranking manufacturing processes on a unit cost basis that can be used early in the design process
- Reference to some of the most widely used computer simulation tools for design for assembly and design for manufacturing

A material and a process for making a part must be chosen at the same time. The overall factor in deciding on the material and the manufacturing process is the cost to make a quality part. When making a decision on the material, the following factors must be considered:

- Material composition: grade of alloy or plastic
- Cost of material
- Form of material: bar, tube, wire, strip, plate, pellet, powder, etc.
- Size: dimensions and tolerance
- Heat-treated condition
- Directionality of mechanical properties (anisotropy)
- Quality level: control of impurities, inclusions, cracks, microstructure, etc.
- Ease of manufacture: workability, weldability, machinability, etc.
- Ease of recycling

The decision on the manufacturing process will be based on the following factors:

- Unit cost of manufacture
- Life cycle cost per unit
- Quantity of parts required
- Complexity of the part, with respect to shape, features, and size
- Compatibility of the process for use with candidate materials
- Ability to consistently make a defect-free part
- Economically achievable surface finish
- Economically achievable dimensional accuracy and tolerances
- Availability of equipment
- Lead time for delivery of tooling
- Make-buy decision. Should we make the part in-house or purchase from a supplier?

Design can decisively influence manufacturing cost. That is why we must adopt methods to bring manufacturing knowledge into the embodiment design. An integrated product design team that contains experienced manufacturing people is a very good way of doing this. Design for manufacture guidelines is another way. Some general DFM guidelines are:

- Minimize total number of parts in a design.
- Standardize components.
- Use common parts across product lines.
- Design parts to be multifunctional.
- Design parts for ease of manufacture.
- Avoid too-tight tolerances.
- Avoid secondary manufacturing and finishing operations.
- Utilize the special characteristics of a process.

Experience has shown that a good way to proceed with DFM is to first do a rigorous design for assembly (DFA) analysis in an attempt to reduce part count. This will trigger a process of critical examination that can be followed up by what-if exercises on critical parts to drive down manufacturing cost. Use manufacturing simulation software to guide part design in improving parts for ease of manufacture and reducing tooling costs.

NEW TERMS AND CONCEPTS

Batch flow process
Blanking
Continuous flow process
Deep drawing
Design for assembly (DFA)
Design for manufacturing (DFM)
Economic batch size
Feed motion in machining
Finishing process
Group technology
Heat affected zone (HAZ)
Job shop
Machinability
Mistake-proofing
Near net shape
Parting surface
Primary manufacturing process
Process cycle time
Process flexibility
Secondary manufacturing process
Shielded metal arc welding
Solidification
Tooling
Undercut

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The following websites will connect you with DFM guidelines for many processes: www.engineersedge.com/manufacturing_design.shtml and www.npd-solutions.com.

PROBLEMS AND EXERCISES

13.1 Classify the following manufacturing processes as to whether they are shape-replication or shape-generative:
(a) honing the bore of a cylinder,
(b) powder metallurgy gear,
(c) rough turning a cast roll,
(d) extrusion of vinyl house siding.