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Manufacturing Processes for Engineering Materials

SIXTH EDITION IN SI UNITS

Serope Kalpakjian • Steven R. Schmid

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Manufacturing Processes for Engineering Materials

SIXTH
EDITION
IN SI UNITS

Serope Kalpakjian
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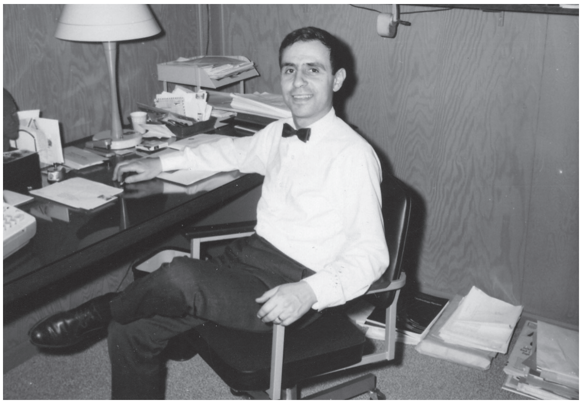

What can be said about Serope Kalpakjian?

He is a giant of manufacturing research, publishing, and education. ("But I am so small," he would say, "far too small to be a giant.")

He has written the world's most popular textbook for over three generations and has had more influence on training engineers than anyone. He has won the ASM and SME Gold Medals, indicating the high esteem that professional societies hold for him, yet he remains humble.

Universally beloved, Serope can work a room, whether it's filled with engineers, scientists, philosophers, or poets. (No one is perfect, he reminds us.) Everyone is his friend, just as he is everyone's friend.

He is a phenomenal speaker. I know of no other person that has been asked to give the commencement address at his own university. He was asked to give a Founder's Lecture at an NAMRC Conference, and told he could speak of whatever he wished: his life as a professor, his 40 years of writing, his decades of innovative teaching, his cutting-edge research; but he only had 30 minutes. ("30 minutes? I'll just speak slowly," he says.)

He is a devoted husband and father, interested and involved. His children and grandchildren have excelled in life—this is perhaps the greatest measure of man. ("I hated that he asked math questions at dinner," complains his daughter—a professor at the University of Michigan.) Always patient and caring, he excelled at advising students and mentoring faculty. Especially coauthors. Especially me. ("Book authors make much less than those that throw a ball for a living," he lamented.)

There are some people, unfortunately a very few, that you meet in your life that you treasure their company and realize that they are genuinely great; people that have a lasting influence on your life; people that are your life-long friends. There are some people that you can hold as a role-model and not be disappointed.

That's Serope.

Sincerely,
Steven Schmid

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Preface

Manufacturing has undergone a rebirth in its development and research activities since the mid-2000s. With the recognition that manufacturing adds value to national economies, governments around the world have been investing in their infrastructure, and are now partnering with industry to bring new manufacturing capabilities to the marketplace.

In view of the advances made in all aspects of manufacturing, the authors have continued to present comprehensive, balanced and, most importantly, up-to-date coverage of the science, engineering, and technology of manufacturing processes and operations. As in the previous editions, this text maintains the same number of chapters while continuing to emphasize the interdisciplinary nature of all manufacturing activities, including the complex interactions among materials, design, and manufacturing processes.

Every attempt has been made to motivate and challenge students to understand and develop an appreciation of the vital importance of manufacturing in the modern global economy. The extensive questions and problems, at the end of each chapter, are designed to encourage students to explore viable solutions to a wide variety of challenges, giving them an opportunity to assess the capabilities as well as limitations of all manufacturing processes and operations. These challenges include economic considerations and the competitive aspects in a global marketplace. The numerous examples and case studies throughout the book also help give students a perspective on the real-world applications of the topics described in the book.

What's New in This Edition

- The text has been thoroughly *updated* with numerous new materials and illustrations relevant to all aspects of manufacturing.
- A major addition to this revised text is the introduction of *QR codes*. Recognizing the proliferation of smart phones and tablets, and the inherent Internet browsing capability in these devices, there are QR codes that provide a readily available video insight into real manufacturing operations. (Please note that users must download a QR code reader on their smart device; data and roaming charges may also apply.)
- Each chapter now begins with a *list of variables* for the topics covered in that chapter.
- Wherever appropriate, *illustrations and examples* have been replaced to indicate *recent advances* in manufacturing.
- The text contains more cross-references to other relevant sections, tables, and illustrations in the book.
- The Questions, Problems, and Design problems at the end of each chapter have been significantly *expanded*.

- The *Bibliographies* at the end of each chapter have been thoroughly *updated*.
- A *Solutions Manual*, available for use by instructors, has been expanded; it now provides *MATLAB code* for numerous problems, allowing instructors to easily change the relevant parameters.

The following are the new or expanded topics in this edition:

Chapter	Topics
1	Economic multiplier; technology readiness level; a case study on three-dimensional printing of guitars; expansion of general trends in manufacturing.
2	Leeb hardness test; expansion of flow stress description.
3	Advanced high-strength steels; third generation steels; expansion of discussion on magnesium, chromium, and rare-earth metals.
4	Environmental-friendly lubricants; validation of products and processes.
5	Strip casting; mold ablation; design of ribs in castings; computer modeling of casting; a case study.
6	Servo presses; electrically assisted forging; the Hall–Héroult process; a case study on the production of aluminum foil.
7	Single-point incremental forming; age forming; hot stamping.
8	Expansion of tool-condition monitoring; through the cutting-tool cooling.
9	Expansion of laser machining; blue-arc machining; laser micro-jet; hybrid machining systems.
10	Electrically conductive polymers; big-area additive manufacturing; laser-engineered net shaping; friction stir modeling; the Maker Movement; design for additive manufacturing.
11	Expansion of metal injection molding; dynamic compaction of powders; combustion synthesis; pseudo-isostatic pressing; roll densification; graphene.
12	Expansion of friction welding; a case study on Blisks.
13	Wafer-scale integration; three-dimensional circuits; clean rooms; immersion lithography; pitch splitting; chip on board; system-in-package; roll-to-roll printing, including silver nanoparticles, inks, inkjet printing, gravure, flexographic, and screen printing; the MolTun process; photonic integrated circuits.
14	Intelligent robots and cobots; smart sensors; sensor validation.
15	ERP, ERP-II, and MES; manufacturing cell design; expansion of lean manufacturing; developments in communications; the Internet of Things; Big Data; cloud storage; cloud computing.
16	Energy consumption in manufacturing; process energy demand and effects of workpiece materials.

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Among other awards, Professor Kalpakjian has received the Forging Industry Educational and Research Foundation Best Paper Award, the Excellence in Teaching Award from lIT, the ASME Centennial Medallion, the International Education Award from SME, A Person of the Millennium Award from lIT; the Albert Easton White Outstanding Teacher Award from ASM International, and the 2016 SME Gold Medal. The Outstanding Young Manufacturing Engineer Award, by SME, in 2001, was named after him. Professor Kalpakjian is a Life Fellow ASME, Fellow SME, Fellow and Life Member ASM International, Fellow Emeritus the International Academy for Production Engineering (CIRP), and is a founding member and past president of NAMRI. He is a graduate of Robert College (High Honor, Istanbul), Harvard University, and the Massachusetts Institute of Technology.

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Professor Schmid served as the President of the North American Manufacturing Research Institution (NAMRI, 2015–2016) and was appointed the first Academic Fellow at the Advanced Manufacturing National Program Office, US Department of Commerce, where he helped design the National Network for Manufacturing Innovation. Starting in 2016, he will serve as the Program Director for the Manufacturing Machines and Equipment program at the National Science Foundation. Dr. Schmid is the author of over 140 technical papers, and has co-authored the texts *Fundamentals of Machine Elements*, *Fundamentals of Fluid Film Lubrication*, and *Manufacturing Engineering and Technology*.

CHAPTER 1

Introduction

CASE STUDIES:

The objectives of this chapter are:

- Define manufacturing and describe the technical and economic considerations involved in manufacturing successful products.
- Explain the relationships among product design and engineering and factors such as materials and processes selection and the various costs involved.
- Describe the important trends in modern manufacturing and how they can be utilized in a highly competitive global marketplace to minimize production costs.

1.1 What Is Manufacturing?

As you read this Introduction, take a few moments to inspect various objects around you: pencil, paper clip, laptop computer, bicycle, and smartphone. You will note that these objects have been transformed from various raw materials into individual parts and then assembled into specific products. Some objects, such as nails, bolts, and paper clips, are made of one material; the vast majority of products are, however, made of numerous parts from a wide variety of materials (Fig. 1.1). A ball-point pen, for example, consists of about a dozen parts, a lawn mower about 300 parts, a grand piano about 12,000 parts, a typical automobile about 15,000 parts, and a Boeing 787 about 2.3 million parts. All are produced by a combination of processes, called manufacturing.

Manufacturing is the process of converting raw materials into products; it encompasses the design and manufacturing of goods using various production methods and techniques. Manufacturing began during 5000 to 4000 B.C. with the production of various articles, such as pottery, knives and tools, from wood, clay, stone, and metal (Table 1.1). The word *manufacturing* is derived from the Latin *manu* and *factus*, meaning made by hand; the word *manufacture* first appeared in 1567, and the word *manufacturing*, in 1683. The word **production** is also used interchangeably with the word manufacturing.

FIGURE 1.1 John Deere tractor showing the variety of materials and processes incorporated. *Source:* Shutterstock/Nils Versemann.

Manufacturing may produce *discrete products*, meaning individual parts, such as nails, rivets, bolts, and steel balls. On the other hand, wire, sheet metal, tubing, and pipe are *continuous products*, that may then be cut into individual pieces and thus become discrete products.

Because a manufactured item has undergone a number of changes whereby raw material has become a specific and useful product, it has **added value**, defined by its monetary worth. Clay, for example, has a certain value as mined; when the clay is used to make a ceramic dinner plate, a cutting tool, or an electrical insulator, value is added to the clay. Similarly, a wire coat hanger has added value over and above the cost of a piece of wire from which it is made.

Manufacturing is extremely important for national and global economies. Consider Fig. 1.2, which shows the economic multiplier of different sectors in the US economy. The economic multiplier indicates the amount of general activity in the economy generated from one dollar of activity in a given sector. Note that manufacturing has a multiplier over 1.5, and that it is higher than any other sector in the economy. This high economic multiplier has a number of implications, including:

1. The wealth of a country is closely tied to the level of its manufacturing activity, especially in advanced manufacturing or high value-added processes.

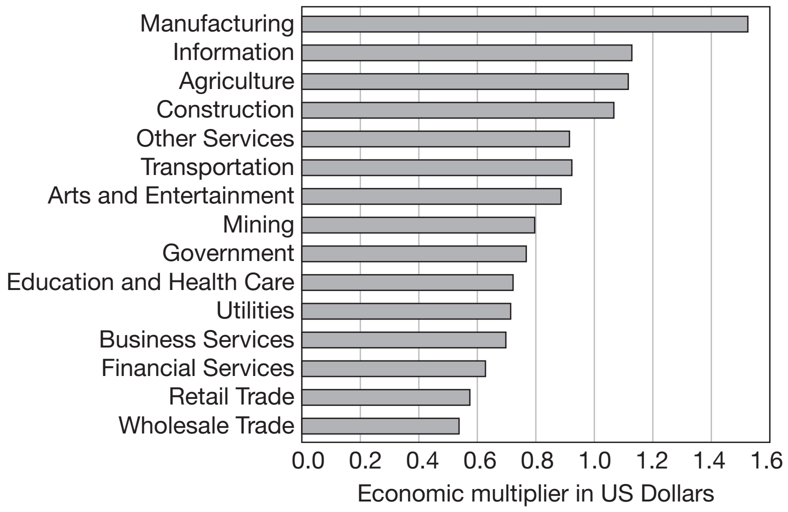

FIGURE 1.2 Economic multiplier for different sectors of the US Economy. *Source:* US Dept. of Commerce.

2. Although the emergence of global economies is often perceived as detrimental in the media, global trading leads to an increase in the wealth of each participating nation, due to the economic multiplier effect. However, to take advantage of this multiplier, a vibrant manufacturing sector is essential.
3. Nations with large Gross Domestic Product (GDP) growth have their economic activity concentrated on high value-added products, such as automobiles, airplanes, medical devices, computers, electronics, and various machinery. Other products, such as clothing, toys, and hand-held tools, are labor-intensive and thus are generally concentrated in countries where labor rates are lower.
4. Nations where labor rates are high can still compete by the application of automation and by continuous improvements in worker productivity.

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

1. A product must fully meet **design requirements**, **specifications**, and **standards**.
2. It must be manufactured by the most **economical** and **environmentally friendly** methods.
3. **Quality** must be **built into the product** at each stage, from design to assembly, rather than relying on quality testing after the product is made.
4. In a highly competitive and global environment, production methods must be sufficiently **flexible** to respond to constantly changing market demands, types of products, production rates and quantities, and **on-time delivery** to the customer.

TABLE I.1 Historical development of materials and manufacturing processes.

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
Egypt: ~ 3100 B.C. to ~ 300 B.C. Greece: ~ 1100 B.C. to ~ 146 B.C. Roman Empire: ~ 500 B.C. to 476 A.D.	Before 4000 B.C.	Gold, copper, meteoric iron	Earthenware, glazing, natural fibers	Hammering		Tools of stone, flint, wood, bone, ivory, composite tools
	4000–3000 B.C.	Copper casting, stone and metal molds, lost-wax process, silver, lead, tin, bronze		Stamping, jewelry	Soldering (Cu-Au, Cu-Pb, Pb-Sn)	Corundum (alumina, emery)
	3000–2000 B.C.	Bronze casting and drawing, gold leaf	Glass beads, potter's wheel, glass vessels	Wire by slitting sheet metal	Riveting, brazing	Hoe making, hammered axes, tools for ironmaking and carpentry
	2000–1000 B.C.	Wrought iron, brass				
	1000–1 B.C.	Cast iron, cast steel	Glass pressing and blowing	Stamping of coins	Forge welding of iron and steel, gluing	Improved chisels, saws, files, woodworking lathes
Middle Ages: ~ 476 to 1492 Renaissance: 14th to 16th centuries	1–1000 A.D.	Zinc, steel	Venetian glass	Armor, coining, forging, steel swords		Etching of armor
	1000–1500	Blast furnace, type metals, casting of bells, pewter	Crystal glass	Wire drawing, gold- and silversmith work		Sandpaper, windmill-driven saw
	1500–1600	Cast-iron cannon, tinplate	Cast plate glass, flint glass	Water power for metalworking, rolling mill for coinage strips		Hand lathe for wood
	1600–1700	Permanent-mold casting, brass from copper and metallic zinc	Porcelain	Rolling (lead, gold, silver), shape rolling (lead)		Boring, turning, screw-cutting lathe, drill press

Industrial Revolution: ~ 1750 to 1850	1700–1800	Malleable cast iron, crucible steel (iron bars and rods)		Extrusion (lead pipe), deep drawing, rolling		
WWI	1800–1900	Centrifugal casting, Bessemer process, electrolytic aluminum, nickel steel, babbitt, galvanized steel, powder metallurgy, open-hearth steel	Window glass from slit cylinder, light bulb, vulcanization, rubber processing, polyester, styrene, celluloid, rubber extrusion, molding	Steam hammer, steel rolling, seamless tube, steel-rail rolling, continuous rolling, electroplating		Shaping, milling, copying lathe for gunstocks, turret lathe, universal milling machine, vitrified grinding wheel
	1900–1920		Automatic bottle making, bakelite, borosilicate glass	Tube rolling, hot extrusion	Oxyacetylene; arc, electrical-resistance, and thermit welding	Geared lathe, automatic screw machine, hobbing, high-speed steel tools, aluminum oxide, and silicon carbide (synthetic)
	1920–1940	Die casting	Development of plastics, casting, molding, polyvinyl chloride, cellulose acetate, polyethylene, glass fibers	Tungsten wire from metal powder	Coated electrodes	Tungsten carbide, mass production, transfer machines
WWII	1940–1950	Lost-wax process for engineering parts	Acrylics, synthetic rubber, epoxies, photosensitive glass	Extrusion (steel), swaging, powder metals for engineering parts	Submerged arc welding	Phosphate conversion coatings, total quality control
	1950–1960	Ceramic mold, nodular iron, semiconductors, continuous casting	Acrylonitrile-butadiene-styrene, silicones, fluorocarbons, polyurethane, float glass, tempered glass, glass ceramics	Cold extrusion (steel), explosive forming, thermochemical processing	Gas metal arc, gas tungsten arc, and electroslag welding; explosion welding	Electrical and chemical machining, automatic control.

(*continued*)

TABLE 1.1 Historical development of materials and manufacturing processes (*continued*).

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining, and manufacturing systems
	1960–1970	Squeeze casting, single-crystal turbine blades	Acetals, polycarbonate, cold forming of plastics, reinforced plastics, filament winding	Hydroforming, hydrostatic extrusion, electroforming	Plasma-arc and electron-beam welding, adhesive bonding	Titanium carbide, synthetic diamond, numerical control, integrated circuit chip
Space Age	1970–1990	Compacted graphite, vacuum casting, organically-bonded sand, automation of molding and pouring, rapid solidification, metal-matrix composites, semi-solid metalworking, amorphous metals, shape-memory alloys	Adhesives, composite materials, semiconductors, optical fibers, structural ceramics, ceramic-matrix composites, biodegradable plastics, electrically-conducting polymers	Precision forging, isothermal forging, superplastic forming, dies made by computer-aided design and manufacturing, net-shape forging and forming, computer simulation	Laser beam, diffusion bonding (also combined with superplastic forming), surface-mount soldering	Cubic boron nitride, coated tools, diamond turning, ultraprecision machining, computer-integrated manufacturing, industrial robots, machining and turning centers, flexible manufacturing systems, sensor technology, automated inspection, computer simulation and optimization
Information Age	1990–2000	Rheocasting, computer-aided design of molds and dies, rapid tooling	Nanophase materials, metal foams, high-temperature superconductors, machinable ceramics, diamond-like carbon	Additive manufacturing, rapid tooling, environmentally-friendly metalworking fluids	Friction stir welding, lead-free solders, laser butt-welded (tailored) sheet-metal blanks	Micro- and nanofabrication, LIGA, dry etching, linear motor drives, artificial neural networks, Six Sigma
	2000–2010s	TRIP and TWIP steels	Carbon nanotubes, graphene	Single point incremental forming, hot stamping, electrically assisted forming	Linear friction welding	Digital manufacturing, three-dimensional computer chips, blue-arc machining, soft lithography, flexible electronics

5. New developments in **materials, production methods,** and **computer integration** of both technological and managerial activities must constantly be evaluated with a view to their timely and economic implementation.
6. Manufacturing activities must be viewed as a large **system**, each part of which is interrelated. Such systems can be modeled in order to study the effect of various factors, such as changes in market demand, product design, materials, costs, and production methods, on product quality and cost.
7. A manufacturer must work with the customer for timely feedback for **continuous product improvement**.
8. **Global sourcing** of components and products requires adherence to quality systems, and the management of global supply chains.
9. A manufacturing organization must constantly strive for **higher productivity**, defined as the optimum use of all its resources: materials, technology, machines, energy, capital, and labor.

1.2 Product Design and Concurrent Engineering

Product design is a critical activity because it has been estimated that, generally, 70 to 80% of the cost of product development and manufacture, as well as environmental impact and energy consumption, are determined at the *initial* stages of product design. The design process for a particular product first requires a clear understanding of the functions and the performance expected of that product. The product may be new or it may be an improved model of an existing product. The market for the product and its anticipated uses must be defined clearly, with the assistance of sales personnel, market analysts, and others in the organization.

Product development generally follows the flow outlined in Table 1.2. *Technology Readiness Level* (TRL) and *Manufacturing Readiness Level* (MRL) are measures of a product's ability to be produced, marketed, and sold. In practice, all technologies must progress from some starting point up to a TRL and MRL of 9. A new scientific discovery or product idea begins at a TRL of 1 and it may or may not ever be suitable for commercial application. New versions of existing products may start at some higher TRL or MRL level, but the flow of development is always the same.

Note that each stage of a product development generally requires different skills and resources. Demonstrating a new concept in a laboratory environment (TRL 3) and demonstrating the concept in a new system in a real environment (TRL 7) are very different tasks. Similarly, producing a laboratory prototype (MRL 4) is very different from demonstrating manufacturing strategies for producing a product at scale (MRL 7), which is also very different from having a production facility in place.

Another proposed product development process is shown in Fig. 1.3; it still has a general product flow, from market analysis to design and to manufacturing, but it contains deliberate iterations. Also, while not shown explicitly, it is recognized that all disciplines are involved in the earliest stages of product design. They progress concurrently, so that the iterations (which, by nature, occur from design changes or decisions

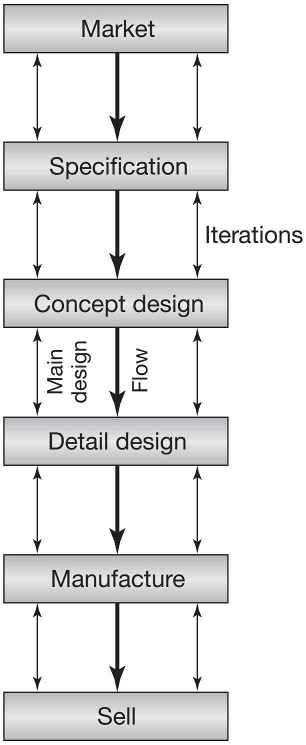

FIGURE 1.3 General product flow, from market analysis to selling the product, and depicting concurrent engineering. *Source:* After S. Pugh.

TABLE 1.2 Definitions of Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL).

TRL	Description	MRL	Description
1	Basic principles observed and reported	1	Manufacturing feasibility assessed
2	Technology concept and/or application formulated	2	Manufacturing concepts defined
3	Analytical and experimental critical function and/or characteristic proof of concept	3	Manufacturing concepts developed
4	Component and/or breadboard validation in a laboratory environment	4	Capability to produce the technology in a laboratory environment
5	Component or breadboard validation in a relevant environment	5	Capability to produce prototype components in a production relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment	6	Capability to produce a prototype system or subsystem in a production relevant environment
7	System prototype demonstration in an operational environment	7	Capability to produce systems, subsystems or components in a production representative environment
8	Actual system completed and qualified through test and demonstration	8	Pilot line capability demonstrated; ready to begin low rate initial production
9	Actual system proven through successful mission operations	9	Low rate production demonstrated; capability in place to begin full rate production

between alternatives) result in less wasted effort and lost time. A key to this approach is the well-recognized importance of *communication* among and within different disciplines. While there must be communication among engineering, marketing, and service functions, there must also be avenues of interaction between engineering sub-disciplines, such as design for manufacture, design for recyclability, and design for safety.

Concurrent engineering, also called **simultaneous engineering**, is a systematic approach integrating the design and manufacture of products with the view toward optimizing all elements involved in the *life cycle* of the product (see Section 1.4). The basic goals of concurrent engineering are to minimize product design and engineering changes, as well as the time and costs involved in taking the product from design concept to production and introduction of the product into the marketplace.

Although the concept of concurrent engineering appears to be logical and efficient, its implementation can require considerable time and effort, especially when those using it either are not able to work as a team or fail to appreciate its real benefits. For concurrent engineering to succeed it must: (a) have the full support of an organization's top management; (b) have multifunctional and interacting work teams, including support groups; and (c) utilize all available state-of-the-art technologies.

A powerful and effective tool, particularly for complex production systems, is **computer simulation** in evaluating the performance of the product and the design of the manufacturing system to produce it. Computer simulation also helps in the early detection of design flaws, identifying possible problems in a particular production system, and optimizing manufacturing lines for minimum product cost. Several computer simulation software packages, using animated graphics and with various capabilities, are widely available.

Some steps in the production process will require a **prototype**, a physical model of the product. An important technique is **additive manufacturing** (Section 10.12), that relies on CAD/CAM and various manufacturing techniques (typically using polymers or metal powders) to rapidly produce prototypes of a part. These techniques are now advanced to such an extent that they can be used for low-volume economical production of actual parts.

During the prototype stage, modifications of the original design, the materials selected, or production methods may be necessary. After this phase has been completed, appropriate process plans, manufacturing methods (Table 1.3), equipment, and tooling are selected, with the cooperation of manufacturing engineers, process planners, and all those involved in production.

TABLE 1.3 Shapes and some common methods of production.

Shape or feature	Production method[a]
Flat surfaces	Rolling, planing, broaching, milling, shaping, grinding
Parts with cavities	End milling, electrical-discharge machining, electrochemical machining, ultrasonic machining, blanking, casting, forging, extrusion, injection molding, metal injection molding
Parts with sharp features	Permanent-mold casting, machining, grinding, fabricating[b], powder metallurgy, coining
Thin hollow shapes	Slush casting, electroforming, fabricating, filament winding, blow molding, sheet forming, spinning
Tubular shapes	Extrusion, drawing, filament winding, roll forming, spinning, centrifugal casting
Tubular parts	Rubber forming, tube hydroforming, explosive forming, spinning, blow molding, sand casting, filament winding
Curvature on thin sheets	Stretch forming, peen forming, fabricating, thermoforming
Openings in thin sheets	Blanking, chemical blanking, photochemical blanking, laser machining
Cross sections	Drawing, extrusion, shaving, turning, centerless grinding, swaging, roll forming
Square edges	Fine blanking, machining, shaving, belt grinding
Small holes	Laser or electron-beam machining, electrical-discharge machining, electrochemical machining, chemical blanking
Surface textures	Knurling, wire brushing, grinding, belt grinding, shot blasting, etching, laser texturing, injection molding, compression molding
Detailed surface features	Coining, investment casting, permanent-mold casting, machining, injection molding, compression molding
Threaded parts	Thread cutting, thread rolling, thread grinding, injection molding
Very large parts	Casting, forging, fabricating, assembly
Very small parts	Investment casting, etching, powder metallurgy, nanofabrication, LIGA, micromachining

Note:
[a] Rapid prototyping operations can produce all of these features to some degree.
[b] ‘Fabricating’ refers to assembly from separately manufactured components.

CASE STUDY 1.1 Three-Dimensional Printing of Guitars

The design flexibility of additive manufacturing is illustrated by the custom guitars produced by ODD, Inc. These guitars are designed in CAD programs, with full artistic freedom to pursue innovative designs; those in Figure 1.4 are only a selection of the many available. The CAD file is then sent to a three-dimensional printer, using the selective laser sintering process and produced from nylon (Duraform PA). As printed, the guitars are white. They are first dyed to a new base color, then subsequently hand-painted and sprayed with a clear satin lacquer. The customer-specified hardware (pickups, bridges, necks, tuning heads, etc.) are then mounted to produce the electric guitar.

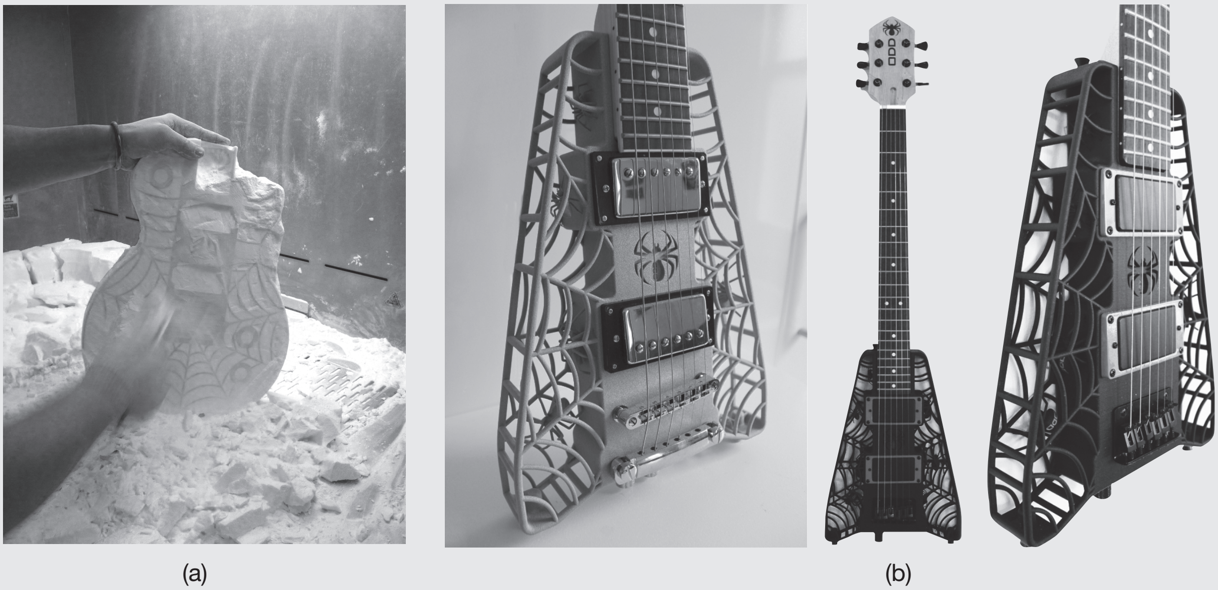

FIGURE 1.4 Guitars produced through additive manufacturing. (a) Spider design being removed from a powder bed. Note that the support material, or *cake*, has some strength and needs to be carefully removed; (b) finished Spider guitars. *Source:* Courtesy of O. Diegel, Massey University, New Zealand.

1.3 Design for Manufacture, Assembly, Disassembly, and Service

Design and manufacturing should never be viewed as separate disciplines and activities. Each part or component of a product must be designed so that it not only meets design requirements and specifications but also so it can be manufactured economically and with relative ease. This broad concept, known as **design for manufacture** (DFM), is a comprehensive approach to the production of goods. It integrates the product design process with materials, manufacturing methods, process planning, assembly, testing, and quality assurance.

Effective implementation of design for manufacture requires that designers acquire a fundamental understanding of the characteristics, capabilities, and limitations of materials, production methods, machinery, and equipment. Also included are such characteristics as variability in machine performance, dimensional accuracy and surface finish of the parts produced, processing time, and the effect of processing methods on part quality.

Designers and product engineers assess the impact of any design modifications on manufacturing process selection, tools and dies, assembly methods, inspection and, especially, product cost. Establishing quantitative relationships is essential in order to optimize the design for ease of manufacture and assembly at *minimum cost* (also called *producibility*). Computer-aided design, engineering, manufacturing, and process planning techniques, using powerful computer software, are indispensable to such analysis. They include **expert systems**, which are computer programs with optimization capabilities, thus expediting the traditional iterative process in design optimization.

After individual parts have been manufactured, they are assembled into a product. **Assembly** is an important phase of the overall manufacturing operation, requiring the consideration of the ease, speed, and cost of putting parts together (Fig. 1.5). Products should be designed for quick and easy **disassembly** so that they can be taken apart for maintenance, servicing, or recycling of their components.

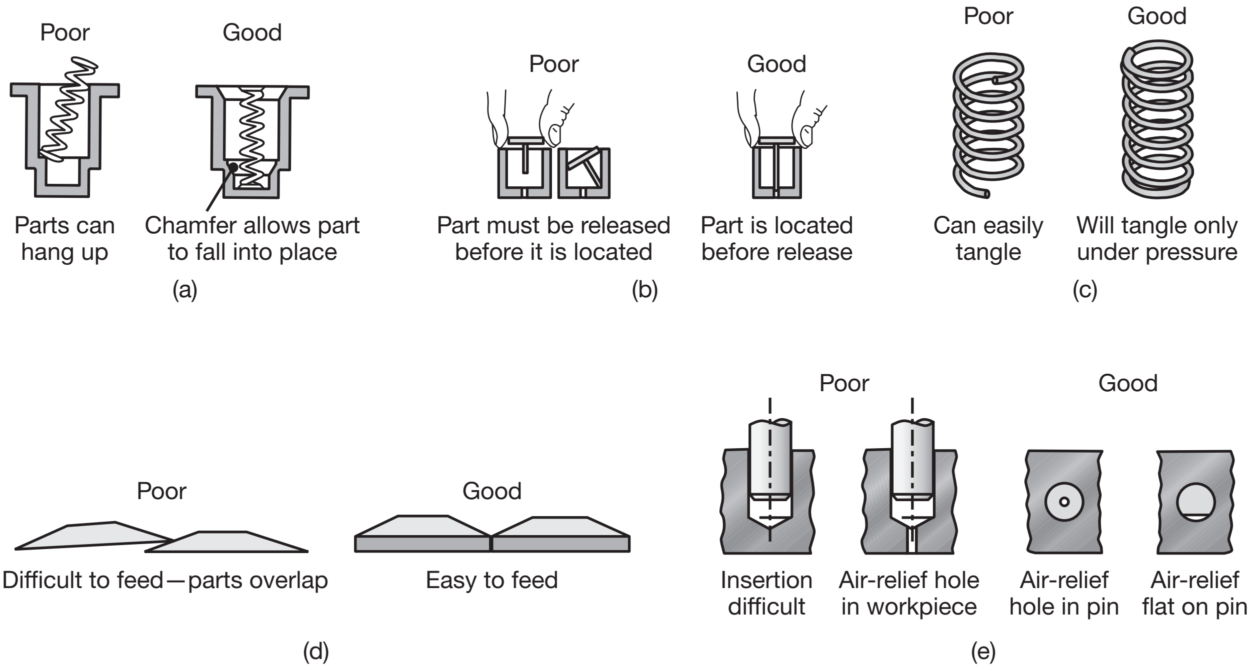

FIGURE 1.5 Redesign of parts to facilitate automated assembly.
Source: Boothroyd, G., Dewhurst, P., and Knight, W.A., *Product Design for Manufacture and Assembly*, 3rd ed., 2010, CRC Press.

Because assembly operations can contribute significantly to product cost, **design for assembly** (DFA), and **design for disassembly** are important aspects of manufacturing. **Design for service** is another important aspect, ensuring that individual parts in a product are easy to reach and service; if they are difficult to access for service, they are generally designed to be more robust. These activities have now been combined into **design for manufacture and assembly** (DFMA), which recognizes the inherent and important interrelationships among design, manufacturing, and assembly of products.

Design principles for economical production may be summarized as follows:

- Designs should be as simple as possible to manufacture, assemble, disassemble, service, and recycle.
- Materials should be chosen for their appropriate design and manufacturing characteristics as well as for their service life.
- Dimensional accuracy and surface finish requirements should be as broad as permissible.
- Secondary and finishing operations should be avoided or minimized, because they can add significantly to product cost.

1.4 Environmentally Conscious Design, Sustainable Manufacturing, and Product Life Cycle

In Europe, about 22.5 million metric tonnes of plastic waste and 20.7 million metric tonnes of paper waste are discarded each year. Every three months, US industries and consumers discard enough aluminum to rebuild the country's commercial air fleet. Globally, countless tons of automobiles, televisions, appliances, and computers are discarded each year. Metalworking fluids, such as lubricants and coolants, and fluids and solvents, such as those used in cleaning manufactured products, can pollute the air and water, unless recycled or disposed of properly.

Likewise, there are numerous byproducts from manufacturing plants: (a) sand with additives, used in metal-casting processes; (b) water, oil, and other fluids from heat-treating and facilities; (c) slag from foundries and welding operations; and (d) a wide variety of metallic and nonmetallic scrap produced in such operations as sheet forming, casting, and molding. Consider also the various effects of water and air pollution, acid rain, ozone depletion, hazardous wastes, landfill seepage, and global warming. Recycling efforts have gained increasing momentum over the years; aluminum cans, for example, are now recycled at a rate of 67% and plastics at around 9%.

The present and potential adverse effects of these activities, their damage to the environment and to the earth's ecosystem, and, ultimately, their effects on the quality of human life are now well recognized. In response, a wide range of laws and regulations have been and continue to be promulgated by local, state, and federal governments and international