DeGARMO'S

J T. BLACK • RONALD A. KOHSER

MATERIALS & PROCESSES IN MANUFACTURING

TWELFTH EDITION

WILEY

Degarmo's Materials and Processes in Manufacturing

12th Edition

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WILEY

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PREFACE

It's a world of manufactured goods. Whether we like it or not, we all live in a technological society. Every day we come in contact with hundreds of manufactured items, made from every possible material. From the bedroom to the kitchen to the workplace, we use appliances, phones, cars, trains, and planes, TVs, cell phones, VCRs, DVDs, furniture, clothing, sports equipment, books and more. These goods are manufactured in factories all over the world using manufacturing processes.

Basically, manufacturing is a value-adding activity, where the conversion of materials into products adds value to the original material. Thus, the objective of a company engaged in manufacturing is to add value and to do so in the most efficient manner, with the least amount of waste in terms of time, material, money, space, and labor. To minimize waste and increase productivity, the processes and operations need to be properly selected and arranged to permit smooth and controlled flow of material through the factory and provide for product variety. Meeting these goals requires an engineer who can design and operate an efficient manufacturing system. Here are some trends that are having impacts on the manufacturing world.

- **Manufacturing is a global activity**

  Manufacturing is a global activity with work often being performed at locations based on proximity to materials, labor, or marketplace. US firms often have plants in other countries, and foreign companies operate plants in the United States. Final product assembly often involves components made at a variety of locations.

- **It's a digital world**

  Information technology and computers are growing exponentially, with usage in virtually every aspect of manufacturing. Design and material selection are performed on computers, and this information is then transmitted to manufacture, where machines are often operated and controlled by computers. Computerized inspection processes ensure product quality.

- **Lean manufacturing is widely practiced**

  Most manufacturing companies have restructured their factories (their manufacturing systems) to become lean producers—making goods of superior quality, cheaper and faster, in a flexible way (i.e., they are more responsive to the customers). Almost every plant is doing something to become leaner. Many have adopted some version of the Toyota Production System. More importantly, these manufacturing factories are also designed with the internal customer (the workforce) in mind, so things such as ergonomics and safety are key design requirements. While this book is all about materials and processes for making products, the design of the factory cannot be ignored when it comes to making the external customer happy with the product and the internal customer satisfied with the employer.

- **New products and materials need new processes**

  The number and variety of products and the materials from which they are made continues to proliferate, while production quantities (lot sizes) have become smaller. Existing processes must be modified to be more flexible, and new processes must be developed.

- **Customers expect great quality**

  Consumers want better quality and reliability, so the methods, processes, and people responsible for that quality must improve continually. Reducing the number and magnitude of flaws and defects often requires continual changes to the manufacturing system.

- **Rapid product development is required**

  Being competitive often requires reducing the time to market for new products. Many companies are taking holistic or systemwide perspectives, including concurrent engineering efforts to bring product design and manufacturing closer to the customer. Products are being designed to be easier to manufacture and assemble (design for manufacture/assembly). Manufacturing systems are becoming more flexible (able to rapidly adapt to and assimilate new products).

- **3-D printing and additive manufacturing is exploding**

  New and improved processes, new materials, and expanded capability machines and equipment are entering the market on an almost weekly basis. Technology that once produced lookalike prototype parts is now producing fully functional products from the full range of materials, including metals, ceramics, polymers, and biomaterials.

History of the Text

E. Paul DeGarmo was a mechanical engineering professor at the University of California, Berkley, when he wrote the first edition of *Materials and Processes in Manufacturing*, published by Macmillan in 1957. The book quickly became the emulated standard for introductory texts in manufacturing. Second, third, and fourth editions followed in 1962, 1969, and 1974. DeGarmo began teaching at Berkeley in 1937, after earning his master's of science degree in mechanical engineering from California Institute of Technology. He was a founder of the Department of Industrial Engineering (now Industrial Engineering and Operations Research) and served as its chairman from 1956–1960. He was also assistant dean of the College of Engineering for three years while continuing his teaching responsibilities.

Paul DeGarmo observed that engineering education had begun to place more emphasis on the underlying sciences at the expense of hands-on experience. Most of his students were coming to college with little familiarity with materials, machine tools, and manufacturing methods that their predecessors had acquired through their former "shop" classes. If these engineers and technicians were to successfully convert their ideas into reality, they needed a foundation in materials and processes, with emphasis on capabilities and limitations. Paul sought to provide a text that could be used in either a one- or two-semester course designed to meet these objectives. The materials sections were written with an emphasis on use and application. Processes and machine tools were described in terms of how they worked, what they could do, and their relative advantages and limitations, including economic considerations. The text was written for students who would be encountering the material for the first time, providing clear descriptions and numerous visual illustrations.

Paul's efforts were well-received, and the book quickly became the standard text in many schools and curricula. As materials and processes evolved, the advances were incorporated into subsequent editions. Computer usage, quality control, and automation were added to the text, along with other topics, so that it continued to provide state-of-the-art instruction in both materials and processes. As competing books entered the market, their subject material and organization tended to mimic the DeGarmo text.

Paul DeGarmo retired from active teaching in 1971, but he continued his research, writing, and consulting for many years. In 1977, after the publication of the fourth edition of *Materials and Processes in Manufacturing*, he received a letter from Ron Kohser, then an assistant professor at the University of Missouri-Rolla, containing numerous suggestions regarding the materials chapters. Paul DeGarmo asked Dr. Kohser to rewrite those chapters for the upcoming fifth edition. After that edition, Paul decided he was really going to retire and, after a national search, recruited J T. Black, then a professor at Ohio State, to co-author the book with Dr. Kohser.

For the sixth through 11th editions (published in 1984 and 1988 by Macmillan, 1997 by Prentice Hall, and 2003, 2008 and 2012 by John Wiley & Sons), Dr. Kohser and Dr. Black have shared the responsibility for the text. The chapters about engineering materials, casting, forming, powder metallurgy, additive manufacturing, joining and nondestructive testing have been written or revised by Dr. Kohser. Dr. Black has responsibility for the introduction and chapters about material removal, metrology, surface finishing, quality control, manufacturing systems design, and lean engineering.

Paul DeGarmo died in 2000, three weeks short of his 93rd birthday. For the 10th edition, which coincided with the 50th anniversary of the text, Dr. Black and Dr. Kohser honored their mentor with a change in the title to include his name—*DeGarmo's Materials and Processes in Manufacturing*. We recognize Paul DeGarmo for his insight and leadership and are forever indebted to him for selecting us to carry on the tradition of his book for this, the 12th edition.

Purpose of the Book

The purpose of this book is to provide basic information on materials, manufacturing processes and systems to students of engineering and technology. The materials section focuses on properties and behavior. Aspects of smelting, refining, or other material production processes are presented only as they affect subsequent use and application. In terms of the processes used to manufacture items (converting materials into useful shapes with desired properties), this text seeks to provide a descriptive introduction to a wide variety of options, emphasizing how each process works and its relative advantages and limitations. The goal is to present this material in a way that can be understood by individuals seeing it for the very first time. This is not a graduate text where the objective is to thoroughly understand and optimize manufacturing processes. Mathematical models and analytical equations are used only when they enhance the basic understanding of the material. Although the text is introductory in nature, new and emerging technologies, such as direct-digital and micro- and nano-manufacturing processes, are included as they transition into manufacturing usage.

Organization of the Book

E. Paul DeGarmo wanted a book that explained to engineers how the things they designed could be made. *DeGarmo's Materials and Processes in Manufacturing* is still being written to provide a broad, basic introduction to the fundamentals of manufacturing. The text begins with a survey of engineering materials, the “stuff” that manufacturing begins with, and seeks to provide the basic information that could be used to match the properties of a material to the service requirements of a component. A variety of engineering materials are presented, along with their properties and means of modifying them. The materials section can be used in curricula that lack preparatory courses in metallurgy, materials science, or strength of materials, or where the student has not yet been exposed to those topics. In addition, various chapters in this section can be used as supplements to a basic materials course, providing additional information about topics such as heat treatment, plastics, composites, and material selection.

Following the materials chapters are sections about casting, powder metallurgy, forming, material removal, and joining. Each section begins with a presentation of the fundamentals on which those processes are based. These introductions are followed by a discussion about the various process alternatives, which can be selected to operate individually or be combined into an integrated system.

Reflecting the many recent developments and extreme interest in additive manufacturing (often called 3-D printing), the chapter about this technology has been significantly updated to present the various technologies in place at the time of textbook printing. Uses and applications are summarized, including prototype manufacture, rapid tooling, and direct-digital manufacture. The advantages and limitations of additive manufacturing are summarized, along with a description of current and future trends.

Manufacturing processes are often designed to accommodate specific materials. A separate chapter presents those processes that are somewhat unique to plastics, ceramics, and composites.

Chapters have been included to provide information about surface engineering, measurements, nondestructive testing, and quality control. Engineers need to know how to determine process capability and, if they get involved in Six Sigma projects, to know what sigma really measures. There is also introductory material about surface integrity, since so many processes produce the finished surface and impart residual stresses to the components.

Many of the advances in manufacturing relate to the way the various processes are implemented and integrated in a production plant or on the shop floor—the design of manufacturing systems. Aspects of automation, numerical control, and robotics are presented in a separate chapter. In addition, there is expanded coverage of lean engineering, in which the mass production system is converted into a lean production system, capable of rapidly manufacturing variations of a product, small quantities of a product, or even one-of-a-kind items on a very flexible and continual basis.

With each new edition, new and emerging technology is incorporated, and existing technologies are updated to accurately reflect current capabilities. Through its nearly 60-year history and 11 previous editions, the DeGarmo text was often the first introductory book to incorporate processes such as friction-stir welding, microwave heating and sintering, and machining dynamics.

Each chapter closes with a listing of *Review Questions*, designed to assess a student’s understanding of the material presented in the text. The *Problems* section further applies this understanding, with a bit of focus on application. Somewhat open-ended case studies are provided in the Internet supplements that accompany this text. These have been designed to make students aware of the great importance of properly integrating design, material selection, and manufacturing to produce cost competitive, reliable products.

The DeGarmo text is intended for use by engineering (mechanical, lean, manufacturing, industrial, and materials) and engineering technology students, in both two- and four-year undergraduate degree programs. In addition, the book is also used by engineers and technologists in other disciplines concerned with design and manufacturing (such as aerospace and electronics). Factory personnel find this book to be a valuable reference that concisely presents the various production alternatives and the advantages and limitations of each. Additional or more in-depth information about specific materials or processes can be found in an expanded list of supplemental references that is organized by topic.

Supplements

An instructor solutions manual for instructors adopting the text for use in their courses is available on a companion website: www.wiley.com/college/black. A collection of manufacturing process videos also is available to both instructors and students in the Fundamental Manufacturing Processes Sampler also on that site.

Acknowledgments

The authors wish to acknowledge the multitude of assistance, information, and illustrations that have been provided by a variety of industries, professional organizations, and trade associations. The text has become known for the large number of clear and helpful photos and illustrations that have been provided graciously by a variety of sources. In some cases, equipment is photographed or depicted without safety guards, so as to show important details, and personnel are not wearing certain items of safety apparel that would be worn during normal operation.

Over the many editions, hundreds of reviewers, user faculty, and students have submitted suggestions and corrections to the text. We continue to be grateful for their input.

The authors also would like to acknowledge the contributions of Dr. Elliot Stern for the dynamics of machining section in Chapter 21, Dr. Brian Paul for writing the micro-manufacturing chapter, Dr. Kavit Antani for his contributions in lean engineering and system design, Dr. Andres Carrano for his work in measurements/metrology, Prof. Julia Morse for her contributions to NC and CNC, and Mr. Kevin Slattery of the Boeing Company for his review of the chapter on additive manufacturing.

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Both Dr. Black and Dr. Kohser lost their wives to COPD and cancer, respectively, since the publication of the 11th edition. Carol Black was a great editor, and Barb Kohser endured being a “textbook widow” through the preparation of seven editions. They will be dearly missed.

About the Authors

J T. Black received his PhD from Mechanical and Industrial Engineering, University of Illinois, Urbana, in 1969, a master's of science degree in industrial engineering from West Virginia University in 1963, and his bachelor of science degree in industrial engineering, Lehigh University, in 1960. J T. is professor emeritus from Industrial and Systems Engineering at Auburn University. He was the chairman and a professor of Industrial and Systems Engineering at University of Alabama-Huntsville. He also taught at Ohio State University, University of Rhode Island, University of Vermont, and University of Illinois. He taught his first processes class in 1960 at West Virginia University. J T. is a Fellow in the American Society of Mechanical Engineers, the Institute of Industrial Engineering and the Society of Manufacturing Engineers. J loves to write music (mostly down-home country) and poetry, play tennis in the backyard, and show his champion pug dogs.

Ron Kohser received his PhD from Lehigh University Institute for Metal Forming in 1975. He then joined the faculty of the University of Missouri-Rolla, now the Missouri University of Science & Technology, where he held positions of professor of metallurgical engineering, dean's teaching scholar, department chairman and associate dean for undergraduate instruction. Ron consistently carried a full teaching load, including metallurgy for engineers; introduction to manufacturing processes; material selection, fabrication, and failure analysis; materials processing; powder metallurgy; and metal deformation processes. In 2013, he retired as professor emeritus, and moved to the Lake of the Ozarks, where he and his wife helped build their retirement home. He looks forward to some time of fishing on the lake.

About the Cover

Although there are some similarities to function and design, the four airplanes on the cover represent a spectrum of manufacturing and operating conditions, and meeting those conditions often requires different “materials” and “processes.” The 1903 Wright Flyer was a hand-built one-of-a-kind airplane with a wooden propeller and an airframe made of ash and spruce wood, stiffened by bracing wires, and covered with linen cloth. As airplane technology developed, the materials changed, along with the methods to convert the new materials to the desired shapes. Desired material properties usually included light weight and high strength, coupled with features that might include fracture resistance, corrosion resistance, and others.

The four airplanes on the cover are a large commercial passenger airliner or freight hauler, a small private light aircraft, the F35 Lightning II military stealth fighter, and the SR-71 Blackbird supersonic, stealth spy plane. Most manufacturing decisions for the passenger airliner or freight hauler are driven by economics, with the bottom line being the resulting cost per mile of travel for a passenger or ton of cargo. For the small private airplane, objectives might include purchase and operational affordability, as well as ease of maintenance at diverse local facilities. Desired features for the military fighter are usually performance driven, with cost being secondary. The fighter must be versatile and able to perform a range of operations under various combat conditions. Supersonic speed, agility, and stealth might come at justifiable additional cost. Common materials include aluminum, titanium, and carbon-fiber composites. The SR-71 Blackbird was designed to operate under never-before-attained conditions, namely Mach 3 supersonic speed and altitudes as high as 80,000 feet (more than 15 miles). Prolonged supersonic flight would raise surface temperatures to more than 1000°F, bringing a new and critical demand to the usual material properties of light weight and high strength. Body sheet and other components had to be fabricated from titanium, and thermal expansion was a critical design property. Until spy planes were replaced by satellite surveillance, the SR-71 was the ultimate airplane.

These four planes are also powered by different types of engines with widely different designs, horsepower, operating temperatures, and speeds of internal components. The landing gear must support different weights and endure different shocks and impacts. The production quantity also varies. Only a few Blackbirds were made, while passenger planes are usually made in the hundreds, and several thousand of a particular model private plane might be produced. A $5000 die, mold, or tool adds $500 per part if the production run is only 10 planes, but only $5 per plane if the production run is 1000. Some processes favor small quantities, while others favor large runs.

Nearly all of the materials and processes described in this book find themselves employed in one or more of the four airplanes. Each of the material-process combinations was selected because it offered the best match to the needs of the specific product and component. However, as new materials and processes are developed, the current “best” solutions will be constantly changing. We invite the reader to open the text and explore this fascinating area of engineering and technology.

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FIGURE 4.7 Equilibrium diagram showing the changes that occur during the cooling of alloy X.

FIGURE 4.8 Schematic summary of three-phase reactions and intermetallic compounds.

FIGURE 4.9 The iron–carbon equilibrium phase diagram. Single phases are α, ferrite; γ, austenite; δ, δ–ferrite; and Fe_3C, cementite.

FIGURE 4.10 Simplified iron–carbon phase diagram with labeled regions. Figure 4.9 shows the more-standard Greek letter notation.

FIGURE 4.11 Pearlite; 1000X.

FIGURE 4.12 Photomicrograph of a hypoeutectoid steel showing regions of primary ferrite (white) and pearlite; 500x.

FIGURE 4.13 Photomicrograph of a hypereutectoid steel showing primary cementite along grain boundaries; 500X.

FIGURE 4.14 An iron–carbon diagram showing two possible high-carbon phases. Solid lines denote the iron–graphite system; dashed lines denote iron–cementite (or iron–carbide).

Chapter 5

FIGURE 5.1 Simplified iron–carbon phase diagram for steels with transition lines labeled in standard notation as A_1, A_3, and A_{cm}.

FIGURE 5.2 Graphical summary of the process heat treatments for steels on an equilibrium diagram.

FIGURE 5.3 High-aluminum section of the aluminum–copper equilibrium phase diagram.

FIGURE 5.4 Enlargement of the solvus-line region of the aluminum–copper equilibrium diagram of Figure 5.3.

FIGURE 5.5 Two-dimensional illustrations depicting: (a) a coherent precipitate cluster where the precipitate atoms are larger than those in the host structure, and (b) its companion overaged or discrete second-phase precipitate particle. Parts (c) and (d) show equivalent sketches where the precipitate atoms are smaller than the host.

FIGURE 5.6 Aging curves for the Al–4% Cu alloy at various temperatures showing peak strengths and times of attainment.

FIGURE 5.7 Isothermal transformation diagram (T-T-T diagram) for eutectoid composition steel. Structures resulting from transformation at various temperatures are shown as insets.

FIGURE 5.8 Photomicrograph of martensite; 1000X.

FIGURE 5.9 Effect of carbon on the hardness of martensite.

FIGURE 5.10 Schematic representation depicting the amount of martensite formed upon quenching to various temperatures from M_s through M_f.

FIGURE 5.11 Variation of M_s and M_f temperatures with carbon content. Note that for high carbon steels, completion of the martensite transformation requires cooling to below room temperature.

FIGURE 5.12 Isothermal transformation diagram for a hypoeutectoid steel (1050) showing the additional region for primary ferrite.

FIGURE 5.13 Properties of an AISI 4140 steel that has been austenitized, oil-quenched, and tempered at various temperatures.

FIGURE 5.14 C-C-T diagram for a eutectoid composition steel (bold), with several superimposed cooling curves and the resultant structures. The lighter curves are the T-T-T transitions for the same steel.

FIGURE 5.15 Schematic diagram of the Jominy hardenability test.

FIGURE 5.16 Typical hardness distribution along a Jominy test specimen.

FIGURE 5.17 Jominy hardness curves for engineering steels with the same carbon content, but varying types and amounts of alloy elements.

FIGURE 5.18 Jominy hardness curves for engineering steels with identical alloy conditions but variable carbon content.

FIGURE 5.19 Three-layer model of a plate undergoing cooling: upper sequence depicts a material such as aluminum that contracts on cooling, whereas the bottom sequence depicts steel, which expands during the cooling-induced phase transformation.

FIGURE 5.20 (a) Shape containing nonuniform sections and a sharp interior corner that might crack during quenching. This is improved by using a large radius to join the sections. (b) Original design containing sharp corner holes, which can be further modified to produce more uniform sections.

FIGURE 5.21 Warping can occur when subsequent machining upsets the equilibrium balance of residual stresses. (a) Sketch of the desired product, a flat plate with a milled slot. (b) Resulting geometry if the unmachined plate contained the residual stress pattern described in the upper portion of Figure 5.19.

FIGURE 5.22 (a) Schematic representation of the cooling paths of surface and center during a direct quench. (b) The modified cooling paths experienced during the austemper and martemper processes.

FIGURE 5.23 T-T-T diagram for 4340 steel showing the “bay,” along with a schematic of the ausforming process.

FIGURE 5.24 Section of gear teeth showing induction-hardened surfaces.

FIGURE 5.25 Box-type electric heat-treating furnace.

FIGURE 5.26 Car-bottom box furnace.

Chapter 6

FIGURE 6.1 Classification of common ferrous metals and alloys.

FIGURE 6.2 Diagram of a bottom-pouring ladle.

FIGURE 6.3 (a) Schematic representation of the continuous casting process for producing billets, slabs, and bars. (b) Simultaneous continuous casting of multiple strands.

FIGURE 6.4 Solubility of gas in a metal as a function of temperature showing significant decrease upon solidification.

FIGURE 6.5 A comparison of low-carbon, medium-carbon, and high-carbon steels in terms of their relative balance of properties. (a) Low-carbon has excellent ductility and fracture resistance, but lower strength. (b) Medium-carbon has balanced properties. (c) High-carbon has high strength and hardness at the expense of ductility and fracture resistance.

FIGURE 6.6 Relationships between the mechanical properties of a variety of properly heat-treated AISI–SAE 0.3% carbon alloy steels.

FIGURE 6.7 Relative strength and formability (elongation) of conventional, high-strength low-alloy, and advanced high-strength steels. BH = bake hardenable; DP = dual phase; and Mart = martensitic. Also included is the newer TWIP steels.

FIGURE 6.8 Different types of stainless steels, along with popular alloys within each type and key properties.

FIGURE 6.9 Photomicrograph showing the distribution of graphite flakes in gray cast iron;

unetched, 100X.

FIGURE 6.10 Photomicrograph of malleable iron showing the irregular graphite clusters, etched to reveal the ferrite matrix, 100×.

FIGURE 6.11 Ductile cast iron with a ferrite matrix. Note the spheroidal shape of the graphite. 100×.

Chapter 7

FIGURE 7.1 Some common nonferrous metals and alloys, classified by attractive engineering property.

FIGURE 7.2 Copper and copper alloys are used for a variety of electrical and plumbing applications, as shown in these illustrations.

FIGURE 7.3 The all-aluminum space frame of the 2012 Audi S8 sedan.

FIGURE 7.4 Strength retention at elevated temperature for various titanium alloys.

FIGURE 7.5 Superalloys and refractory metals are needed to withstand the high temperatures of jet engine exhaust as seen when this F/A 18 Hornet launches from an aircraft carrier.

FIGURE 7.6 Temperature scale indicating the upper limit to useful mechanical properties for various engineering metals.

FIGURE 7.7 Densities of the various engineering metals. The elevated-temperature superalloys and refractory metals are all heavier than steel.

Chapter 8

FIGURE 8.1 The linking of carbon and hydrogen to form methane and ethane molecules. Each dash represents a shared electron pair or covalent bond.

FIGURE 8.2 Double and triple covalent bonds exist between the carbon atoms in unsaturated ethylene and acetylene molecules.

FIGURE 8.3 Linking of eight hydrogen, one oxygen, and three carbon atoms to form two isomers: propyl alcohol and isopropyl alcohol. Note the different locations of the –OH attachment.

FIGURE 8.4 Addition polymerization—the linking of monomers, in this case, identical ethylene molecules.

FIGURE 8.5 Addition polymerization with two kinds of mers—here, the copolymerization of butadiene and styrene.

FIGURE 8.6 The formation of (a) phenol–formaldehyde (Bakelite) and (b) polyethylene terephthalate (PET) by condensation polymerization. Note the H_2O or water by-product.

FIGURE 8.7 Ceramic investment-casting mold for casting gas turbine engine rotor blades. The positioned cores create intricate internal cooling passages.

FIGURE 8.8 A variety of high-strength alumina components.

FIGURE 8.9 Gas-turbine rotors made from advanced ceramic silicon nitride. The lightweight material (one-half the weight of stainless steel) offers strength at elevated temperature as well as excellent resistance to corrosion and thermal shock.

FIGURE 8.10 A variety of components manufactured from silicon nitride.

FIGURE 8.11 Graphical mapping of the combined toughness and hardness for a variety of cutting-tool materials. Note the superior hardness of the ceramic materials. [CBN = cubic boron nitride].

FIGURE 8.12 Schematic of a bimetallic strip where material A has the greater coefficient of thermal expansion. Note the response to cold and hot temperatures.

FIGURE 8.13 The strength/weight ratio of various aerospace materials as a function of temperature. Note the superiority of the various fiber-reinforced composites.

FIGURE 8.14 Schematic diagram showing the materials used in the various sections of the F-22 Raptor fighter airplane. Traditional materials, such as aluminum and steel, comprise only 20 wt%. Titanium accounts for 42%, and 24% is composite material. The plane is capable of flying at Mach 2. (*Note:* RTM is resin-transfer molding.)

FIGURE 8.15 Composite materials are often used in sporting goods, like this snowboard, to improve performance through light weight, high stiffness, and high strength, and also to provide attractive styling.

Chapter 9

FIGURE 9.1 (a) Cutaway drawing showing the internal design of a Rolls-Royce jet engine. Notice the number and intricacy of the components. Ambient air enters the front, and hot exhaust exits the back. A wide range of materials and processes will be used in its construction. (b) A full-size Rolls-Royce engine showing the size and complexity of the product.

FIGURE 9.2 (a) A traditional two-wheel bicycle frame (1970s vintage) made from joined segments of metal tubing (Courtesy Ronald Kohser). (b) A top-of-the-line (Tour de France or triathlon-type) bicycle with one-piece frame made from fiber-reinforced polymer-matrix composite.

FIGURE 9.3 Schematic showing the interrelation between material, properties, processing, and performance.

FIGURE 9.4 Sequential flowchart showing activities leading to the production of a part or product.

FIGURE 9.5 Alternative flowchart showing parallel selection of material and process.

FIGURE 9.6 Compatibility chart of materials and processes. Selection of a material may restrict possible processes. Selection of a process may restrict possible materials.

FIGURE 9.7 Rating chart for comparing materials for a specific application.

Chapter 10

FIGURE 10.1 Standard set of gage blocks with 0.000050-in. accuracy.

FIGURE 10.2 Wrung-together gage blocks in a special holder, used with a dial gage to form an accurate comparator.

FIGURE 10.3 Three gage blocks wrung together to build up a desired dimension.

FIGURE 10.4 Accuracy versus precision. Dots in targets represent location of shots. Cross (3) represents the location of the average position of all shots. (a) Accurate and precise; (b) precise, not accurate; (c) accurate, not precise; (d) precise within sample, not precise between samples, not accurate overall or within sample.

FIGURE 10.5 When mating parts are designed, each shaft must be smaller than each hole for a clearance fit.

FIGURE 10.6 (a) In the ideal situation, the process would make all parts exactly the same size. (b) In the real world of manufacturing, parts have variability in size. The distribution of sizes can often be modeled with a normal distribution.

FIGURE 10.7 The normal distributional can be used to model many processes.

FIGURE 10.8 (a) The manner in which the distributions of the two mating parts interact determines the fit. UNTL (upper natural tolerance limit) = $\mu + 3\sigma$; LNTL (lower natural tolerance limit) = $\mu - 3\sigma$. (b) Shifting the means of the distributions toward each other results in some interface fits.

FIGURE 10.9 The ISO System of Limits and Fits.

FIGURE 10.10 (a) Geometric tolerancing symbols; (b) feature control symbols for part drawings; (c) how a geometric tolerance for flatness is specified; (d) what the specification means.

FIGURE 10.11 The rule of 10 states that for reliable measurements each successive step in the inspection sequence should have 10 times the *precision* of the preceding step.

FIGURE 10.12 Machinist's rules: (a) metric and (b) inch graduations; 10ths and 100ths on one side, 32nds and 64ths on the opposite side.

FIGURE 10.13 Combination set.

FIGURE 10.14 This vernier caliper can make measurements using both inside (for holes) and outside (shafts) anvils.

FIGURE 10.15 Vernier caliper graduated for English and metric (direct) reading. The metric reading is 27 + 0.42 = 27.42 mm.

FIGURE 10.16 Variations in the vernier caliper design result in other basic gages, like the vernier height gage.

FIGURE 10.17 Two styles of calipers in common use today: (a) dial caliper with 0.001-in. accuracy; (b) digital electronic caliper with 0.001-in. (0.03-mm) accuracy and 0.0001-in. resolution with inch/metric conversion.

FIGURE 10.18 Micrometer caliper graduated in ten-thousandths of an inch with insets A, B, and C showing two example readings.

FIGURE 10.19 Digital micrometer for measurements from 0 to 1 in., in 0.0001-in. graduations.

FIGURE 10.20 Toolmaker's micrometer, bench micrometers, and gages with direct digital readouts.

FIGURE 10.21 The optical comparator uses light to show the magnified contour of a workpiece, projecting the image on a screen for measurement.

FIGURE 10.22 Interference bands can be used to measure the size of objects to great accuracy.

FIGURE 10.23 Method of measuring object U using calibrating gage block S and light-wave interference.

FIGURE 10.24 (Top) Calibrating the *x*-axis linear table displacement of a vertical-spindle milling machine; (middle) schematic of optical setup; (bottom) schematic of components of a twofrequency laser interferometer.

FIGURE 10.25 Scanning laser measuring system.

FIGURE 10.26 Schematic of elements of a machine vision system.

FIGURE 10.27 Vision systems use a gray scale to identify objects. (a) Object with three different gray values. (b) One frame of object (pixels). (c) Each pixel assigned a gray-scale number.

FIGURE 10.28 Examples of geometric form tolerances developed by probing surface with a CMM.

FIGURE 10.29 Coordinate measuring machine with inset showing probe and a part being measured.

FIGURE 10.30 Measuring an angle on a part with a bevel protractor.

FIGURE 10.31 Setup to measure an angle on a part using a sine bar. The dial indicator is used to determine when the part surface X is parallel to the surface plate.

FIGURE 10.32 Plain plug gage having the go member on the left end (1.1250-in. diameter) and no-go member on the right end.

FIGURE 10.33 Step-type plug gage with go and no-go elements on the same end.

FIGURE 10.34 Go and no-go (on right) ring gages for checking a shaft.

FIGURE 10.35 Adjustable go-not go limit snap gages come in sizes up-to 12 in.

FIGURE 10.36 Set of radius gages, showing how they are used.

FIGURE 10.37 Thread pitch gages.

FIGURE 10.38 Flush-pin gage being used to check height of step.

FIGURE 10.39 A digital dial indicator with 1-in. range and 0.0001-in. accuracy is an example of a deviation type gage.

FIGURE 10.A Courtesy of The L.S. Starrett Company

FIGURE 10.B Courtesy of The L.S. Starrett Company

FIGURE 10.C

FIGURE 10.D

FIGURE 10.E

FIGURE 10.F

FIGURE CS-10A Part drawing

FIGURE CS-10B Setup for checking the angle θ

Chapter 11

FIGURE 11.1 Liquid-penetrant testing: (a) initial surface with open crack; (b) penetrant is applied and is pulled into the crack by capillary action; (c) excess penetrant is removed; and (d) developer is applied, some penetrant is extracted, and the product inspected.

FIGURE 11.2 (a) Magnetic field showing disruption by a surface crack; (b) magnetic particles are applied and are preferentially attracted to field leakage; (c) subsurface defects can also produce surface-detectable disruptions if they are sufficiently close to the surface.

FIGURE 11.3 (a) A bar placed within a magnetizing coil will have an axial magnetic field. Defects parallel to this field may go unnoticed, while those that disrupt the field and are sufficiently close to a surface are likely to be detected. (b) When magnetized by a current passing through it, the bar has a circumferential magnetic field, and the geometries of detectable flaws are reversed.

FIGURE 11.4 Front-axle king pin for a truck: (a) As manufactured and apparently sound; (b) inspected under conventional magnetic particle inspection to reveal numerous grinding-induced cracks; (c) fluorescent particles and ultraviolet light make the cracks even more visible.

FIGURE 11.5 (a) Ultrasonic inspection of a flat plate with a single transducer; (b) plot of sound intensity or transducer voltage versus time showing the initial pulse and echoes from the bottom surface and intervening defect.

FIGURE 11.6 (a) Dual-transducer ultrasonic inspection in the pulse-echo mode; (b) dual transducers in through-transmission configuration.

FIGURE 11.7 Radiograph of the Liberty Bell. The photo reveals the famous crack, as well as the iron spider installed in 1915 to support the clapper and the steel beam and supports, which were set into the yoke in 1929.

FIGURE 11.8 Relation of the magnetizing coil, magnetizing current, and induced eddy currents. The magnetizing current is actually an alternating current, producing a magnetic field that forms, collapses, and reforms in the opposite direction. This dynamic magnetic field induces the eddy currents, and the changes in the eddy currents produce a secondary magnetic field that interacts with the sensor coil or probe.

FIGURE 11.9 Eddy currents are constrained to travel within the conductive material, but the magnitude and path of the currents will be affected by defects and changes in material properties. By focusing on the magnitude of the eddy currents, features such as differences in heat treatment can be detected.

Chapter 12

FIGURE 12.1 The concepts of accuracy (aim) and precision (repeatability) are shown in the four target outcomes. Accuracy refers to the ability of the process to hit the true value (nominal) on the average, while precision is a measure of the inherent variability of the process.

FIGURE 12.2 The process capability study compares the part as made by the manufacturing process to the specifications called out by the designer. Measurements from the parts are collected into run charts and for histograms for analysis.

FIGURE 12.3 Examples of calculations to obtain estimates of the mean (μ) and standard deviation (σ) of a process.

FIGURE 12.4 The normal or bell-shaped curve with the areas within ±1σ, ±2σ, and ±3σ for a normal distribution; 68.26% of the observations will fall within ±1 σ from the mean, and 99.73% will fall within ±3σ from the mean.

FIGURE 12.5 Common probability distributions that can be used to describe the outputs from manufacturing processes.

FIGURE 12.6 The output from the process is shifting toward the USL, which changes the C_{pk} ratio but not C_p ratio.

FIGURE 12.7 Five different scenarios for a process output versus the designer's specifications for the nominal (50) and upper and lower specifications of 65 and 38, respectively.

FIGURE 12.8 A linear variable-differential transformer (LVDT) is a key element in an insp ection station checking part diameters. Momentarily clamped into the sensor fixture, a part pushed the LVDT armature into the device winding. The LVDT output is proportional to the displacement of the armature. The transformer makes highly accurate measurements over a small displacement range.

FIGURE 12.9 Example of $\overline{X}$ and R charts and the data set of 25 samples [k = 25 of size 5 (n = 5)].

FIGURE 12.10 Quality control chart calculations. On the charts, plot $\overline{X}$ and R values over time. UCL and LCL values based on three standard deviations.

FIGURE 12.11 When you look at some of the output from a process and decide about the whole (i.e., the quality of the process), you can make two kinds of errors.

FIGURE 12.12 Gage capability (variation) contributes to the total observed variation in the measurement of a part.

FIGURE 12.13 Histogram shows the output mean, μ, from the process versus nominal and the tolerance specified by the designer versus the spread as measured by the standard deviation, σ. Nominal 49.2 USL = 60 LSL = 38 μ = 50.2 σ = 2.

FIGURE 12.14 An example of a run chart or graph, which can reveal trends in the process behavior not shown by the histogram.

FIGURE 12.15 Example of a check sheet for gathering data on a process.

FIGURE 12.16 Example of a cause-and-effect diagram using a RUN chart to track effects.

FIGURE 12.17 Typical patterns of corellation for scatter diagrams.

FIGURE 12.18 Usage rate of TQC methods and techniques reported at a QC conference.

FIGURE 12.19 Process flow diagram for refrigerator manufacturing showing monitoring points.

FIGURE 12.20 Example of a current-value-stream map.

FIGURE 12.21 Source inspection involves defect prevention—that is, prevent errors from turning into defects.

FIGURE 12.22 To move to six-sigma capability from four-sigma capability requires that the process capability (variability) be greatly improved (σ reduced). The curves in these figures represent histograms or curves fitted to histograms.

FIGURE 12.23 The use of Taguchi methods can reduce the inherent process variability as shown in the upper figure. Factors *A*, *B*, *C*, and *D* versus process variable *Y* shown in lower figure.

FIGURE 12.A

FIGURE 12.B

FIGURE CS-12

Chapter 13

FIGURE 13.1 The five materials processing families with subgroups and typical processes.

FIGURE 13.2 Cross section of a typical two-part sand mold indicating various mold components and terminology.

FIGURE 13.3 Cooling curve for a pure metal or eutectic-composition alloy (metals with a distinct freezing point) indicating major features related to solidification.

FIGURE 13.4 Phase diagram and companion cooling curve for an alloy with a freezing range. The slope changes indicate the onset and termination of solidification.

FIGURE 13.5 Internal structure of a cast metal bar showing the chill zone at the periphery, columnar grains growing toward the center, and a central shrinkage cavity.

FIGURE 13.6 Two types of ladles are used to pour castings. Note how each extracts molten material from the bottom, avoiding transfer of the impure material from the top of the molten pool.

FIGURE 13.7 The maximum solubility of hydrogen in aluminum as a function of temperature.

FIGURE 13.8 Demonstration casting made from aluminum that has been saturated in dissolved hydrogen. Note the extensive gas porosity.

FIGURE 13.9 Fluidity test using a spiral mold. The distance that the liquid travels prior to solidification is taken as a measure of metal fluidity.

FIGURE 13.10 Typical gating system for a horizontal-parting-plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

FIGURE 13.11 Various types of ceramic filters that may be inserted into the gating systems of metal castings.

FIGURE 13.12 Dimensional changes experienced by a metal column as the material cools from a superheated liquid to a room-temperature solid. Note the significant shrinkage that occurs on solidification.

FIGURE 13.13 A three-tier step-block aluminum casting made with (top) and without (bottom) a riser. Note how the riser has moved the shrinkage void external to the desired casting.

FIGURE 13.14 Schematic of a sand casting mold showing (a) an open-type top riser and (b) a blind-type side riser (right). The side riser is a live riser receiving the last hot metal to enter the mold. The top riser is a dead riser receiving metal that has flowed through the mold cavity.

FIGURE 13.15 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

FIGURE 13.16 Elimination of a core by changing the location or orientation of the parting plane.

FIGURE 13.17 Elimination of a dry-sand core by a change in part design.

FIGURE 13.18 Multiple options to cast a simple ring with draft to the parting line. Evaluate the six options with respect to the following possible concerns: (1) flat and parallel side surfaces, (2) flat and parallel inner and outer diameters, (3) amount of material that must be removed if no tapers are allowed on any surfaces, and (4) possibility for nonuniform wall thickness if one of the mold segments is shifted with respect to the other.

FIGURE 13.19 Typical guidelines for section change transitions in castings.

FIGURE 13.20 (a) The “hot spot” at section r_2 is caused by intersecting sections. (b) An interior fillet and exterior radius leads to more uniform thickness and more uniform cooling.

FIGURE 13.21 Hot spots often result from intersecting sections of various thickness.

FIGURE 13.22 Design modifications to reduce cracking and hot spot shrinkage in ribbed castings.

FIGURE 13.23 Computer model showing the progressive solidification of a cast steel mining shovel adapter. As time passes (left-to-right) the material directionally solidifies back toward the riser at the left side of the casting. Light material is liquid; dark material is solid.

FIGURE 13.A

FIGURE CS-13

Chapter 14

FIGURE 14.1 Sequential steps in making a sand casting. (a) A pattern board is placed between the bottom (drag) and top (cope) halves of a flask, with the bottom side up. (b) Sand is then packed into the bottom or drag half of the mold. (c) A bottom board is positioned on top of the packed sand, and the mold is turned over, showing the top (cope) half of pattern with sprue and riser pins in place. (d) The upper or cope half of the mold is then packed with sand. (e) The mold is opened, the pattern board is drawn (removed), and the runner and gate are cut into the bottom parting surface of the sand. (e’) The parting surface of the upper or cope half of the mold is also shown with the pattern and pins removed. (f) The core is positioned, the pattern board is removed, the mold is reassembled, and molten metal is poured through the sprue. (g) The contents are shaken from the flask, and the metal segment is separated from the sand, ready for further processing.

FIGURE 14.2 Single-piece pattern for a pinion gear.

FIGURE 14.3 Method of using a follow board to position a single-piece pattern and locate a parting surface. The final figure shows the flask of the previous operation (the drag segment) inverted in preparation for construction of the upper portion of the mold (cope segment).

FIGURE 14.4 Split pattern, showing the two sections together and separated. The light-colored portions are core prints.

FIGURE 14.5 Match-plate pattern used to produce two identical parts in a single flask. (Left) Cope side; (right) drag side. (*Note:* The views are opposite sides of a single pattern board.)

FIGURE 14.6 Cope-and-drag pattern for producing two heavy parts. (Left) Cope section; (right) drag section. (*Note:* These are two separate pattern boards.)

FIGURE 14.7 Loose-piece pattern for molding a large worm gear. After sufficient sand has been packed around the pattern to hold the pieces in position, the wooden pins are withdrawn. The mold is then completed, after which the pieces of the pattern can be removed in a designated sequence.

FIGURE 14.8 Schematic diagram of a continuous (left) and batch-type (right) sand muller. Plow blades move and loosen the sand, and the muller wheels compress and mix the components.

FIGURE 14.9 Schematic of a permeability tester in operation. A standard sample in a metal sleeve is sealed by an O-ring onto the top of the unit while air is passed through the sand.

FIGURE 14.10 Sand mold hardness tester.

FIGURE 14.11 Bottom and top halves of a snap flask. *(*Left*)* drag segment in closed position, *(*right*)* cope segment with latches opened for easy removal from the mold.

FIGURE 14.12 Jolting a mold section. (*Note*: The pattern is on the bottom where the greatest packing is expected.)

FIGURE 14.13 Squeezing a sand-filled mold section. While the pattern is on the bottom, the highest packing will be directly under the squeeze head.

FIGURE 14.14 Schematic diagram showing relative sand densities obtained by flat-plate squeezing where all areas get vertically compressed by the same amount of movement (left) and by flexible-diaphragm squeezing where all areas flow to the same resisting pressure (right).

FIGURE 14.15 Activity sequence for automatic match-plate molding. Green sand is blown from the side and compressed vertically. The final mold is ejected from the flask and poured in a flaskless condition.

FIGURE 14.16 Vertically parted flaskless molding with inset cores. Note how one mold block now contains both the cope and drag impressions.

FIGURE 14.17 A variety of sand cast aluminum parts.

FIGURE 14.18 Schematic of the dump-box version of shell molding. (a) A heated pattern is placed over a dump box containing granules of resin-coated sand. (b) The box is inverted and the heat forms a partially cured shell around the pattern. (c) The box is righted, the top is removed, and the pattern and partially cured sand is placed in an oven to further cure the shell. (d) The shell is stripped from the pattern. (e) Matched shells are then joined and supported in a flask ready for pouring.

FIGURE 14.19 (Top) Two halves of a shell-mold pattern. (Bottom) The two shells before clamping, and the final shell-mold casting with attached pouring basin, runner, and riser.

FIGURE 14.20 Schematic of the V-process or vacuum molding. (a) A vacuum is pulled on a pattern, drawing a heated shrink-wrap plastic sheet tightly against it. (b) A vacuum flask is placed over the pattern and filled with dry unbonded sand; a pouring basin and sprue are formed; the remaining sand is leveled; a second heated plastic sheet is placed on top; and a mold vacuum is drawn to compact the sand and hold the shape. (c) With the mold vacuum being maintained, the pattern vacuum is then broken and the pattern is withdrawn. The cope and drag segments are assembled, and the molten metal is poured.

FIGURE 14.21 Four methods of making a hole in a cast pulley. Three involve the use of a core.

FIGURE 14.22 (Upper right) A dump-type core box; (bottom) Two core halves ready for baking; and (upper left) a completed core made by gluing two opposing halves together.

FIGURE 14.23 (Left) Typical chaplets. (Right) Method of supporting a core by use of chaplets (relative size of the chaplets is exaggerated).

FIGURE 14.24 Method of making a reentrant angle or inset section by using a three-piece flask.

FIGURE 14.25 Molding an inset section using a dry-sand core.

FIGURE 14.26 Investment casting steps for the flask-cast method.

FIGURE 14.27 Investment casting steps for the shell-casting procedure.

FIGURE 14.28 Parts produced by investment casting. (a) Nickel and cobalt superalloys, (b) copper alloy, and (c) Aluminum fuel metering unit for an aircraft engine.

FIGURE 14.29 Illustration of the basic counter-gravity investment casting process.

FIGURE 14.30 Schematic of the full-mold process. (Left) An uncoated expanded polystyrene pattern is surrounded by bonded sand to produce a mold. (Right) Hot metal progressively vaporizes the expanded polystyrene pattern and fills the resulting cavity.

FIGURE 14.31 Schematic of the lost-foam casting process. In this process, the polystyrene pattern is dipped in a ceramic slurry, and the coated pattern is then surrounded with loose, unbonded sand.

FIGURE 14.32 The Styrofoam pattern and the finished casting of an automotive engine block produced by lost foam casting.

FIGURE CS-14 Dcwcreations/ iStock/ Getty Images

Chapter 15

FIGURE 15.1 An example of automotive pistons that have been mass-produced by the millions using permanent-mold casting.

FIGURE 15.2 Schematic of the tilt-pour permanent-mold process, showing the mold assembly in its tilted or vertical position.

FIGURE 15.3 Schematic of the low-pressure permanent-mold process.

FIGURE 15.4 Schematic illustration of vacuum permanent-mold casting. Note the similarities to the low-pressure process.

FIGURE 15.5 Various types of die-casting dies.

FIGURE 15.6 Principal components of a hot-chamber die-casting machine.

FIGURE 15.7 Principal components of a cold-chamber die-casting machine.

FIGURE 15.8 A variety of die cast products: zinc door handles and executive desk staplers; magnesium housings for pneumatic staplers and nailers; and aluminum aircraft food tray arms.

FIGURE 15.9 High-pressure aluminum die casting of an automotive transmission housing. Dimensions are 15 x 13 x 14.25 in.

FIGURE 15.10 Schematic representation of a horizontal centrifugal casting machine.

FIGURE 15.11 Vertical centrifugal casting, showing the effect of rotational speed on the shape of the inner surface. Paraboloid A results from fast spinning, whereas slower spinning will produce paraboloid B.

FIGURE 15.12 Brass and bronze bushings that have been produced by centrifugal casting.

FIGURE 15.13 Schematic of a semicentrifugal casting process.

FIGURE 15.14 Schematic of a centrifuging process. Metal is poured into the central pouring sprue and spun into the various mold cavities.

FIGURE 15.15 Gear produced by continuous casting. (Left) As-cast material; (right) after machining.

FIGURE 15.16 Cross section of a direct fuel-fired furnace. Hot combustion gases pass across the surface of a molten metal pool.

FIGURE 15.17 Schematic diagram of a three-phase electric-arc furnace.

FIGURE 15.18 Electric-arc furnace, tilted for pouring.

FIGURE 15.19 Schematic showing the basic principle of a coreless induction furnace.

FIGURE 15.20 Cross section showing the principle of the low-frequency or channel-type induction furnace.

FIGURE 15.21 Automatic pouring of molds on a conveyor line.

FIGURE 15.22 Typical unit cost of castings comparing sand casting and die casting. Note how the large cost of a die-casting die diminishes as it is spread over a larger quantity of parts.

FIGURE CS-15 Baseplate of a steam iron: *Left:* From bottom, *Right:* From top

Chapter 16

FIGURE 16.1 Simplified flowchart of the basic powder metallurgy process.

FIGURE 16.2 Two methods for producing metal powders: (a) melt atomization; (b) atomization from a rotating consumable electrode.

FIGURE 16.3 (a) Scanning electron microscope image of gas-atomized nickel powder showing the smooth surfaces that form by surface tension prior to solidification; (b) similar image of water-atomized iron powder showing the irregular shapes created by the rapid freezing of the shapes created by the water stream.

FIGURE 16.4 An 880-ton compacting press, capable of compacting multilevel powder metallurgy products. A second die set can be seen at the lower right side of the press, enabling quick change of the compaction tooling.

FIGURE 16.5 Typical compaction sequence for a single-level part, showing the functions of the feed shoe, die, core rod, and upper and lower punches. Loose powder is shaded; compacted powder is solid black.

FIGURE 16.6 Compaction with a single moving punch, showing the resultant nonuniform density (*shaded*), highest where particle movement is the greatest.

FIGURE 16.7 Density distribution obtained with a double-acting press and two moving punches. Note the increased uniformity compared to Figure 16.5. Thicker parts can be effectively compacted.

FIGURE 16.8 Effect of compacting pressure on green density (the density after compaction but before sintering). Separate curves are for several commercial powders.

FIGURE 16.9 Compaction of a two-thickness part with only one moving punch. (*a*) Initial conditions; (*b*) after compaction by the upper punch. Note the drastic difference in compacted density.

FIGURE 16.10 Two methods of compacting a double-thickness part to near-uniform density. Both involve the controlled movement of two or more punches.

FIGURE 16.11 Sample geometries of the four basic classes of press-and-sinter powder metallurgy parts shown in side view. Note the increased pressing complexity that would be required as class increases.

FIGURE 16.12 One method of producing continuous sheet products from powdered feedstock.

FIGURE 16.13 Flowchart of the metal injection molding process (MIM) used to produce small, intricate-shaped parts from metal powder.

FIGURE 16.14 Metal injection molding (MIM) is ideal for producing small, complex parts.

FIGURE 16.15 Comparison of conventional forging and the forging of a powder metallurgy preform to produce a gear blank (or gear). Moving left to right, the top sequence shows the sheared stock, upset section, forged blank, and exterior and interior scrap associated with conventional forging. The finished gear is generally machined from the blank with the generation of additional scrap. The bottom pieces are the powder metallurgy preform and forged gear produced entirely without scrap by P/M forging.

FIGURE 16.16 P/M forged connecting rods have been produced by the millions.

FIGURE 16.17 Mechanical properties versus as-sintered density for two iron-based powders. Properties depicted include yield strength, tensile strength, Charpy impact energy (shown in ft-lbs), and percent elongation in a 1-in. gage length.

FIGURE 16.18 Examples of poor and good design features for powder metallurgy products. Recommendations are based on ease of pressing, design of tooling, uniformity of properties, and ultimate performance.

FIGURE 16.19 Typical parts produced by the powder metallurgy process.

Chapter 17

FIGURE 17.1 Schematic representation of a metal forming system showing independent variables, dependent variables, and the various means of linking the two.

FIGURE 17.2 The effect of contact pressure on the frictional resistance between two surfaces.

FIGURE 17.3 Cross section of a 4-inch-diameter cast copper bar polished and etched to show the as-cast grain structure.

FIGURE 17.4 Etched surface of a forged component showing the grain flow pattern that gives forged parts enhanced strength, fracture resistance and fatigue life.

FIGURE 17.5 Schematic comparison of the grain flow in a machined thread (a) and a rolled thread (b). The rolling operation further deforms the axial structure produced by the previous wire- or rod-forming operations, while machining simply cuts through it.

FIGURE 17.6 Use of true stress–true strain diagrams to assess the suitability of two metals for cold working.

FIGURE 17.7 (*Left*) Stress–strain curve for a low-carbon steel showing the commonly observed yield-point runout; (*Right*) Luders bands or stretcher strains that form when this material is stretched to an amount less than the yield-point runout.

FIGURE 17.8 Mechanical properties of pure copper as a function of the amount of cold work (expressed in percent).

FIGURE 17.9 Increasing the temperature increases the formability of aluminum, decreasing the strength and increasing the ductility.

FIGURE 17.10 Yield strength of various materials (indicated by pressure required to forge a standard specimen) as a function of temperature. Materials with steep curves require isothermal forming.

Chapter 18

FIGURE 18.1 Flowchart for the production of various finished and semifinished steel shapes. Note the abundance of rolling operations.

FIGURE 18.2 Schematic representation of the hot-rolling process, showing the deformation and recrystallization of the metal being rolled.

FIGURE 18.3 Various roll configurations used in rolling operations.

FIGURE 18.4 The effect of roll diameter on the length of contact for a given reduction.

FIGURE 18.5 Typical roll-pass sequences used in producing structural shapes.

FIGURE 18.6 Schematic of a horizontal ring rolling operation. As the thickness of the ring is reduced, its diameter will increase.

FIGURE 18.7 (a) Loading on a rolling mill roll. The top roll is pressed upward in the center while being supported on the ends. (b) The elastic response to the three-point bending.

FIGURE 18.8 Use of a “crowned” roll to compensate for roll flexure. When the roll flexes in three-point bending, the crowned roll flexes into flatness.

FIGURE 18.9 (Left) Double-frame drop hammer. (Right) Schematic diagram of a forging hammer.

FIGURE 18.10 *(Top)* Illustration of the unrestrained flow of material in open-die forging. Note the barrel shape that forms due to friction between the die and material. *(Middle)* Open-die forging of a multidiameter shaft. *(Bottom)* Forging of a seamless ring by the open-die method.

FIGURE 18.11 Schematic of the impression-die forging process showing partial die filling and the beginning of flash formation in the center sketch, and the final shape with flash in the right-hand sketch.

FIGURE 18.12 Impression drop-forging dies and the product resulting from each impression. The flash is trimmed from the finished connecting rod in a separate trimming die. The sectional view shows the grain flow resulting from the forging process.

FIGURE 18.13 Schematic diagram of an impactor in the striking and returning modes.

FIGURE 18.14 A comparison of metal flow in conventional forging and impacting.

FIGURE 18.15 A forged-and-machined automobile engine crankshaft. Forged steel crankshafts provide superior performance, compared to those of ductile cast iron.

FIGURE 18.16 Schematic depiction of orbital forging.

FIGURE 18.17 Set of upset forging dies and punches. The product resulting from each of the four positions is shown along the bottom.

FIGURE 18.18 Schematics illustrating the rules governing upset forging.

FIGURE 18.19 (a) Typical four-step sequence to produce a spur-gear forging by automatic hot forging. The sheared billet is progressively shaped into an upset pancake, blocker forging, and finished gear blank. (b) Samples of ferrous parts produced by automatic hot forging at rates between 90 and 180 parts per minute.

FIGURE 18.20 (Left) Roll-forging machine in operation. (Right) Rolls from a roll-forging machine and the various stages in roll forging a part.

FIGURE 18.21 Schematic of the roll-forging process showing the two shaped rolls and the stock being formed.

FIGURE 18.22 Tube being reduced in a rotary swaging machine.

FIGURE 18.23 Basic components and motions of a rotary swaging machine. (*Note:* The cover plate has been removed to reveal the interior workings.)

FIGURE 18.24 A variety of swaged parts, some with internal details.

FIGURE 18.25 Steps in swaging a tube to form the neck of a gas cylinder.

FIGURE 18.26 Direct extrusion schematic showing the various equipment components.

FIGURE 18.27 Typical shapes produced by extrusion. (Left) Aluminum products. (Right) Steel products.

FIGURE 18.28 Direct and indirect extrusion. In direct extrusion, the ram and billet both move, and friction between the billet and the chamber opposes forward motion. For indirect extrusion, the billet is stationary. There is no billet–chamber friction because there is no relative motion.

FIGURE 18.29 Diagram of the ram force versus ram position for both direct and indirect extrusion of the same product. The area under the curve corresponds to the amount of work (force x distance) performed. The difference between the two curves is attributed to billet-chamber friction.

FIGURE 18.30 Grid pattern showing the metal flow in a direct extrusion. The billet was sectioned and the grid pattern was engraved prior to extrusion.

FIGURE 18.31 Two methods of extruding hollow shapes using internal mandrels. (a) The mandrel and ram have independent motions; (b) they move as a single unit.

FIGURE 18.32 Hot extrusion of a hollow shape using a spider-mandrel die. Note the four arms connecting the external die and the central mandrel.

FIGURE 18.33 Comparison of conventional (left) and hydrostatic (right) extrusion. Note the addition of the pressurizing fluid and the O-ring and miter-ring seals on both the die and ram.

FIGURE 18.34 Cross-sectional schematic of the Conform continuous extrusion process. The material upsets at the abutment and extrudes. Section x–x shows the material in the shoe.

FIGURE 18.35 Schematic diagram of the rod- or bar-drawing process.

FIGURE 18.36 Diagram of a chain-driven, multiple-die, draw bench used to produce finite lengths of straight rod or tube.

FIGURE 18.37 Cold-drawing smaller tubing from larger tubing. The die sets the outer dimension while the stationary mandrel sizes the inner diameter.

FIGURE 18.38 Tube drawing with a floating plug.

FIGURE 18.39 Schematic of wire drawing with a rotating draw block. The rotating motor on the draw block provides a continuous pull on the incoming wire.

FIGURE 18.40 Cross section through a typical carbide wire drawing die showing the characteristic regions of the contour.

FIGURE 18.41 Schematic of a multistation synchronized wire drawing machine. To prevent accumulation or breakage, it is necessary to ensure that the same volume of material passes through each station in a given time. The loops around the sheaves between the stations use wire tensions and feedback electronics to provide the necessary speed control.

FIGURE 18.42 Typical steps in a shearing and cold-heading operation.

FIGURE 18.43 Method of upsetting the center portion of a rod. The stock is supported in both dies during upsetting.

FIGURE 18.44 Backward and forward extrusion with open and closed dies.

FIGURE 18.45 (a) Reverse, (b) forward, and (c) combined forms of cold extrusion.

FIGURE 18.46 Steps in the forming of a bolt by cold extrusion, cold heading, and thread rolling.

FIGURE 18.47 Cold-forming sequence involving cutoff, squaring, two extrusions, an upset, and a trimming operation. Also shown are the finished part and the trimmed scrap.

FIGURE 18.48 Typical parts made by upsetting and related operations.

FIGURE 18.49 Manufacture of a spark plug body: (left) by machining from hexagonal bar stock; (right) by cold forming. Note the reduction in waste.

FIGURE 18.50 Section of the cold-formed spark-plug body of Figure 18.49, etched to reveal the flow lines. The cold-formed structure produces an 18% increase in strength over the machined product.

FIGURE 18.51 (Left) Principle of the Mannesmann process of producing seamless tubing. (Right) Mechanism of crack formation in the Mannesmann process.

FIGURE 18.52 The roll extrusion process: (a) with internal rollers expanding the inner diameter; (b) with external rollers reducing the outer diameter.

FIGURE 18.53 Joining components by riveting.

FIGURE 18.54 Rivets for use in “blind” riveting: (left) explosive type;(center) shank-type pull-up; (right) installation sequence for the shank-type pull-up rivet

FIGURE 18.55 Permanently attaching a shaft to a plate by staking.

FIGURE 18.56 The coining process.

FIGURE 18.57 Hubbing a die block in a hydraulic press. Inset shows close-up of the hardened hub and the impression in the die block. The die block is contained in a reinforcing ring. The upper surface of the die block is then machined flat to remove the bulged metal.

FIGURE 18.58 Tools for roller burnishing. (a) Tool for internal diameter burnishing; (b) Tool for the burnishing of outer diameters. The burnishing rollers move inward or outward by means of an adjustable taper.

FIGURE 18.A Some typical defects that occur during rolling: wavy edges, edge cracking, and center cracking.

FIGURE 18.B Strip rolling where the width of the strip remains unchanged. The lines across the

workpiece identify the area of contact with the rolls. The top roll has been removed for ease of visualization.

Chapter 19

FIGURE 19.1 Simple blanking with a punch and die.

FIGURE 19.2 (Top) Conventionally sheared surface showing the distinct regions of deformation and fracture. (Bottom) Magnified view of the sheared edge.

FIGURE 19.3 Fineblanking method of obtaining a smooth edge in shearing by using a shaped pressure plate to put the metal into localized compression and a punch and opposing punch descending in unison. The resulting product shows die roll and burr formation on opposite sides and a smooth edge surface.

FIGURE 19.4 Fine-blanked surface of the same component shown in Figure 19.2 .

FIGURE 19.5 Method of smooth shearing a rod by putting it into compression during shearing.

FIGURE 19.6 A 3-m (10 ft) power shear for 6.5-mm (1/4-in.) steel.

FIGURE 19.7 Schematic showing the difference between piercing and blanking.

FIGURE 19.8 (Left to right) Piercing, lancing, and blanking precede the forming of the final disc-shaped piece. The small round holes assist positioning and alignment.

FIGURE 19.9 Shearing operation being performed on a nibbling machine.

FIGURE 19.10 The dinking process.

FIGURE 19.11 The basic components of piercing and blanking dies.

FIGURE 19.12 Blanking with a square-faced punch (left) and one containing angular shear (right). Note the difference in maximum force and contact stroke. The total work (the area under the curve) is the same for both processes.

FIGURE 19.13 Typical die set having two alignment guideposts.

FIGURE 19.14 Modular tooling (subpress dies) assembled to produce a desired pattern.

FIGURE 19.15 Progressive piercing and blanking die for making a square washer. Note that the punches are of different lengths.

FIGURE 19.16 The various stages of an 11-station progressive die.

FIGURE 19.17 Method for making a simple washer in a compound piercing and blanking die. Part is (a) blanked and (b) subsequently pierced in the same stroke. The blanking punch contains the die for piercing.

FIGURE 19.18 (Top) Nature of a bend in sheet metal showing tension on the outside and compression on the inside. (Bottom) The upper portion of the bend region, viewed from the side, shows how the center portion will thin more than the edges.

FIGURE 19.19 Phantom section of a bar folder, showing position and operation of internal components.

FIGURE 19.20 (Left) A commercial press brake. (Right) Close-up view of press brake dies forming corrugations.