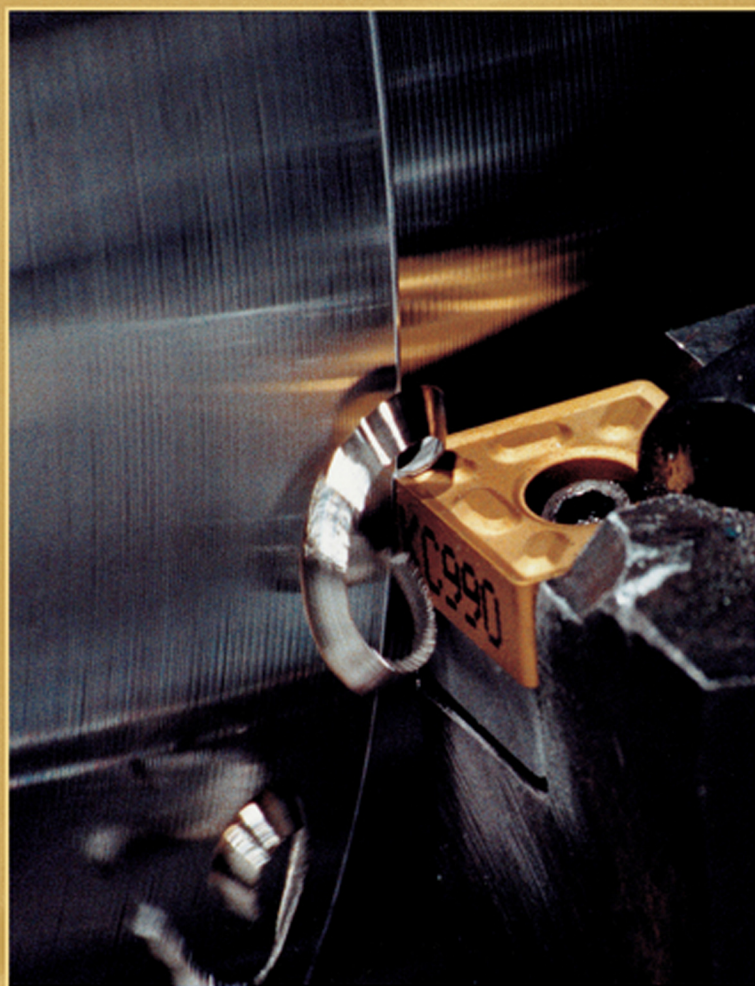


FUNDAMENTALS OF
**MODERN
MANUFACTURING**

MATERIALS, PROCESSES, AND SYSTEMS



MIKELL P. GROOVER

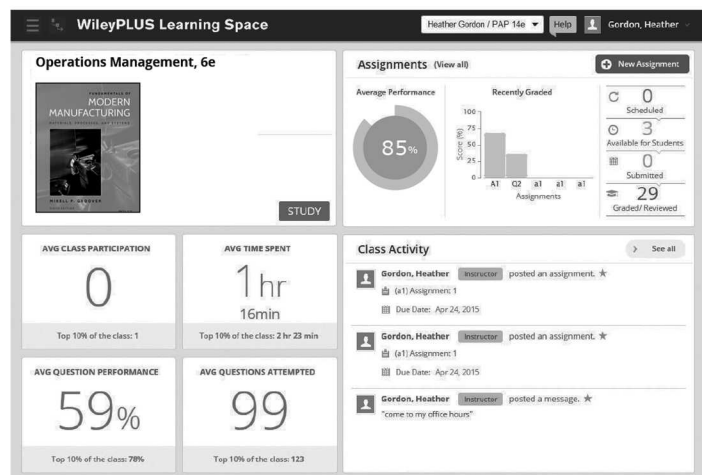
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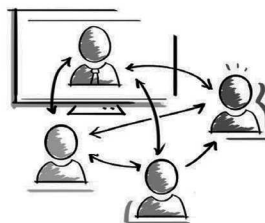
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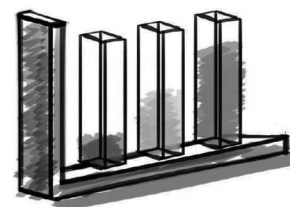
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- Remember what you have learned because you have made deeper connections to the content

Fundamentals of Modern Manufacturing

Fundamentals of Modern Manufacturing

Materials, Processes, and Systems
Sixth Edition

Mikell P. Groover

Professor Emeritus of Industrial and
Systems Engineering, Lehigh University

The author and publisher gratefully acknowledge the contributions of Dr. Gregory L. Tonkay, Associate Professor of Industrial and Systems Engineering, and Associate Dean, College of Engineering and Applied Science, Lehigh University.

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PREFACE

Fundamentals of Modern Manufacturing: Materials, Processes, and Systems is designed for a first course or two-course sequence in manufacturing at the junior or senior level in mechanical, industrial, and manufacturing engineering curricula. Given its coverage of engineering materials, it may also be suitable for materials science and engineering courses that emphasize materials processing. Finally, it may be appropriate for technology programs related to the preceding engineering disciplines. Most of the book's content is concerned with manufacturing processes (about 65% of the text), but it also provides significant coverage of engineering materials and production systems. Materials, processes, and systems are the basic building blocks of modern manufacturing and the three broad subject areas covered in the book.

Approach

The author's objective in this and the preceding editions is to provide a treatment of manufacturing that is modern and quantitative. Its claim to be "modern" is based on (1) its balanced coverage of the basic engineering materials (metals, ceramics, polymers, and composite materials), (2) its inclusion of recently developed manufacturing processes in addition to the traditional processes that have been used and refined over many years, and (3) its comprehensive coverage of electronics manufacturing technologies. Competing textbooks tend to emphasize metals and their processing at the expense of the other engineering materials, whose applications and methods of processing have grown significantly in the last several decades. Also, most competing books provide minimum coverage of electronics manufacturing. Yet the commercial importance of electronics products and their associated industries have increased substantially during recent decades.

The book's claim to be quantitative is based on its emphasis on manufacturing science and its greater use of mathematical models and quantitative (end-of-chapter) problems than other manufacturing textbooks. In the case of some processes, it was the first book on manufacturing processes to provide a quantitative coverage of the topic.

Organization of the Book

The first chapter provides an introduction and overview of manufacturing. Manufacturing is defined, and the materials, processes, and systems of manufacturing are briefly described. The final section provides an introduction to manufacturing economics. The remaining 39 chapters are organized into 11 parts. Part I, titled Material Properties and Product Attributes, consists of four chapters that describe the important characteristics of materials and the products made from them. Part II discusses the four basic engineering materials: metals, ceramics, polymers, and composites.

Part III begins the coverage of the part-shaping processes, which are organized into four categories: (1) solidification processes, (2) particulate processes, (3) deformation processes, and (4) material removal processes. Part III consists of five chapters on the solidification processes that include casting of metals, glassworking, and polymer shaping. In Part IV, the processing of powders of metals and ceramics is covered in two chapters. Part V deals with metal deformation processes such as rolling, forging, extrusion, and sheet metalworking. Finally, Part VI discusses the material removal processes. Four chapters are devoted to machining, and two chapters cover grinding (and related abrasive processes) and nontraditional material removal technologies.

Part VII consists of two chapters on property-enhancing processes and surface processing. Property enhancing is accomplished by heat treatment, and surface processing includes operations such as cleaning, electroplating, vapor deposition processes, and coating (painting).

Joining and assembly processes are considered in Part VIII, which is organized into four chapters on welding, brazing, soldering, adhesive bonding, and mechanical assembly.

Several unique processes that do not neatly fit into the preceding classification scheme are covered in Part IX, titled Special Processing and Assembly Technologies. Its five chapters cover rapid prototyping and additive manufacturing, processing of integrated circuits, electronics assembly, microfabrication, and nanofabrication.

Part X begins the coverage of the systems of manufacturing. Its two chapters deal with the types of automation technologies in a factory, such as numerical control and industrial robotics, and how these technologies are integrated into systems, such as production lines, manufacturing cells, and flexible manufacturing systems. Finally, Part XI deals with manufacturing support systems: process planning, production planning and control, lean production, and quality control and inspection.

New to this Edition

The organization of the sixth edition remains the same as the fifth edition, although several new sections have been added and others have been updated. The following material is new or revised in the sixth edition:

- The section on Manufacturing Economics in Chapter 1 (Introduction and Overview of Manufacturing) has been expanded.
- The section on Heating the Metal in Chapter 10 (Fundamentals of Metal Casting) has been revised to introduce the concept of “unit energy for melting and pouring” and a new example problem and several end-of-chapter problems have been added.
- A new section on Casting Economics has been added to Chapter 11 (Metal Casting Processes), including equations, example problems, and end-of-chapter problems.
- A new section on Automated Lay-up has been added to Chapter 14 (Processing of Polymer Matrix Composites and Rubber).
- The sections on Power and Energy Relationships in Machining and Cutting Temperature in Chapter 20 (Metal Machining Theory) have been revised and simplified.
- A new section on Welding Economics has been added to Chapter 29 (Welding Processes), including equations, example problems, and end-of-chapter problems.
- Chapter 33 (Processing of Integrated Circuits) has been updated.
- The section on Microsystem Products in Chapter 35 (Microfabrication Technologies) has been simplified to place more emphasis on microfabrication processes.
- About 30% of the end-of-chapter problems are new or revised.

On the other hand, the page count in the sixth edition has been reduced through a more compact page format, elimination of certain material, editorial enhancements, and other changes. Among these changes are the following:

- The section on Recent Developments in Manufacturing in Chapter 1 has been removed.
- All Historical Notes have been removed from the book; instead, they are posted on the website for the book.
- Tables in Chapter 6 (Metals) and Chapter 8 (Polymers) have been consolidated to simplify data presentation. Other tables in the text have been updated.

- The section on NC Computer-Assisted Part Programming in Chapter 37 (Automation Technologies) has been eliminated; the author's observation is that it has been largely superseded by CAD/CAM-assisted part programming.

Support Material for Instructors

Three levels of support materials are available for instructors who adopt *Fundamentals of Modern Manufacturing* for their courses.

First, for instructors who adopt the printed book for their courses and desire to have only the traditional support materials, the following items are available on the website for the book:

- A complete set of Powerpoint Lecture Slides for all chapters is available to instructors for their class lectures. Instructors can decide whether to make these slides available to their students.
- Illustrations from the book are available to instructors in the Arts PowerPoints and Image Gallery for instructors who wish to create their own lecture slides.
- A *Solutions Manual* (in digital format) covering all review questions and end-of-chapter problems is available on the website for the book. Instructors can use these materials as homework exercises or to make up quizzes for their courses.

These support materials may be found at the website www.wiley.com/college/groover. Evidence that the book has been adopted as the main textbook for the course must be verified.

WileyPLUS Learning Space

In addition to the resources described above, the following resources are available to instructors in *WileyPLUS Learning Space*. These items can be used either as support materials only for instructors to use or as support materials to be shared between instructors and their students. Instructors can learn more about these resources and register for access to them at www.wileypluslearningspace.com. The following support materials are available only for instructors in *WileyPLUS Learning Space*:

- Video clips of many of the manufacturing processes described in the printed textbook. Instructors can select which clips to use in support of their lectures.
- Multiple-choice questions associated with most sections of the book are available in *WileyPLUS Learning Space* for instructors to assign to their students as individual learning exercises or to make up quizzes for their courses.
- Case studies developed by Prof. Dan Waldorf of California State Polytechnic University, which are designed to be used in conjunction with the video clips. Instructors can assign these case studies as homework or laboratory exercises.

Finally, the following resources and features are available to students whose instructors adopt *WileyPLUS Learning Space* for their courses:

- The complete, dynamic e-textbook in which students can highlight, take notes, interact with their instructor and other students, and create their own personal study guide.
- Learning Objectives for each major section of the e-textbook.
- Multiple-choice questions following each section of the e-textbook give students an opportunity to test their understanding of the material in the section. Students receive immediate feedback on their answers. Instructors may also assign these questions.

- Video clips of many manufacturing processes are linked contextually within the e-textbook in *WileyPLUS Learning Space*.
- Case studies developed by Prof. Dan Waldorf of California State Polytechnic University, which are designed to be used in conjunction with the video clips. Instructors can assign these case studies as homework or laboratory exercises.

For educators who adopt *WileyPLUS Learning Space* for their course, their students will have access to an integrated on-line experience, blending the e-textbook with the resources and features listed here. To facilitate access, an instructor must set up their *WileyPLUS Learning Space* course in advance and require their students to register and use it. Students may obtain access using a registration code that can be packaged with the print edition, or they may purchase access at www.wiley-plus.com after the instructor's course has been set up. Since *WileyPLUS Learning Space* includes the complete digital e-textbook, students can save up to 60% off the cost of a printed textbook if they choose to purchase online access alone.

An e-textbook version of the book is available to students whose instructors do not adopt *WileyPLUS Learning Space* for their course, but it does not include the resources and features listed above (learning objectives, multiple-choice questions, video clips, and case studies).

Individual questions or comments may be directed to the author personally at Mikell.Groover@Lehigh.edu.

ACKNOWLEDGEMENTS

This book has been published in five previous editions. I like to believe that each new revision has been an improvement over its predecessor and that this sixth edition is the culmination of these successive improvements. If I indulge myself this belief, it has been made possible by many people who have (1) participated in surveys conducted by the publisher, (2) served as technical reviewers of the book, (3) identified errors in the text, and (4) communicated their opinions and suggestions to me. In all cases, I have appreciated the feedback and would like to acknowledge the individuals for their contributions, apologizing in advance for any unintended omissions. In alphabetical order, with affiliations in parentheses, they are Iftikhar Ahmad (George Mason University), John T. Berry (Mississippi State University), J. T. Black (Auburn University), David Bourell (University of Texas at Austin), Richard Budihas (Voltaic LLC), David Che (Geneva College), Paul Cotnoir (Worcester Polytechnic Institute), John Coulter (Lehigh University), Robert E. Eppich (American Foundryman's Society), Gayle Ermer (Calvin College), Osama Eyeda (Virginia Polytechnic Institute and State University), Wolter Fabricky (Virginia Polytechnic Institute and State University), Jack Feng (formerly of Bradley University and now at Caterpillar, Inc.), Keith Gardiner (Lehigh University), Jay R. Geddes (San Jose State University), Shivan Haran (Arkansas State University), R. Heikes (Georgia Institute of Technology), Andrew Herzing (Lehigh University), Yong Huang (Clemson University), Ralph Jaccodine (Lehigh University), Marian Kennedy (Clemson University), Aram Khachatourians (California State University, Northridge), Steven Liang (Georgia Institute of Technology), Harlan MacDowell (Michigan State University), Wojciech Misiolek (Lehigh University), Barbara Mizdail (Pennsylvania State University – Berks campus), Joe Mize (Oklahoma State University), Amy Moll, (Boise State University), Colin Moodie (Purdue University), Victor Okhuysen (California State Polytechnic University, Pomona), Nicholas Odrey (Lehigh University), Michael Philpott (University of Illinois at Champaign-Urbana), Corrado Poli (University of Massachusetts at Amherst), Chell Roberts (Arizona State University), Anil Saigal (Tufts University), Huseyin Sarper (Colorado State University-Pueblo), G. Sathyanarayanan (Lehigh University), Rajiv Shivpuri (Ohio State University), Larry Smith (St. Clair College, Windsor, Ontario), Malur Srinivasan (Texas A&M University), Brent Strong (Brigham Young University), James B. Taylor (North Carolina State University), Yonglai Tian (George Mason University), Gregory L. Tonkay (Lehigh University), Joel Troxler (Montana State University), Ampere A. Tseng (Arizona State University), Chester VanTyne (Colorado School of Mines), Robert Voigt (Pennsylvania State University), Daniel Waldorf (California State Polytechnic University, San Luis Obispo), Jim Waterman (Program Manager, Army ManTech Program; and Adjunct Professor, Rowan University), Charles White (GMI Engineering and Management Institute), Marvin White (Lehigh University), and Parviz Yavari (California State University, Long Beach).

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CONTENTS

1 INTRODUCTION AND OVERVIEW OF MANUFACTURING 1

- 1.1 What Is Manufacturing? 2
- 1.2 Materials in Manufacturing 6
- 1.3 Manufacturing Processes 9
- 1.4 Production Systems 14
- 1.5 Manufacturing Economics 17

Part I Material Properties and Product Attributes 26

2 THE NATURE OF MATERIALS 26

- 2.1 Atomic Structure and the Elements 26
- 2.2 Bonding between Atoms and Molecules 29
- 2.3 Crystalline Structures 31
- 2.4 Noncrystalline (Amorphous) Structures 36
- 2.5 Engineering Materials 37

3 MECHANICAL PROPERTIES OF MATERIALS 40

- 3.1 Stress–Strain Relationships 40
- 3.2 Hardness 53
- 3.3 Effect of Temperature on Properties 57
- 3.4 Fluid Properties 59
- 3.5 Viscoelastic Behavior of Polymers 61

4 PHYSICAL PROPERTIES OF MATERIALS 66

- 4.1 Volumetric and Melting Properties 66
- 4.2 Thermal Properties 69
- 4.3 Mass Diffusion 70
- 4.4 Electrical Properties 72
- 4.5 Electrochemical Processes 74

5 DIMENSIONS, SURFACES, AND THEIR MEASUREMENT 77

- 5.1 Dimensions, Tolerances, and Related Attributes 77

- 5.2 Conventional Measuring Instruments and Gages 78
- 5.3 Surfaces 85
- 5.4 Measurement of Surfaces 89
- 5.5 Effect of Manufacturing Processes 91

Part II Engineering Materials 94

6 METALS 94

- 6.1 Alloys and Phase Diagrams 95
- 6.2 Ferrous Metals 99
- 6.3 Nonferrous Metals 115
- 6.4 Superalloys 123

7 CERAMICS 126

- 7.1 Structure and Properties of Ceramics 127
- 7.2 Traditional Ceramics 129
- 7.3 New Ceramics 131
- 7.4 Glass 133
- 7.5 Some Important Elements Related to Ceramics 136

8 POLYMERS 140

- 8.1 Fundamentals of Polymer Science and Technology 141
- 8.2 Thermoplastic Polymers 150
- 8.3 Thermosetting Polymers 155
- 8.4 Elastomers 158
- 8.5 Polymer Recycling and Biodegradability 162

9 COMPOSITE MATERIALS 166

- 9.1 Technology and Classification of Composite Materials 167
- 9.2 Metal Matrix Composites 174
- 9.3 Ceramic Matrix Composites 176
- 9.4 Polymer Matrix Composites 177

Part III Solidification Processes 181

10 FUNDAMENTALS OF METAL CASTING 181

- 10.1 Overview of Casting Technology 182
- 10.2 Heating and Pouring 184
- 10.3 Solidification and Cooling 188

11 METAL CASTING PROCESSES 198

- 11.1 Sand Casting 198
- 11.2 Other Expendable-Mold Casting Processes 202
- 11.3 Permanent-Mold Casting Processes 207
- 11.4 Foundry Practice 215
- 11.5 Casting Quality 219
- 11.6 Castability and Casting Economics 221
- 11.7 Product Design Considerations 225

12 GLASSWORKING 230

- 12.1 Raw Materials Preparation and Melting 230
- 12.2 Shaping Processes in Glassworking 231
- 12.3 Heat Treatment and Finishing 236
- 12.4 Product Design Considerations 237

13 SHAPING PROCESSES FOR PLASTICS 239

- 13.1 Properties of Polymer Melts 240
- 13.2 Extrusion 242
- 13.3 Production of Sheet and Film 251
- 13.4 Fiber and Filament Production (Spinning) 254
- 13.5 Coating Processes 255
- 13.6 Injection Molding 256
- 13.7 Compression and Transfer Molding 266
- 13.8 Blow Molding and Rotational Molding 268
- 13.9 Thermoforming 273
- 13.10 Casting 277
- 13.11 Polymer Foam Processing and Forming 278
- 13.12 Product Design Considerations 279

14 PROCESSING OF POLYMER MATRIX COMPOSITES AND RUBBER 285

- 14.1 Overview of PMC Processing 285
- 14.2 Open-Mold Processes 289

- 14.3 Closed-Mold Processes 293
- 14.4 Other PMC Shaping Processes 295
- 14.5 Rubber Processing and Shaping 299
- 14.6 Manufacture of Tires and Other Rubber Products 304

Part IV Particulate Processing of Metals and Ceramics 309

15 POWDER METALLURGY 309

- 15.1 Characterization of Engineering Powders 310
- 15.2 Production of Metallic Powders 314
- 15.3 Conventional Pressing and Sintering 316
- 15.4 Alternative Pressing and Sintering Techniques 322
- 15.5 Materials and Products for Powder Metallurgy 325
- 15.6 Design Considerations in Powder Metallurgy 326

16 PROCESSING OF CERAMICS AND CERMETS 331

- 16.1 Processing of Traditional Ceramics 331
- 16.2 Processing of New Ceramics 339
- 16.3 Processing of Cermets 341
- 16.4 Product Design Considerations 343

Part V Metal Forming and Sheet Metalworking 345

17 FUNDAMENTALS OF METAL FORMING 345

- 17.1 Overview of Metal Forming 345
- 17.2 Material Behavior in Metal Forming 348
- 17.3 Temperature in Metal Forming 349
- 17.4 Strain Rate Sensitivity 351
- 17.5 Friction and Lubrication in Metal Forming 353

18 BULK DEFORMATION PROCESSES IN METAL WORKING 356

- 18.1 Rolling 356
- 18.2 Forging 365
- 18.3 Extrusion 380
- 18.4 Wire and Bar Drawing 390

19 SHEET METALWORKING 401

- 19.1 Cutting Operations 401
- 19.2 Bending Operations 408
- 19.3 Drawing 412
- 19.4 Dies and Presses for Sheet Metal Processes 419
- 19.5 Other Sheet-Metal-Forming Operations 425
- 19.6 Sheet Metal Operations Not Performed on Presses 428
- 19.7 Bending of Tube Stock 433

Part VI Material Removal Processes 439**20 THEORY OF METAL MACHINING 439**

- 20.1 Overview of Machining Technology 441
- 20.2 Theory of Chip Formation in Metal Machining 444
- 20.3 Force Relationships and the Merchant Equation 448
- 20.4 Power and Energy Relationships in Machining 453
- 20.5 Cutting Temperature 455

21 MACHINING OPERATIONS AND MACHINE TOOLS 459

- 21.1 Machining and Part Geometry 459
- 21.2 Turning and Related Operations 462
- 21.3 Drilling and Related Operations 470
- 21.4 Milling 475
- 21.5 Machining Centers and Turning Centers 482
- 21.6 Other Machining Operations 484
- 21.7 Machining Operations for Special Geometries 489
- 21.8 High-Speed Machining 495

22 CUTTING-TOOL TECHNOLOGY 500

- 22.1 Tool Life 500
- 22.2 Tool Materials 506
- 22.3 Tool Geometry 513
- 22.4 Cutting Fluids 523

23 ECONOMIC AND PRODUCT DESIGN CONSIDERATIONS IN MACHINING 529

- 23.1 Machinability 529
- 23.2 Tolerances and Surface Finish 530
- 23.3 Machining Economics 535
- 23.4 Product Design Considerations in Machining 541

24 GRINDING AND OTHER ABRASIVE PROCESSES 546

- 24.1 Grinding 546
- 24.2 Related Abrasive Processes 562

25 NONTRADITIONAL MACHINING AND THERMAL CUTTING PROCESSES 568

- 25.1 Mechanical Energy Processes 569
- 25.2 Electrochemical Machining Processes 572
- 25.3 Thermal Energy Processes 576
- 25.4 Chemical Machining 585
- 25.5 Application Considerations 590

Part VII Property Enhancing and Surface Processing Operations 595**26 HEAT TREATMENT OF METALS 595**

- 26.1 Annealing 595
- 26.2 Martensite Formation in Steel 596
- 26.3 Precipitation Hardening 600
- 26.4 Surface Hardening 601
- 26.5 Heat Treatment Methods and Facilities 602

27 SURFACE PROCESSING OPERATIONS 606

- 27.1 Industrial Cleaning Processes 606
- 27.2 Diffusion and Ion Implantation 610
- 27.3 Plating and Related Processes 611
- 27.4 Conversion Coating 615
- 27.5 Vapor Deposition Processes 616
- 27.6 Organic Coatings 622
- 27.7 Porcelain Enameling and Other Ceramic Coatings 624
- 27.8 Thermal and Mechanical Coating Processes 625

Part VIII Joining and Assembly Processes 628

28 FUNDAMENTALS OF WELDING 628

- 28.1 Overview of Welding Technology 629
- 28.2 The Weld Joint 631
- 28.3 Physics of Welding 634
- 28.4 Features of a Fusion-Welded Joint 637

29 WELDING PROCESSES 641

- 29.1 Arc Welding 641
- 29.2 Resistance Welding 650
- 29.3 Oxyfuel Gas Welding 657
- 29.4 Other Fusion-Welding Processes 661
- 29.5 Solid-State Welding 663
- 29.6 Weld Quality 669
- 29.7 Weldability and Welding Economics 673
- 29.8 Design Considerations in Welding 676

30 BRAZING, SOLDERING, AND ADHESIVE BONDING 681

- 30.1 Brazing 681
- 30.2 Soldering 686
- 30.3 Adhesive Bonding 690

31 MECHANICAL ASSEMBLY 697

- 31.1 Threaded Fasteners 697
- 31.2 Rivets and Eyelets 704
- 31.3 Assembly Methods Based on Interference Fits 705
- 31.4 Other Mechanical Fastening Methods 708
- 31.5 Molding Inserts and Integral Fasteners 709
- 31.6 Design for Assembly 710

Part IX Special Processing and Assembly Technologies 716

32 RAPID PROTOTYPING AND ADDITIVE MANUFACTURING 716

- 32.1 Fundamentals of Rapid Prototyping and Additive Manufacturing 717
- 32.2 Additive Manufacturing Processes 719

- 32.3 Cycle Time and Cost Analysis 726
- 32.4 Additive Manufacturing Applications 730

33 PROCESSING OF INTEGRATED CIRCUITS 734

- 33.1 Overview of IC Processing 735
- 33.2 Silicon Processing 738
- 33.3 Lithography 743
- 33.4 Layer Processes Used in IC Fabrication 747
- 33.5 Integrating the Fabrication Steps 753
- 33.6 IC Packaging 755
- 33.7 Yields in IC Processing 759

34 ELECTRONICS ASSEMBLY AND PACKAGING 764

- 34.1 Electronics Packaging 764
- 34.2 Printed Circuit Boards 766
- 34.3 Printed Circuit Board Assembly 773
- 34.4 Electrical Connector Technology 780

35 MICROFABRICATION TECHNOLOGIES 785

- 35.1 Microsystem Products 785
- 35.2 Microfabrication Processes 788

36 NANOFABRICATION TECHNOLOGIES 797

- 36.1 Nanotechnology Products and Applications 797
- 36.2 Introduction to Nanoscience 801
- 36.3 Nanofabrication Processes 805

Part X Manufacturing Systems 812

37 AUTOMATION TECHNOLOGIES FOR MANUFACTURING SYSTEMS 812

- 37.1 Automation Fundamentals 812
- 37.2 Hardware for Automation 815
- 37.3 Computer Numerical Control 819
- 37.4 Industrial Robotics 830

38 INTEGRATED MANUFACTURING SYSTEMS 838

- 38.1 Material Handling 838
- 38.2 Fundamentals of Production Lines 839

- 38.3 Manual Assembly Lines 841
- 38.4 Automated Production Lines 845
- 38.5 Cellular Manufacturing 849
- 38.6 Flexible Manufacturing Systems 853
- 38.7 Computer-Integrated Manufacturing 857

Part XI Manufacturing Support Systems 861

39 PROCESS PLANNING AND PRODUCTION CONTROL 861

- 39.1 Process Planning 862
- 39.2 Other Manufacturing Engineering Functions 869
- 39.3 Production Planning and Control 872

- 39.4 Just-In-Time Delivery Systems 879
- 39.5 Lean Production 882

40 QUALITY CONTROL AND INSPECTION 887

- 40.1 Product Quality 887
- 40.2 Process Capability and Tolerances 888
- 40.3 Statistical Process Control 890
- 40.4 Quality Programs in Manufacturing 894
- 40.5 Inspection Principles 898
- 40.6 Modern Inspection Technologies 900

APPENDIX: Answers to Selected Problems 909

INDEX 913

Introduction and Overview of Manufacturing

1.1 What Is Manufacturing?

- 1.1.1 Manufacturing Defined
- 1.1.2 Manufacturing Industries and Products
- 1.1.3 Manufacturing Capability

1.2 Materials in Manufacturing

- 1.2.1 Metals
- 1.2.2 Ceramics
- 1.2.3 Polymers
- 1.2.4 Composites

1.3 Manufacturing Processes

- 1.3.1 Processing Operations
- 1.3.2 Assembly Operations
- 1.3.3 Production Machines and Tooling

1.4 Production Systems

- 1.4.1 Production Facilities
- 1.4.2 Manufacturing Support Systems

1.5 Manufacturing Economics

- 1.5.1 Production Cycle Time Analysis
- 1.5.2 Manufacturing Cost Models

Making things has been an essential activity of human civilizations since before recorded history. Today, the term *manufacturing* is used for this activity. For technological and economic reasons, manufacturing is important to the welfare of the United States and most other developed and developing nations. **Technology** can be defined as the application of science to provide society and its members with those things that are needed or desired. Technology affects our daily lives, directly and indirectly, in many ways. Consider the list of products in Table 1.1. They represent various technologies that help society and its members to live better. What do all these products have in common? They are all manufactured. These technological wonders would not be available to society if they could not be manufactured. Manufacturing is the critical factor that makes technology possible.

Economically, manufacturing is an important means by which a nation creates material wealth. In the United States, the manufacturing industries account for about 12% of gross domestic product (GDP). A country's natural resources, such as agricultural lands, mineral deposits, and oil reserves, also create wealth. In the U.S., agriculture, mining, and similar industries account

■ **Table 1.1** Products representing various technologies, most of which affect nearly all of us.

Athletic shoes	Fax machine	One-piece molded plastic patio chair
Automatic teller machine	Global positioning system	Optical scanner
Automatic dishwasher	Hand-held electronic calculator	Personal computer (PC)
Automobile	High-density PC diskette	Photocopying machine
Ballpoint pen	Home security system	Pull-tab beverage cans
Camcorder	Hybrid gas-electric automobile	Quartz crystal wrist watch
Cell phone	Industrial robot	Self-propelled mulching lawnmower
Compact disc (CD)	Ink-jet color printer	Smart phone
Compact disc player	Laptop computer	Supersonic aircraft
Compact fluorescent light bulb	LCD and plasma TVs	Tablet computer
Contact lenses	LED lamp	Tennis racket of composite materials
Digital camera	Magnetic resonance imaging (MRI) machine for medical diagnosis	Video games
Digital video disc (DVD)	Medicines	Washing machine and dryer
Digital video disc player	Microwave oven	
E-book reader		

for less than 5% of GDP (agriculture alone is only about 1%). Construction and public utilities make up around 5%. The rest is service industries, which include retail, transportation, banking, communication, education, and government. The service sector accounts for more than 75% of U.S. GDP. Government (federal, state, and local) accounts for more of GDP than the manufacturing sector; however, government services do not create wealth. In the modern global economy, a nation must have a strong manufacturing base (or it must have significant natural resources) if it is to provide a strong economy and a high standard of living for its people.

This opening chapter considers some general topics about manufacturing. What is manufacturing? How is it organized in industry? What are the materials, processes, and systems by which it is accomplished?

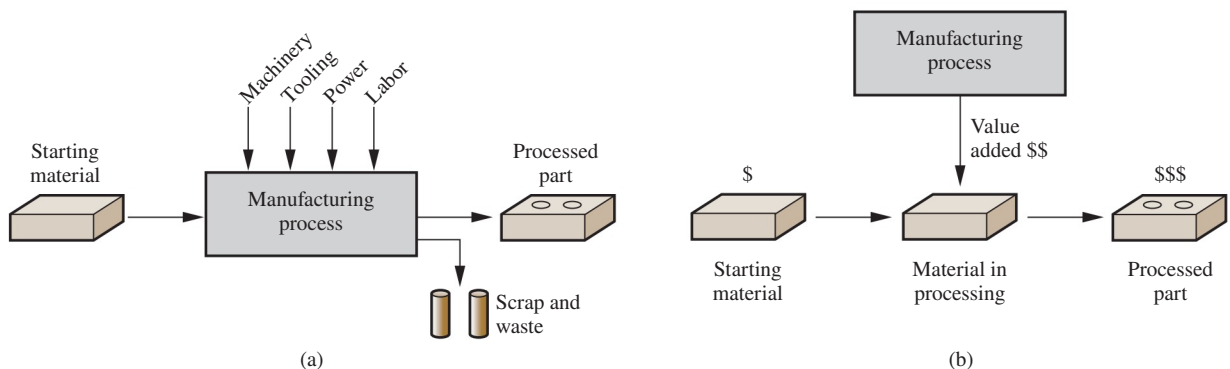
1.1 What Is Manufacturing?

The word *manufacture* is derived from two Latin words: *manus* (hand) and *factus* (make); the combination means made by hand. The English word *manufacture* is several centuries old, and “made by hand” accurately described the manual methods used when the word was first coined.¹ Most modern manufacturing is accomplished by automated and computer-controlled machinery (see Historical Note 1.1 at www.wiley.com/college/groover).

1.1.1 | MANUFACTURING DEFINED

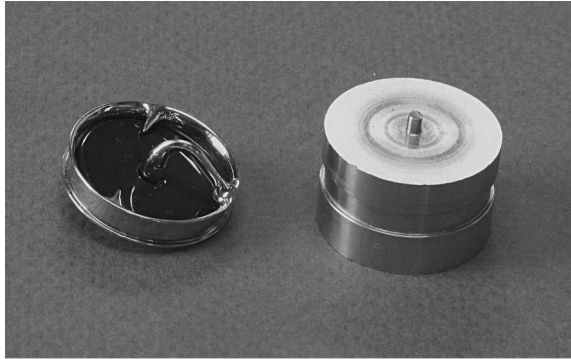
As a field of study in the modern context, manufacturing can be defined two ways, one technologic, and the other economic. Technologically, *manufacturing* is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labor, as depicted in Figure 1.1(a). Manufacturing is almost always carried out as a sequence of operations. Each operation brings the material closer to the desired final state.

Economically, *manufacturing* is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as depicted in Figure 1.1(b). The key point is that manufacturing *adds value* to the material by changing its shape or properties, or by combining it with other materials that have been similarly altered. The material has been made



■ **Figure 1.1** Two ways to define manufacturing: (a) as a technical process and (b) as an economic process.

¹ As a noun, the word *manufacture* first appeared in English around 1567 A.D. As a verb, it first appeared around 1683 A.D.



Courtesy George E. Kane Manufacturing Technology Laboratory, Lehigh University

■ **Figure 1.2** A mechanical heart valve on the left and the titanium workpiece from which the circular frame of the valve is machined on the right.

more valuable through the manufacturing operations performed on it. When iron ore is converted into steel, value is added. When sand is transformed into glass, value is added. When petroleum is refined into plastic, value is added. And when plastic is molded into the complex geometry of a patio chair, it is made even more valuable.

Figure 1.2 shows a product on the left and the starting workpiece from which the circular frame of the product was produced on the right. The starting workpiece is a titanium billet, and the product consists of a carbon wafer assembled to the hook that protrudes from the right of the frame. The product is an artificial heart valve costing thousands of dollars, well worth it for patients who need one. In addition, the surgeon who implants it charges several more thousand dollars (call it an “installation fee”). The titanium billet costs a small fraction of the selling price. It measures about 25 mm (1 in) in diameter. The frame was machined (a material removal process, Section 1.3.1) from the starting billet. Machining time was about 1 hour. Note the added value provided by this operation. Note also the waste in the operation, as depicted in Figure 1.1(a); the finished frame has only about 5% of the mass of the starting workpiece (although the titanium swarf can be recycled).

The words *manufacturing* and *production* are often used interchangeably. The author’s view is that production has a broader meaning than manufacturing. To illustrate, one might speak of “crude oil production,” but the phrase “crude oil manufacturing” seems out of place. Yet when used in the context of products such as metal parts or automobiles, either word seems okay.

1.1.2 | MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity performed by companies that sell products to customers. The type of manufacturing done by a company depends on the kinds of products it makes.

MANUFACTURING INDUSTRIES Industry consists of enterprises and organizations that produce goods and/or provide services. Industries can be classified as primary, secondary, or tertiary. *Primary industries* cultivate and exploit natural resources, such as agriculture and mining. *Secondary industries* take the outputs of the primary industries and convert them into consumer and capital goods. Manufacturing is the principal activity in this category, but construction and power utilities are also included. *Tertiary industries* constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 1.2.

This book is concerned with the secondary industries in Table 1.2, which include the companies engaged in manufacturing. However, the International Standard Industrial Classification (ISIC) used to compile Table 1.2 includes several industries whose production technologies are not covered in this text; for example, beverages, chemicals, and food processing. In this book, manufacturing

■ **Table 1.2** Specific industries in the primary, secondary, and tertiary categories.

Primary	Secondary	Tertiary (service)		
Agriculture	Aerospace	Food processing	Banking	Insurance
Forestry	Apparel	Glass, ceramics	Communications	Legal
Fishing	Automotive	Heavy machinery	Education	Real estate
Livestock	Basic metals	Paper	Entertainment	Repair and maintenance
Quarries	Beverages	Petroleum refining	Financial services	Restaurant
Mining	Building materials	Pharmaceuticals	Government	Retail trade
Petroleum	Chemicals	Plastics (shaping)	Health and medical	Tourism
	Computers	Power utilities	Hotel	Transportation
	Construction	Publishing	Information	Wholesale trade
	Consumer appliances	Textiles		
	Electronics	Tire and rubber		
	Equipment	Wood and furniture		
	Fabricated metals			

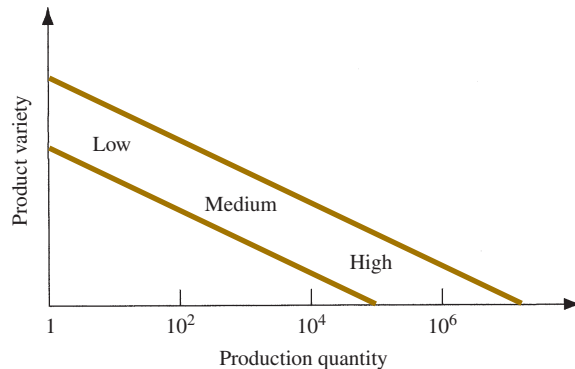
means production of *hardware*, which ranges from nuts and bolts to digital computers and military weapons. Plastic and ceramic products are included, but apparel, paper, pharmaceuticals, power utilities, publishing, and wood products are not.

MANUFACTURED PRODUCTS Final products made by the manufacturing industries can be divided into two major classes: consumer goods and capital goods. *Consumer goods* are products purchased directly by consumers, such as cars, cell phones, TVs, tires, and tennis rackets. *Capital goods* are those purchased by companies to produce goods and/or provide services. Examples of capital goods include aircraft, computers, communication equipment, medical apparatus, trucks and buses, railroad locomotives, machine tools, and construction equipment. Most of these capital goods are purchased by the service industries. It was noted in the introduction that manufacturing accounts for about 12% of gross domestic product and services about 75% of GDP in the United States. Yet the manufactured capital goods purchased by the service sector are the enablers of that sector. Without the capital goods, the service industries could not function.

In addition to final products, other manufactured items include the materials, components, tools, and supplies used by the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings, cutting tools, dies, molds, and lubricants. Thus, the manufacturing industries consist of a complex infrastructure with various categories and layers of intermediate suppliers that the final consumer never deals with.

This book is generally concerned with *discrete items*—individual parts and assembled products rather than items produced by *continuous processes*. A metal stamping is a discrete item, but the sheet-metal coil from which it is made is continuous (almost). Many discrete parts start out as continuous or semicontinuous products, such as extrusions and electrical wire. Long sections made in almost continuous lengths are cut to the desired size. An oil refinery is a better example of a continuous process.

PRODUCTION QUANTITY AND PRODUCT VARIETY The quantity of products made by a factory has an important influence on the way its people, facilities, and procedures are organized. Annual production quantities can be classified into three ranges: (1) *low* production, quantities in the range 1 to 100 units per year; (2) *medium* production, from 100 to 10,000 units annually; and (3) *high* production, 10,000 to millions of units. The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the kinds of products, these boundaries may shift by an order of magnitude or so.



■ **Figure 1.3** Relationship between product variety and production quantity in discrete product manufacturing.

Production quantity refers to the number of units produced annually of a particular product type. Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. Product variety refers to different product designs or types that are produced in the plant. Different products have different shapes and sizes; they perform different functions; they are intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. When the number of product types made in the factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. If a factory's product variety is high, then its production quantity is likely to be low; but if production quantity is high, then product variety will be low, as depicted in Figure 1.3. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.3.

Although product variety has been identified as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity because details on how much the designs differ are not captured simply by the number of different designs. Differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Within each product type, there are differences among specific models.

The extent of the product differences may be small or great, as illustrated in the automotive industry. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are virtually the same. In different plants, the company builds heavy trucks. The terms “soft” and “hard” might be used to describe these differences in product variety. **Soft product variety** occurs when there are only small differences among products, such as the differences among car models made on the same production line. In an assembled product, soft variety is characterized by a high proportion of common parts among the models. **Hard product variety** occurs when the products differ substantially, and there are few common parts, if any. The difference between a car and a truck exemplifies hard variety.

1.1.3 | MANUFACTURING CAPABILITY

A manufacturing plant consists of a set of *processes* and *systems* (and people, of course) designed to transform a certain limited range of *materials* into products of increased value. These three building blocks—materials, processes, and systems—constitute the subject of modern manufacturing. There is a strong interdependence among these factors. A company engaged in manufacturing cannot do everything. It must do only certain things, and it must do those things well. **Manufacturing capability**

refers to the scope of technical and physical capabilities and limitations of a manufacturing company and each of its plants. Manufacturing capability has three dimensions: (1) technological processing capability, (2) physical size and weight of product, and (3) production capacity.

TECHNOLOGICAL PROCESSING CAPABILITY The technological processing capability of a plant (or company) is its available set of manufacturing processes. Certain plants perform machining operations, others roll steel billets into sheet stock, and others build automobiles. A machine shop cannot roll steel, and a rolling mill cannot build cars. The underlying feature that distinguishes these plants is the processes they can perform. Technological processing capability is closely related to material type. Certain manufacturing processes are suited to certain materials, whereas other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in certain material types. Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies must concentrate on the design and manufacture of products that are compatible with their technological processing capability.

PHYSICAL PRODUCT LIMITATIONS A second aspect of manufacturing capability is imposed by the physical product. A plant with a given set of processes is limited in terms of the size and weight of the products that can be accommodated. Large, heavy products are difficult to move. To move these products about, the plant must be equipped with cranes of the required load capacity. Smaller parts and products made in large quantities can be moved by conveyor or other means. The limitation on product size and weight extends to the physical capacity of the manufacturing equipment as well. Production machines come in different sizes. Larger machines must be used to process larger parts. The production and material handling equipment must be planned for products that lie within a certain size and weight range.

PRODUCTION CAPACITY A third limitation on a plant's manufacturing capability is the production quantity that can be produced in a given time period (e.g., month or year). This quantity limitation is commonly called *plant capacity*, or *production capacity*, defined as the maximum rate of production output that a plant can achieve under assumed operating conditions. The operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and so on. These factors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?

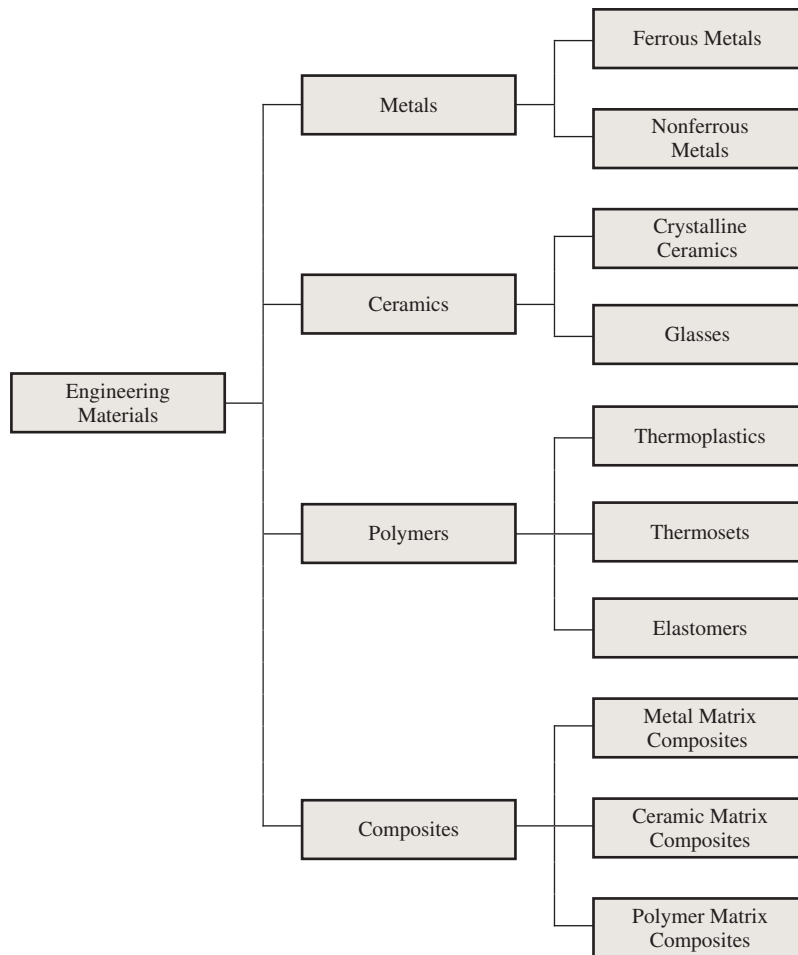
Plant capacity is usually measured in terms of output units, such as annual tons of steel produced by a steel mill, or number of cars produced by a final assembly plant. In these cases, the outputs are homogeneous, more or less. In cases in which the output units are not homogeneous, other factors may be more appropriate measures, such as available labor hours of productive capacity in a machine shop that produces a variety of parts.

Materials, processes, and systems are the fundamental topics of manufacturing and the three broad subject areas of this book. This introductory chapter provides an overview of these areas before embarking on a detailed coverage in the remaining chapters.

1.2

Materials in Manufacturing

Most engineering materials can be classified into one of three basic categories: (1) metals, (2) ceramics, and (3) polymers. Their chemistries are different, their mechanical and physical properties are different, and these differences affect the manufacturing processes that can be used to produce products from them. In addition to the three basic categories, there are (4) *composites*—



■ **Figure 1.4** Classification of engineering materials.

nonhomogeneous mixtures of the other three basic types rather than a unique category. The classification of the four groups is pictured in Figure 1.4. This section provides a survey of these materials. Chapters 6 through 9 cover the four material types in more detail.

1.2.1 | METALS

Metals used in manufacturing are usually *alloys*, which are composed of two or more elements, with at least one being a metallic element. Metals and alloys can be divided into two basic groups: (1) ferrous and (2) nonferrous.

FERROUS METALS Ferrous metals are based on iron; the group includes steel and cast iron. These metals constitute the most important group commercially, more than three-fourths of the metal tonnage throughout the world. Pure iron has limited commercial use, but when alloyed with carbon, iron has more uses and greater commercial value than any other metal. Alloys of iron and carbon form steel and cast iron.

Steel is defined as an iron–carbon alloy containing 0.02% to 2.11% carbon. It is the most important category within the ferrous metal group. Its composition often includes other alloying elements as well, such as manganese, chromium, nickel, and molybdenum, to enhance the properties of

the metal. Applications of steel include construction (bridges, I-beams, and nails), transportation (trucks, rails, and rolling stock for railroads), and consumer products (automobiles and appliances).

Cast iron is an alloy of iron and carbon (2% to 4%) used in casting (primarily sand casting); silicon is also present in the alloy (in amounts from 0.5% to 3%). Other elements are often added also, to obtain desirable properties in the cast part. Cast iron is available in several different forms, of which gray cast iron is the most common; its applications include blocks and heads for internal combustion engines.

NONFERROUS METALS Nonferrous metals include the other metallic elements and their alloys. In almost all cases, the alloys are more important commercially than the pure metals. The nonferrous metals include the pure metals and alloys of aluminum, copper, gold, magnesium, nickel, silver, tin, titanium, zinc, and other metals.

1.2.2 | CERAMICS

A ceramic is a compound containing metallic (or semimetallic) and nonmetallic elements. Typical nonmetallic elements are oxygen, nitrogen, and carbon. Ceramics include a variety of traditional and modern materials. Traditional ceramics, some of which have been used for thousands of years, include: *clay*, abundantly available, consisting of fine particles of hydrous aluminum silicates and other minerals used in making brick, tile, and pottery; *silica*, the basis for nearly all glass products; and *alumina* and *silicon carbide*, two abrasive materials used in grinding. Modern ceramics include some of the preceding materials, such as alumina, whose properties are enhanced in various ways through modern processing methods. Newer ceramics include: *carbides*, metal carbides such as tungsten carbide and titanium carbide, which are widely used as cutting tool materials; and *nitrides*, metal and semimetal nitrides such as titanium nitride and boron nitride, used as cutting tools and grinding abrasives.

For processing purposes, ceramics can be divided into crystalline ceramics and glasses. Different manufacturing methods are required for the two types. Crystalline ceramics are formed in various ways from powders and then heated to a temperature below the melting point to achieve bonding between the powders. The glass ceramics (namely, glass) can be melted and cast, and then formed in processes such as traditional glass blowing.

1.2.3 | POLYMERS

A polymer is a compound formed of repeating structural units called *mers*, whose atoms share electrons to form very large molecules. Polymers usually consist of carbon plus one or more other elements such as hydrogen, nitrogen, oxygen, and chlorine. Polymers are divided into three categories: (1) thermoplastic polymers, (2) thermosetting polymers, and (3) elastomers.

Thermoplastic polymers can be subjected to multiple heating and cooling cycles without substantially altering the molecular structure of the polymer. Common thermoplastics include polyethylene, polystyrene, polyvinylchloride, and nylon. **Thermosetting polymers** chemically transform (*cure*) into a rigid structure upon cooling from a heated plastic condition; hence the name thermosetting. Members of this type include phenolics, amino resins, and epoxies. Although the name “thermosetting” is used, some of these polymers cure by mechanisms other than heating. **Elastomers** are polymers that exhibit significant elastic behavior; hence the name elastomer. They include natural rubber, neoprene, silicone, and polyurethane.

1.2.4 | COMPOSITES

Composites do not really constitute a separate category of materials; they are mixtures of the other three types. A **composite** is a material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to those of its constituents. The term **phase**

refers to a homogeneous mass of material, such as an aggregation of grains of identical unit cell structure in a solid metal. The usual structure of a composite consists of particles or fibers of one phase mixed in a second phase, called the *matrix*.

Composites are found in nature (e.g., wood), and they can be produced synthetically. The synthesized type is of greater interest here, and it includes glass fibers in a polymer matrix, such as fiber-reinforced plastic; polymer fibers of one type in a matrix of a second polymer, such as an epoxy-Kevlar composite; and ceramic in a metal matrix, such as a tungsten carbide in a cobalt binder to form cemented carbide.

Properties of a composite depend on its components, the physical shapes of the components, and the way they are combined to form the final material. Some composites combine high strength with light weight and are suited to applications such as aircraft components, car bodies, boat hulls, tennis rackets, and fishing rods. Other composites are strong, hard, and capable of maintaining these properties at elevated temperatures, for example, cemented carbide cutting tools.

1.3 Manufacturing Processes

A **manufacturing process** is a designed procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. A manufacturing process is usually carried out as a **unit operation**, which means it is a single step in the sequence of steps required to transform a starting material into a final part or product. Manufacturing operations can be divided into two basic types: (1) processing operations and (2) assembly operations. A **processing operation** transforms a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete work parts, but certain processing operations are also applicable to assembled items (e.g., painting a spot-welded car body). An **assembly operation** joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process (e.g., a welded assembly is called a *weldment*). A classification of manufacturing processes is presented in Figure 1.5. Some of the basic processes date from antiquity (see Historical Note 1.2 at www.wiley.com/college/groover).

1.3.1 | PROCESSING OPERATIONS

A processing operation uses energy to alter a work part's shape, physical properties, or appearance to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but the human workers are generally employed to control the machines, oversee the operations, and load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 1.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed work part exits the process. Most production operations produce waste or scrap, either as a natural aspect of the process (e.g., removing material as in machining) or in the form of occasional defective pieces. An important objective in manufacturing is to reduce waste in either of these forms.

More than one processing operation is usually required to transform the starting material into final form. The operations are performed in the particular sequence required to achieve the geometry and condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations, (2) property-enhancing operations, and (3) surface processing operations. **Shaping operations** alter the geometry of the starting work material by various methods. Common shaping processes include casting,