

# CONTENTS

- 1 INTRODUCTION AND OVERVIEW OF MANUFACTURING 1
  - 1.1 What Is Manufacturing? 2
  - 1.2 Materials in Manufacturing 9
  - 1.3 Manufacturing Processes 11
  - 1.4 Production Systems 18
  - 1.5 Manufacturing Economics 22
  - 1.6 Recent Developments in Manufacturing 27
- Part I Material Properties and Product Attributes 36**
- 2 THE NATURE OF MATERIALS 36
  - 2.1 Atomic Structure and the Elements 37
  - 2.2 Bonding between Atoms and Molecules 39
  - 2.3 Crystalline Structures 41
  - 2.4 Noncrystalline (Amorphous) Structures 47
  - 2.5 Engineering Materials 49
- 3 MECHANICAL PROPERTIES OF MATERIALS 52
  - 3.1 Stress–Strain Relationships 52
  - 3.2 Hardness 67
  - 3.3 Effect of Temperature on Properties 71
  - 3.4 Fluid Properties 73
  - 3.5 Viscoelastic Behavior of Polymers 76
- 4 PHYSICAL PROPERTIES OF MATERIALS 82
  - 4.1 Volumetric and Melting Properties 82
  - 4.2 Thermal Properties 85
  - 4.3 Mass Diffusion 87
  - 4.4 Electrical Properties 89
  - 4.5 Electrochemical Processes 91
- 5 ENGINEERING MATERIALS 94
  - 5.1 Metals and Their Alloys 94
  - 5.2 Ceramics 108
  - 5.3 Polymers 115
  - 5.4 Composites 123
- 6 DIMENSIONS, SURFACES, AND THEIR MEASUREMENT 131
  - 6.1 Dimensions, Tolerances, and Related Attributes 132
  - 6.2 Measuring Instruments and Gages 133
  - 6.3 Surfaces 142
  - 6.4 Measurement of Surfaces 148
  - 6.5 Effect of Manufacturing Processes 150
- Part II Solidification Processes**
- 7 FUNDAMENTALS OF METAL CASTING 154
  - 7.1 Overview of Casting Technology 157
  - 7.2 Heating and Pouring 159
  - 7.3 Solidification and Cooling 163
- 8 METAL CASTING PROCESSES 174
  - 8.1 Sand Casting 174
  - 8.2 Other Expendable-Mold Casting Processes 180
  - 8.3 Permanent-Mold Casting Processes 186
  - 8.4 Foundry Practice 196
  - 8.5 Casting Quality 200
  - 8.6 Metals for Casting 202
  - 8.7 Product Design Considerations 204
- 9 GLASSWORKING 209
  - 9.1 Raw Materials Preparation and Melting 209
  - 9.2 Shaping Processes in Glassworking 210
  - 9.3 Heat Treatment and Finishing 216
  - 9.4 Product Design Considerations 217

**10 SHAPING PROCESSES FOR PLASTICS 219**

- 10.1 Properties of Polymer Melts 221
- 10.2 Extrusion 223
- 10.3 Production of Sheet and Film 233
- 10.4 Fiber and Filament Production (Spinning) 236
- 10.5 Coating Processes 237
- 10.6 Injection Molding 238
- 10.7 Compression and Transfer Molding 249
- 10.8 Blow Molding and Rotational Molding 250
- 10.9 Thermoforming 256
- 10.10 Casting 260
- 10.11 Polymer Foam Processing and Forming 261
- 10.12 Product Design Considerations 263

**11 PROCESSING OF POLYMER MATRIX COMPOSITES AND RUBBER 268**

- 11.1 Overview of PMC Processing 269
- 11.2 Open Mold Processes 272
- 11.3 Closed Mold Processes 276
- 11.4 Other PMC Shaping Processes 279
- 11.5 Rubber Processing and Shaping 284
- 11.6 Manufacture of Tires and Other Rubber Products 289

**Part III Particulate Processing of Metals and Ceramics 295****12 POWDER METALLURGY 295**

- 12.1 Characterization of Engineering Powders 297
- 12.2 Production of Metallic Powders 301
- 12.3 Conventional Pressing and Sintering 303
- 12.4 Alternative Pressing and Sintering Techniques 310
- 12.5 Materials and Products for Powder Metallurgy 313
- 12.6 Design Considerations in Powder Metallurgy 314

**13 PROCESSING OF CERAMICS AND CERMETS 319**

- 13.1 Processing of Traditional Ceramics 320
- 13.2 Processing of New Ceramics 327

- 13.3 Processing of Cermets 330
- 13.4 Product Design Considerations 332

**Part IV Metal Forming and Sheet Metalworking 335****14 FUNDAMENTALS OF METAL FORMING 335**

- 14.1 Overview of Metal Forming 335
- 14.2 Material Behavior in Metal Forming 338
- 14.3 Temperature in Metal Forming 340
- 14.4 Strain Rate Sensitivity 342
- 14.5 Friction and Lubrication in Metal Forming 344

**15 BULK DEFORMATION PROCESSES IN METALWORKING 347**

- 15.1 Rolling 348
- 15.2 Other Deformation Processes Related to Rolling 356
- 15.3 Forging 358
- 15.4 Other Deformation Processes Related to Forging 370
- 15.5 Extrusion 375
- 15.6 Wire and Bar Drawing 386

**16 SHEET METALWORKING 398**

- 16.1 Cutting Operations 399
- 16.2 Bending Operations 405
- 16.3 Drawing 410
- 16.4 Other Sheet-Metal-Forming Operations 417
- 16.5 Dies and Presses for Sheet-Metal Processes 420
- 16.6 Sheet-Metal Operations Not Performed on Presses 427
- 16.7 Bending of Tube Stock 433

**Part V Material Removal Processes 438****17 THEORY OF METAL MACHINING 438**

- 17.1 Overview of Machining Technology 440
- 17.2 Theory of Chip Formation in Metal Machining 444

- 17.3 Force Relationships and the Merchant Equation 448
- 17.4 Power and Energy Relationships in Machining 454
- 17.5 Cutting Temperature 456
- 18 MACHINING OPERATIONS AND MACHINE TOOLS 462**
  - 18.1 Machining and Part Geometry 462
  - 18.2 Turning and Related Operations 466
  - 18.3 Drilling and Related Operations 475
  - 18.4 Milling 480
  - 18.5 Machining Centers and Turning Centers 488
  - 18.6 Other Machining Operations 490
  - 18.7 Machining Operations for Special Geometries 495
  - 18.8 High-Speed Machining 503
- 19 CUTTING-TOOL TECHNOLOGY 508**
  - 19.1 Tool Life 508
  - 19.2 Tool Materials 515
  - 19.3 Tool Geometry 525
  - 19.4 Cutting Fluids 535
- 20 ECONOMIC AND PRODUCT DESIGN CONSIDERATIONS IN MACHINING 543**
  - 20.1 Machinability 543
  - 20.2 Tolerances and Surface Finish 546
  - 20.3 Selection of Cutting Conditions 550
  - 20.4 Product Design Considerations in Machining 557
- 21 GRINDING AND OTHER ABRASIVE PROCESSES 562**
  - 21.1 Grinding 562
  - 21.2 Related Abrasive Processes 580
- 22 NONTRADITIONAL MACHINING AND THERMAL CUTTING PROCESSES 586**
  - 22.1 Mechanical Energy Processes 587
  - 22.2 Electrochemical Machining Processes 591
  - 22.3 Thermal Energy Processes 595
  - 22.4 Chemical Machining 604
  - 22.5 Application Considerations 610
- Part VI Property Enhancing and Surface Processing Operations 616**
  - 23 HEAT TREATMENT OF METALS 616**
    - 23.1 Annealing 617
    - 23.2 Martensite Formation in Steel 617
    - 23.3 Precipitation Hardening 621
    - 23.4 Surface Hardening 623
    - 23.5 Heat Treatment Methods and Facilities 624
  - 24 SURFACE PROCESSING OPERATIONS 628**
    - 24.1 Industrial Cleaning Processes 629
    - 24.2 Diffusion and Ion Implantation 633
    - 24.3 Plating and Related Processes 635
    - 24.4 Conversion Coating 639
    - 24.5 Vapor Deposition Processes 641
    - 24.6 Organic Coatings 647
    - 24.7 Porcelain Enameling and Other Ceramic Coatings 650
    - 24.8 Thermal and Mechanical Coating Processes 651
- Part VII Joining and Assembly Processes 655**
  - 25 FUNDAMENTALS OF WELDING 655**
    - 25.1 Overview of Welding Technology 657
    - 25.2 The Weld Joint 660
    - 25.3 Physics of Welding 662
    - 25.4 Features of a Fusion-Welded Joint 667
  - 26 WELDING PROCESSES 671**
    - 26.1 Arc Welding 671
    - 26.2 Resistance Welding 682
    - 26.3 Oxyfuel Gas Welding 689
    - 26.4 Other Fusion-Welding Processes 693

- 26.5 Solid-State Welding 696
- 26.6 Weld Quality 702
- 26.7 Weldability 706
- 26.8 Design Considerations in Welding 707
- 27 BRAZING, SOLDERING, AND ADHESIVE BONDING 712**
- 27.1 Brazing 712
- 27.2 Soldering 719
- 27.3 Adhesive Bonding 723
- 28 MECHANICAL ASSEMBLY 730**
- 28.1 Threaded Fasteners 731
- 28.2 Rivets and Eyelets 738
- 28.3 Assembly Methods Based on Interference Fits 739
- 28.4 Other Mechanical Fastening Methods 743
- 28.5 Molding Inserts and Integral Fasteners 744
- 28.6 Design for Assembly 746
- Part VIII Special Processing and Assembly Technologies 751**
- 29 RAPID PROTOTYPING AND ADDITIVE MANUFACTURING 751**
- 29.1 Fundamentals of Rapid Prototyping and Additive Manufacturing 753
- 29.2 Additive Manufacturing Processes 756
- 29.3 Cycle Time and Cost Analysis 764
- 29.4 Additive Manufacturing Applications 768
- 30 PROCESSING OF INTEGRATED CIRCUITS 773**
- 30.1 Overview of IC Processing 775
- 30.2 Silicon Processing 778
- 30.3 Lithography 783
- 30.4 Layer Processes Used in IC Fabrication 787
- 30.5 Integrating the Fabrication Steps 794
- 30.6 IC Packaging 796
- 30.7 Yields in IC Processing 802
- 31 ELECTRONICS ASSEMBLY AND PACKAGING 807**
- 31.1 Electronics Packaging 807
- 31.2 Printed Circuit Boards 809
- 31.3 Printed Circuit Board Assembly 818
- 31.4 Electrical Connector Technology 826
- 32 MICROFABRICATION TECHNOLOGIES 831**
- 32.1 Microsystem Products 831
- 32.2 Microfabrication Processes 838
- 33 NANOFABRICATION TECHNOLOGIES 848**
- 33.1 Nanotechnology Products and Applications 849
- 33.2 Introduction to Nanoscience 854
- 33.3 Nanofabrication Processes 858
- Part IX Manufacturing Systems 867**
- 34 AUTOMATION TECHNOLOGIES FOR MANUFACTURING SYSTEMS 867**
- 34.1 Automation Fundamentals 868
- 34.2 Hardware for Automation 871
- 34.3 Computer Numerical Control 876
- 34.4 Industrial Robotics 889
- 35 INTEGRATED MANUFACTURING SYSTEMS 899**
- 35.1 Material Handling 899
- 35.2 Fundamentals of Production Lines 902
- 35.3 Manual Assembly Lines 904
- 35.4 Automated Production Lines 908
- 35.5 Cellular Manufacturing 913
- 35.6 Flexible Manufacturing Systems and Cells 918
- 35.7 Computer Integrated Manufacturing 924
- Part X Manufacturing Support Systems 930**
- 36 PROCESS PLANNING AND PRODUCTION CONTROL 930**
- 36.1 Process Planning 932
- 36.2 Other Manufacturing Engineering Functions 940



36.3 Production Planning and Control 944

36.4 Just-In-Time Delivery Systems 951

36.5 Lean Production 954

**37 QUALITY CONTROL AND INSPECTION 960**

37.1 Product Quality 960

37.2 Process Capability and Tolerances 961

37.3 Statistical Process Control 963

37.4 Quality Programs in Manufacturing 968

37.5 Inspection Principles 974

37.6 Modern Inspection Technologies 977

**APPENDIX 987**

**INDEX 991**