## CONTENTS

1 INTRODUCTION 1  
1.1 What Is Manufacturing? 2  
1.2 Materials in Manufacturing 8  
1.3 Manufacturing Processes 10  
1.4 Production Systems 17  
1.5 Organization of the Book 20  
1.6 Images of Manufacturing 21  

### Part I Material Properties and Product Attributes

2 THE NATURE OF MATERIALS 24  
2.1 Atomic Structure and the Elements 24  
2.2 Bonding between Atoms and Molecules 26  
2.3 Crystalline Structures 29  
2.4 Noncrystalline (amorphous) Structures 34  
2.5 Engineering Materials 36  

3 MECHANICAL PROPERTIES OF MATERIALS 39  
3.1 Stress–Strain Relationships 39  
3.2 Hardness 52  
3.3 Effect of Temperature on Properties 55  
3.4 Fluid Properties 57  
3.5 Viscoelastic Behavior of Polymers 60  

4 PHYSICAL PROPERTIES OF MATERIALS 66  
4.1 Volumetric and Melting Properties 66  
4.2 Thermal Properties 69  
4.3 Mass Diffusion 71  
4.4 Electrical Properties 72  
4.5 Electrochemical Processes 74  

5 DIMENSIONS, TOLERANCES, AND SURFACES 77  
5.1 Dimensions, Tolerances, and Related Attributes 77  
5.2 Surfaces 78  
5.3 Effect of Manufacturing Processes 85  

### Part II Engineering Materials

6 METALS 88  
6.1 Alloys and Phase Diagrams 89  
6.2 Ferrous Metals 93  
6.3 Nonferrous Metals 109  
6.4 Superalloys 120  
6.5 Guide to the Processing of Metals 122  

7 CERAMICS 125  
7.1 Structure and Properties of Ceramics 127  
7.2 Traditional Ceramics 129  
7.3 New Ceramics 132  
7.4 Glass 134  
7.5 Some Important Elements Related to Ceramics 138  
7.6 Guide to Processing Ceramics 140  

8 POLYMERS 143  
8.1 Fundamentals of Polymer Science and Technology 145  
8.2 Thermoplastic Polymers 155  
8.3 Thermosetting Polymers 162  
8.4 Elastomers 165  
8.5 Guide to the Processing of Polymers 172  

9 COMPOSITE MATERIALS 175  
9.1 Technology and Classification of Composite Materials 176  
9.2 Metal Matrix Composites 184  
9.3 Ceramic Matrix Composites 186  
9.4 Polymer Matrix Composites 187  
9.5 Guide to Processing Composite Materials 190  

### Part III Solidification Processes

10 FUNDAMENTALS OF METAL CASTING 193  
10.1 Overview of Casting Technology 196  
10.2 Heating and Pouring 198  
10.3 Solidification and Cooling 202  

11 METAL CASTING PROCESSES 213  
11.1 Sand Casting 214  
11.2 Other Expendable Mold Casting Processes 219  
11.3 Permanent Mold Casting Processes 225  
11.4 Foundry Practice 233  
11.5 Casting Quality 236  
11.6 Metals for Casting 239  
11.7 Product Design Considerations 240  

12 GLASSWORKING 246  
12.1 Raw Materials Preparation and Melting 246  
12.2 Shaping Processes in Glassworking 247  
12.3 Heat Treatment and Finishing 253  
12.4 Product Design Considerations 254
13 SHAPING PROCESSES FOR PLASTICS 256
  13.1 Properties of Polymer Melts 258
  13.2 Extrusion 260
  13.3 Production of Sheet and Film 270
  13.4 Fiber and Filament Production (spinning) 272
  13.5 Coating Processes 274
  13.6 Injection Molding 275
  13.7 Compression and Transfer Molding 285
  13.8 Blow Molding and Rotational Molding 287
  13.9 Thermoforming 292
  13.10 Casting 296
  13.11 Polymer Foam Processing and Forming 297
  13.12 Product Design Considerations 299

14 RUBBER PROCESSING TECHNOLOGY 306
  14.1 Rubber Processing and Shaping 306
  14.2 Manufacture of Tires and Other Rubber Products 311
  14.3 Product Design Considerations 315

15 SHAPING PROCESSES FOR POLYMER MATRIX COMPOSITES 317
  15.1 Starting Materials for PMCs 319
  15.2 Open Mold Processes 321
  15.3 Closed Mold Processes 325
  15.4 Filament Winding 327
  15.5 Pultrusion Processes 329
  15.6 Other PMC Shaping Processes 331

Part IV Particulate Processing of Metals and Ceramics

16 POWDER METALLURGY 334
  16.1 Characterization of Engineering Powders 336
  16.2 Production of Metallic Powders 340
  16.3 Conventional Pressing and Sintering 342
  16.4 Alternative Pressing and Sintering Techniques 348
  16.5 Materials and Products for PM 351
  16.6 Design Considerations in Powder Metallurgy 352

17 PROCESSING OF CERAMICS AND CERMETS 358
  17.1 Processing of Traditional Ceramics 359
  17.2 Processing of New Ceramics 366
  17.3 Processing of Cermets 369
  17.4 Product Design Considerations 371

Part V Metal Forming and Sheet Metalworking

18 FUNDAMENTALS OF METAL FORMING 374
  18.1 Overview of Metal Forming 374
  18.2 Material Behavior in Metal Forming 377
  18.3 Temperature in Metal Forming 378
  18.4 Strain Rate Sensitivity 380
  18.5 Friction and Lubrication in Metal Forming 383

19 BULK DEFORMATION PROCESSES IN METAL WORKING 386
  19.1 Rolling 387
  19.2 Other Deformation Processes Related to Rolling 395
  19.3 Forging 397
  19.4 Other Deformation Processes Related to Forging 408
  19.5 Extrusion 413
  19.6 Wire and Bar Drawing 423

20 SHEET METAL WORKING 435
  20.1 Cutting Operations 436
  20.2 Bending Operations 442
  20.3 Drawing 447
  20.4 Other Sheet-Metal-Forming Operations 454
  20.5 Dies and Presses for Sheet Metal Processes 457
  20.6 Sheet-Metal Operations Not Performed on Presses 463
  20.7 Bending of Tube Stock 469

Part VI Material Removal Processes

21 THEORY OF METAL MACHINING 475
  21.1 Overview of Machining Technology 477
  21.2 Theory of Chip Formation in Metal Machining 481
  21.3 Force Relationships and the Merchant Equation 485
  21.4 Power and Energy Relationships in Machining 490
  21.5 Cutting Temperature 493

22 MACHINING OPERATIONS AND MACHINE TOOLS 499
  22.1 Turning and Related Operations 502
  22.2 Drilling and Related Operations 511
  22.3 Milling 515
  22.4 Machining Centers and Turning Centers 522
  22.5 Other Machining Operations 524
  22.6 High-Speed Machining 529
23 CUTTING TOOL TECHNOLOGY 534
   23.1 Tool Life 534
   23.2 Tool Materials 541
   23.3 Tool Geometry 550
   23.4 Cutting Fluids 558

24 ECONOMIC AND PRODUCT DESIGN CONSIDERATIONS IN MACHINING 565
   24.1 Machinability 565
   24.2 Tolerances and Surface Finish 568
   24.3 Selection of Cutting Conditions 572
   24.4 Product Design Considerations in Machining 578

25 GRINDING AND OTHER ABRASIVE PROCESSES 585
   25.1 Grinding 586
   25.2 Related Abrasive Process 603

26 NONTRADITIONAL MACHINING AND THERMAL CUTTING PROCESSES 610
   26.1 Mechanical Energy Processes 611
   26.2 Electrochemical Machining Processes 615
   26.3 Thermal Energy Processes 619
   26.4 Chemical Machining 627
   26.5 Application Considerations 633

Part VII Property Enhancing and Surface Processing Operations
27 HEAT TREATMENT OF METALS 639
   27.1 Annealing 640
   27.2 Martensite Formation in Steel 640
   27.3 Precipitation Hardening 644
   27.4 Surface Hardening 645
   27.5 Heat Treatment Methods and Facilities 647

28 CLEANING AND SURFACE TREATMENTS 651
   28.1 Chemical Cleaning 651
   28.2 Mechanical Cleaning and Surface Preparation 654
   28.3 Diffusion and Ion Implantation 656

29 COATING AND DEPOSITION PROCESSES 659
   29.1 Plating and Related Processes 660
   29.2 Conversion Coatings 664
   29.3 Physical Vapor Deposition 665
   29.4 Chemical Vapor Deposition 668
   29.5 Organic Coatings 671
   29.6 Porcelain Enameling and Other Ceramic Coatings 674

29.7 Thermal and Mechanical Coating Processes 674

Part VIII Joining and Assembly Processes
30 FUNDAMENTALS OF WELDING 679
   30.1 Overview of Welding Technology 681
   30.2 The Weld Joint 683
   30.3 Physics of Welding 686
   30.4 Features of a Fusion-Welded Joint 690

31 WELDING PROCESSES 694
   31.1 Arc Welding 695
   31.2 Resistance Welding 705
   31.3 Oxyfuel Gas Welding 712
   31.4 Other Fusion-Welding Processes 716
   31.5 Solid-State Welding 719
   31.6 Weld Quality 724
   31.7 Weldability 728
   31.8 Design Considerations in Welding 729

32 BRAZING, SOLDERING, AND ADHESIVE BONDING 734
   32.1 Brazing 735
   32.2 Soldering 740
   32.3 Adhesive Bonding 744

33 MECHANICAL ASSEMBLY 752
   33.1 Threaded Fasteners 753
   33.2 Rivets and Eyelets 759
   33.3 Assembly Methods based on Interference Fits 760
   33.4 Other Mechanical Fastening Methods 763
   33.5 Molding Inserts and Integral Fasteners 765
   33.6 Design for Assembly 766

Part IX Special Processing and Assembly Technologies
34 RAPID PROTOTYPING 772
   34.1 Fundamentals of Rapid Prototyping 773
   34.2 Rapid Prototyping Technologies 774
   34.3 Applications Issues in Rapid Prototyping 782

35 PROCESSING OF INTEGRATED CIRCUITS 786
   35.1 Overview of IC Processing 787
   35.2 Silicon Processing 792
   35.3 Lithography 796
   35.4 Layer Processes Use in IC Fabrication 800
35.5 Integrating the Fabrication Steps 807
35.6 IC Packaging 808
35.7 Yields in IC Processing 813

36 ELECTRONICS ASSEMBLY AND PACKAGING 819
36.1 Electronics Packaging 819
36.2 Printed Circuit Boards 821
36.3 Printed Circuit Board Assembly 831
36.4 Surface Mount Technology 835
36.5 Electrical Connector Technology 839

37 MICROFABRICATION TECHNOLOGIES 845
37.1 Microsystem Products 845
37.2 Microfabrication Processes 850
37.3 Nanotechnology 857

Part X Manufacturing Systems

38 NUMERICAL CONTROL AND INDUSTRIAL ROBOTICS 860
38.1 Numerical Control 861
38.2 Industrial Robotics 873
38.3 Programmable Logic Controllers 878

39 GROUP TECHNOLOGY AND FLEXIBLE MANUFACTURING SYSTEMS 884
39.1 Group Technology 884
39.2 Flexible Manufacturing Systems 889

40 PRODUCTION LINES 896
40.1 Fundamentals of Production Lines 896
40.2 Manual Assembly Lines 900
40.3 Automated Production Lines 904

Part XI Manufacturing Support Systems

41 MANUFACTURING ENGINEERING 912
41.1 Process Planning 913
41.2 Problem Solving and Continuous Improvement 921
41.3 Concurrent Engineering and Design for Manufacturability 922

42 PRODUCTION PLANNING AND CONTROL 928
42.1 Aggregate Planning and the Master Production Schedule 930
42.2 Inventory Control 931
42.3 Material and Capacity Requirements Planning 935
42.4 Just-in-Time and Lean Production 939
42.5 Shop Floor Control 942

43 QUALITY CONTROL 947
43.1 What Is Quality? 947
43.2 Process Capability 949
43.3 Statistical Tolerancing 949
43.4 Taguchi Methods 953
43.5 Statistical Process Control 955

44 MEASUREMENT AND INSPECTION 965
44.1 Metrology 966
44.2 Inspection Principles 969
44.3 Conventional Measuring Instruments and Gages 971
44.4 Measurement of Surfaces 978
44.5 Advanced Measurement and Inspection Technologies 980

INDEX 989