



JOHN A. SCHEY

Introduction to Manufacturing Processes

THIRD EDITION



McGRAW-HILL INTERNATIONAL EDITIONS

Mechanical Engineering Series

CONTENTS

Chapter 1

Introduction to Manufacturing 2

- 1-1 Historical Developments 3
 - 1-1-1 Early Developments 3
 - 1-1-2 The First Industrial Revolution 4
 - 1-1-3 The Second Industrial Revolution 4
- 1-2 The Economic Role of Manufacturing 7
- 1-3 Manufacturing as a Technical Activity 9
- 1-4 Scope and Purpose of Book 13
- 1-5 Summary 15
- Further Reading 16

Chapter 2

Manufacturing 20

- 2-1 The Manufacturing Enterprise 21
 - 2-1-1 Specification Development 22
 - 2-1-2 Conceptual Design 23
 - 2-1-3 Product Design 23
 - 2-1-4 Make or Buy 25
 - 2-1-5 Process Design 25
 - 2-1-6 Production 27
 - 2-1-7 Customer Relations 27
- 2-2 Sequential Manufacturing 28
- 2-3 Concurrent or Simultaneous Engineering 29
- 2-4 Computer-Integrated Manufacturing 30
- 2-5 Control of Manufacturing Processes 31
 - 2-5-1 Control Strategies 31
 - 2-5-2 Automation 33
 - 2-5-3 Numerical Control 34
- 2-6 Summary 38
- Further Reading 39

Chapter 3

Geometric Attributes of Manufactured Parts 42

- 3-1 Shape 43
 - 3-1-1 Shape Classification 44
 - 3-1-2 Group Technology 44
 - 3-1-3 Machine Tool Movement and Control 46
- 3-2 Dimensions 48
 - 3-2-1 Dimensional Units 48
 - 3-2-2 Dimensional Tolerances 48
- 3-3 Shape and Location Deviations 51
- 3-4 Engineering Metrology 52
 - 3-4-1 Principles of Measurement 53
 - 3-4-2 Gages 56
 - 3-4-3 Graduated Measuring Devices 58
 - 3-4-4 Comparative Length Measurement 60
 - 3-4-5 Optical Devices 62
 - 3-4-6 Measuring Machines 64
- 3-5 Surface Topography 64
 - 3-5-1 Roughness and Waviness 65
 - 3-5-2 Surface Finish and Tolerances 67
 - 3-5-3 Surface Roughness Measurement 69
- 3-6 Summary 72
- Problems 73
- Further Reading 74

Chapter 4

Service Attributes of Manufactured Products 76

- 4-1 Mechanical Properties in Tension 78
 - 4-1-1 The Tension Test 78
 - 4-1-2 Process/Equipment Interactions 81

- 4-1-3 Strength in Tension 82
- 4-1-4 Ductility in Tension 85
- 4-1-5 Assuring Increased Ductility 89
- 4-1-6 Notch Effects 90
- 4-1-7 Bending Tests 91
- 4-2 Impact Energy and Fracture Toughness 93
- 4-3 Compression 94
- 4-4 Hardness 97
- 4-5 Fatigue 99
- 4-6 High-Temperature Properties 102
- 4-7 Residual Stresses 105
- 4-8 Nondestructive Testing (NDT) 107
- 4-9 Physical Properties 109
 - 4-9-1 Density 109
 - 4-9-2 Tribological Properties 109
 - 4-9-3 Electrical Properties 113
 - 4-9-4 Magnetic Properties 114
 - 4-9-5 Thermal Properties 114
 - 4-9-6 Optical Properties 116
- 4-10 Chemical Properties 116
- 4-11 Summary 116
- Problems 118
- Further Reading 120

Chapter 5

Materials in Design and Manufacturing 122

- 5-1 Design 123
- 5-2 Major Classes of Engineering Materials 126
 - 5-2-1 Metals 127
 - 5-2-2 Ceramics 130
 - 5-2-3 Plastics 132
 - 5-2-4 Composite Structures 133
 - 5-2-5 Joining 134
- 5-3 Environmental Aspects 134
 - 5-3-1 Impact on Design 134
 - 5-3-2 Impact on Manufacturing 135
- 5-4 Recycling 136
 - 5-4-1 Metals 136
 - 5-4-2 Ceramics 137
 - 5-4-3 Plastics 138
 - 5-4-4 Composites 139
- 5-5 Summary 139
- Further Reading 139

Chapter 6

Solidification and Heat Treatment of Metals 142

- 6-1 Solidification 143
 - 6-1-1 Pure Metals 144
 - 6-1-2 Solid Solutions 146
 - 6-1-3 Eutectic Systems 150
 - 6-1-4 Peritectic Systems 152
 - 6-1-5 Intermetallic Phases 152
 - 6-1-6 Nonequilibrium Solidification 154
 - 6-1-7 Nucleation and Growth of Grains 156
- 6-2 Solid-State Reactions 157
 - 6-2-1 The Iron-Iron Carbide System 158
- 6-3 Structure-Property Relationships 160
 - 6-3-1 Metals and Single-Phase Alloys 161
 - 6-3-2 Two-Phase Materials 163
 - 6-3-3 Ternary and Polycomponent Alloys 167
 - 6-3-4 Inclusions 168
 - 6-3-5 Gases 169
 - 6-3-6 Effects of Grain Size 171
- 6-4 Heat Treatment 172
 - 6-4-1 Annealing 173
 - 6-4-2 Precipitation Hardening 173
 - 6-4-3 Heat Treatment of Steel 175
 - 6-4-4 Surface Treatment of Steel 178
- 6-5 Summary 179
- Problems 180
- Further Reading 182

Chapter 7

Metal Casting 184

- 7-1 Structure and Properties of Castings 185
 - 7-1-1 Solidification of Melts 186
 - 7-1-2 Macrosegregation 189
- 7-2 Casting Properties 190
 - 7-2-1 Viscosity 190
 - 7-2-2 Surface Effects 191
 - 7-2-3 Fluidity 192
- 7-3 Casting Alloys 194
 - 7-3-1 Ferrous Materials 194
 - 7-3-2 Nonferrous Materials 199

- 7-4 Melting and Pouring 202
 - 7-4-1 Melting 202
 - 7-4-2 Pouring 205
 - 7-4-3 Quality Assurance 205
 - 7-5 Casting Processes 206
 - 7-5-1 Classification 206
 - 7-5-2 Ingot Casting 207
 - 7-5-3 Casting of Shapes 208
 - 7-5-4 Expendable-Mold, Permanent-Pattern Casting 216
 - 7-5-5 Expendable-Mold, Expendable-Pattern Casting 223
 - 7-5-6 Permanent-Mold Casting 226
 - 7-5-7 Centrifugal Casting 232
 - 7-6 Finishing Processes 233
 - 7-6-1 Cleaning and Finishing 233
 - 7-6-2 Changing Properties after Casting 234
 - 7-7 Quality Assurance 235
 - 7-7-1 Inspection 235
 - 7-7-2 Casting Defects 235
 - 7-8 Process Capabilities and Design Aspects 236
 - 7-8-1 Process Capabilities 236
 - 7-8-2 Part Design 238
 - 7-9 Summary 243
 - Problems 244
 - Further Reading 248
- Chapter 8**
- Plastic Deformation of Metals 250**
- 8-1 Material Properties 252
 - 8-1-1 Flow Stress in Cold Working 252
 - 8-1-2 Discontinuous Yielding 257
 - 8-1-3 Textures (Anisotropy) 259
 - 8-1-4 Effects of Cold Working 263
 - 8-1-5 Annealing 265
 - 8-1-6 Hot Working 267
 - 8-1-7 Interactions between Deformation and Structure 272
 - 8-2 Mechanics of Deformation Processing 277
 - 8-2-1 Yield Criteria 277
 - 8-2-2 The Relevant Flow Stress 280
 - 8-2-3 Effects of Friction 281
 - 8-2-4 Lubrication 285
 - 8-2-5 Inhomogeneous Deformation 287
 - 8-2-6 Bulk Workability 289
 - 8-2-7 Sheet Formability 290
 - 8-3 Wrought Alloys 291
 - 8-3-1 Carbon Steels 292
 - 8-3-2 Alloy Steels 293
 - 8-3-3 Nonferrous Materials 293
 - 8-4 Summary 296
 - Problems 297
 - Further Reading 299
- Chapter 9**
- Bulk Deformation Processes 302**
- 9-1 Classification 303
 - 9-1-1 Temperature of Deformation 304
 - 9-1-2 Purpose of Deformation 305
 - 9-1-3 Analysis 305
 - 9-2 Open-Die Forging 308
 - 9-2-1 Axial Upsetting of a Cylinder 308
 - 9-2-2 Forging of Rectangular Workpieces 314
 - 9-2-3 Open-Die Forging 319
 - 9-2-4 Process Capabilities and Design Aspects 324
 - 9-3 Impression-Die and Closed-Die Forging 327
 - 9-3-1 Impression-Die Forging 328
 - 9-3-2 Closed-Die Forging 335
 - 9-3-3 Forge Rolling and Rotary Swaging 336
 - 9-3-4 Process Capabilities and Design Aspects 337
 - 9-4 Extrusion 339
 - 9-4-1 The Extrusion Process 339
 - 9-4-2 Hot Extrusion 341
 - 9-4-3 Cold Extrusion 343
 - 9-4-4 Extrusion Force 344
 - 9-4-5 Process Capabilities and Design Aspects 347
 - 9-5 Forging and Extrusion Equipment 350
 - 9-5-1 Tools and Dies 350
 - 9-5-2 Hammers 353
 - 9-5-3 Presses 355

- 9-6 Drawing 357
 - 9-6-1 The Drawing Process 358
 - 9-6-2 Forces 359
 - 9-6-3 Process Capabilities and Design Aspects 360
- 9-7 Rolling 362
 - 9-7-1 Flat Rolling 362
 - 9-7-2 Shape Rolling 364
 - 9-7-3 Ring Rolling 365
 - 9-7-4 Transverse Rolling 365
 - 9-7-5 Forces and Power Requirements 368
 - 9-7-6 Process Capabilities and Design Aspects 370
- 9-8 Summary 374
- Problems 375
- Further Reading 380

Chapter 10

Sheet-Metalworking Processes 382

- 10-1 Sheet Materials 383
 - 10-1-1 Steels 384
 - 10-1-2 Nonferrous Materials 387
 - 10-1-3 Surface Topography 387
- 10-2 Classification 388
- 10-3 Shearing 388
 - 10-3-1 The Shearing Process 389
 - 10-3-2 Forces 391
 - 10-3-3 Improving the Quality of Cut 393
 - 10-3-4 Processes 394
- 10-4 Bending 397
 - 10-4-1 The Bending Process 397
 - 10-4-2 Bending Limits 398
 - 10-4-3 Stresses and Springback 400
 - 10-4-4 Bending Methods 402
- 10-5 Stretch Forming 405
 - 10-5-1 Stretch Forming Processes 405
 - 10-5-2 Stretch Formability 406
 - 10-5-3 Forming Limit Diagram 408
- 10-6 Deep Drawing 409
 - 10-6-1 Drawing Processes 410
 - 10-6-2 Limiting Draw Ratio 412
 - 10-6-3 Further Drawing 415
- 10-7 Stretch-Drawing 416

- 10-8 Press Forming 420
- 10-9 Special Processes 422
- 10-10 Sheet-Metalworking Dies and Equipment 428
- 10-11 Process Capabilities and Design Aspects 428
- 10-12 Summary 432
- Problems 433
- Further Reading 437

Chapter 11

Powder Metallurgy 441

- 11-1 Classification 442
- 11-2 The Powder 442
 - 11-2-1 Powder Production 443
 - 11-2-2 Characterization of Powders 445
 - 11-2-3 Powder Preparation 446
 - 11-2-4 Blending 447
- 11-3 Powder Consolidation 448
 - 11-3-1 Cold Compaction 448
 - 11-3-2 Injection Molding 453
- 11-4 Sintering and Finishing 454
 - 11-4-1 Sintering 455
 - 11-4-2 Finishing 458
- 11-5 Hot Compaction 459
- 11-6 Powder-Metallurgy Products 461
- 11-7 Process Capabilities and Design Aspects 463
- 11-8 Electroforming 466
- 11-9 Summary 468
- Problems 469
- Further Reading 471

Chapter 12

Processing of Ceramics 474

- 12-1 Characteristics of Ceramics 476
 - 12-1-1 Bonding and Structure 476
 - 12-1-2 Properties of Ceramics 478
- 12-2 Classification of Ceramics Processes 481
- 12-3 Ceramic Materials 482
 - 12-3-1 Natural Ceramics 483
 - 12-3-2 Manufactured Ceramics 484

- 12-4 Processing of Particulate Ceramics 485
 - 12-4-1 Preparation of Powders 485
 - 12-4-2 Consolidation of Ceramic Powders 487
 - 12-4-3 Drying and Green Machining 489
 - 12-4-4 Sintering 489
 - 12-4-5 Hot Compaction 490
 - 12-4-6 Applications 492
 - 12-4-7 Process Capabilities and Design Aspects 495
- 12-5 Glasses 497
 - 12-5-1 Structure and Properties of Glasses 497
 - 12-5-2 Manufacturing Processes 499
 - 12-5-3 Coatings 506
 - 12-5-4 Process Capabilities and Design Aspects 507
- 12-6 Summary 507
- Problems 508
- Further Reading 510

Chapter 13

Polymers and Plastics 512

- 13-1 Polymerization Reactions 514
- 13-2 Linear (Thermoplastic) Polymers 516
 - 13-2-1 Structure of Linear Polymers 516
 - 13-2-2 Sources of Strength 518
 - 13-2-3 Crystalline and Amorphous Polymers 520
 - 13-2-4 Rheology of Linear Polymers 522
- 13-3 Cross-Linked (Thermosetting) Polymers 529
- 13-4 Elastomers 531
- 13-5 Additives and Fillers 533
 - 13-5-1 Additives 533
 - 13-5-2 Fillers 534
- 13-6 Service Properties of Polymers 535
 - 13-6-1 Mechanical Properties 535
 - 13-6-2 Physical and Chemical Properties 539
- 13-7 Plastics 540
 - 13-7-1 Thermoplastics 541
 - 13-7-2 Thermosets 546
 - 13-7-3 Elastomers 548
- 13-8 Summary 549

- Problems 549
- Further Reading 551

Chapter 14

Processing of Plastics 552

- 14-1 Classification 553
 - 14-2 Casting 554
 - 14-3 Melt Processing (Molding) 556
 - 14-3-1 Principles of Melt Processing 556
 - 14-3-2 Extrusion 557
 - 14-3-3 Injection Molding 566
 - 14-3-4 Other Molding Techniques 570
 - 14-3-5 Process Capabilities and Design Aspects 573
 - 14-4 Processing in the Rubbery State 577
 - 14-4-1 Blow Molding 577
 - 14-4-2 Thermoforming 581
 - 14-4-3 Cold Drawing 583
 - 14-4-4 Matched-Die Forming 583
 - 14-4-5 Process Capabilities and Design Aspects 583
 - 14-5 Particulate Processing Techniques 584
 - 14-6 Cellular or Foam Plastics 584
 - 14-7 Processing of Elastomers 585
 - 14-8 Plastics-Processing Equipment 586
 - 14-9 Summary 586
 - Problems 587
 - Further Reading 590
- ### Chapter 15
- ## Composites 592
- 15-1 Classification of Composites 594
 - 15-1-1 Particulate Composites 594
 - 15-1-2 Fiber Reinforcement 594
 - 15-2 Reinforcing Fibers 598
 - 15-3 Polymer-Matrix Composites 599
 - 15-3-1 Polymers 599
 - 15-3-2 Application of Polymers 600
 - 15-4 Fabrication of Polymer-Matrix Composites 602
 - 15-4-1 Open-Mold Processes 602
 - 15-4-2 Pultrusion 605
 - 15-4-3 Matched-Die Molding 605
 - 15-4-4 Process Capabilities and Design Aspects 606

- 15-5 Metal-Matrix Composites 607
- 15-6 Ceramic-Matrix Composites 610
- 15-7 Summary 612
- Problems 612
- Further Reading 614

- Chapter 16**
- Machining 616**
- 16-1 The Metal-Cutting Process 618
 - 16-1-1 Ideal Orthogonal Cutting 618
 - 16-1-2 Forces in Cutting 620
 - 16-1-3 Realistic Orthogonal Cutting 622
 - 16-1-4 Oblique Cutting 629
 - 16-1-5 Forces and Energy Requirements 631
 - 16-1-6 Temperatures 634
 - 16-1-7 Cutting Fluids 636
 - 16-1-8 Tool Life 639
 - 16-1-9 Surface Quality 643
- 16-2 Work Material 646
 - 16-2-1 Machinability 646
 - 16-2-2 Machinable Materials 647
 - 16-2-3 Ferrous Materials 648
 - 16-2-4 Nonferrous Materials 650
- 16-3 Cutting Tools 651
 - 16-3-1 Tool Materials 652
 - 16-3-2 Tool Construction 658
 - 16-3-3 Tool Holders and Fixtures 660
- 16-4 Classification 660
 - 16-4-1 Forming 660
 - 16-4-2 Generating 662
- 16-5 Single-Point Machining 663
 - 16-5-1 The Tool 663
 - 16-5-2 Turning 664
 - 16-5-3 Boring 667
 - 16-5-4 Gun Drilling and Trepanning 668
 - 16-5-5 Facing 669
 - 16-5-6 Forming 669
 - 16-5-7 Automatic Lathe 670
 - 16-5-8 Turret Lathe 670
 - 16-5-9 Automatic Screw Machines 670
 - 16-5-10 Shaping and Planing 672
- 16-6 Multipoint Machining 673
 - 16-6-1 Drilling 674
 - 16-6-2 Milling 677
 - 16-6-3 Sawing and Filing 680
 - 16-6-4 Broaching and Thread Cutting 681
 - 16-6-5 Gear Production 682
- 16-7 Choice of Process Variables 684
 - 16-7-1 Cutting Speeds and Feeds 685
 - 16-7-2 Cutting Time and Power 689
 - 16-7-3 Choice of Machine Tool 690
 - 16-7-4 Numerical Control and Automation 691
 - 16-7-5 Optimization of the Cutting Process 694
- 16-8 Abrasive Machining 697
 - 16-8-1 Classification 697
 - 16-8-2 The Process of Abrasive Machining 697
 - 16-8-3 Abrasives 699
 - 16-8-4 Grinding 700
 - 16-8-5 Other Bonded-Abrasive Processes 705
 - 16-8-6 Loose-Abrasive Processes 707
- 16-9 Process Capabilities and Design Aspects 710
 - 16-9-1 Design Aspects 710
 - 16-9-2 Precision Machining 713
- 16-10 Summary 715
- Problems 716
- Further Reading 722

- Chapter 17**
- Nontraditional Machining Processes 724**
- 17-1 Classification 725
- 17-2 Chemical Machining (CM or CHM) 726
- 17-3 Electrochemical Machining (ECM) 728
- 17-4 Electrical Discharge Machining (EDM) 730
- 17-5 High-Energy-Beam Machining 733
 - 17-5-1 Electron Beam Machining (EBM) 733
 - 17-5-2 Laser Beam Machining (LBM) 734
- 17-6 Machining of Nonmetallic Materials 736
 - 17-6-1 Machining of Ceramics 736
 - 17-6-2 Machining of Plastics 737
 - 17-6-3 Machining of Composites 738
- 17-7 Process Capabilities and Design Aspects 738
- 17-8 Summary 739
- Problems 740
- Further Reading 742

Chapter 18**Joining Processes 744**

- 18-1 Classification 745
- 18-2 Mechanical Joining 747
- 18-3 Solid-State Welding 749
 - 18-3-1 Cold Welding 750
 - 18-3-2 Diffusion Welding 752
 - 18-3-3 Hot Welding 753
 - 18-3-4 Friction Welding (FRW) 754
- 18-4 Fusion Welding 755
 - 18-4-1 The Fusion Joint 755
 - 18-4-2 Weldability and Weld Quality 759
 - 18-4-3 Weldable Materials 762
- 18-5 Resistance Welding 765
- 18-6 Electric Arc Welding 768
 - 18-6-1 Nonconsumable-Electrode Welding 769
 - 18-6-2 Consumable-Electrode Welding 771
 - 18-6-3 Consumable-Workpiece Welding 774
- 18-7 Other Welding Processes and Cutting 775
 - 18-7-1 Chemical Heat Sources 775
 - 18-7-2 High-Energy-Beam Welding 777
 - 18-7-3 Cutting 779
- 18-8 Liquid-Solid-State Bonding 780
 - 18-8-1 The Bond 780
 - 18-8-2 Brazing 783
 - 18-8-3 Soldering 784
- 18-9 Adhesive Bonding 786
 - 18-9-1 Characteristics of Structural Adhesives 786
 - 18-9-2 Adhesive Types and Their Application 788
- 18-10 Joining of Plastics and Ceramics 790
 - 18-10-1 Joining of Plastics 790
 - 18-10-2 Joining of Ceramics 791
- 18-11 Process Capabilities and Design Aspects 792
- 18-12 Laminates 796
- 18-13 Solid Freeform Fabrication (SFF) 798
 - 18-13-1 Purposes of Freeform Fabrication 799
 - 18-13-2 SFF Processes 800
- 18-14 Summary 802
- Problems 803
- Further Reading 806

Chapter 19**Surface Treatments 808**

- 19-1 Classification 809
- 19-2 Removal Processes 810
- 19-3 Conversion Coatings 811
- 19-4 Thermal Treatments 812
 - 19-4-1 Surface Heat Treatment 812
 - 19-4-2 Diffusion Coating 812
 - 19-4-3 Hot-Dip Coatings 813
 - 19-4-4 Weld Overlay Coatings 814
- 19-5 Metal Coatings 816
 - 19-5-1 Electroplating 816
 - 19-5-2 Electroless Coatings 817
 - 19-5-3 Metallizing of Plastics and Ceramics 818
- 19-6 Physical Vapor Deposition (PVD) 818
 - 19-6-1 Thermal PVD 819
 - 19-6-2 Sputter Deposition 820
 - 19-6-3 Ion Plating 822
 - 19-6-4 Plasma Carburizing and Nitriding 822
- 19-7 Chemical Vapor Deposition (CVD) 822
- 19-8 Ion Implantation 824
- 19-9 Organic Coatings 825
- 19-10 Process Capabilities and Design Aspects 827
- 19-11 Summary 827
- Problems 828
- Further Reading 829

Chapter 20**Manufacture of Semiconductor Devices 830**

- 20-1 Elements of Semiconductor Devices 833
 - 20-1-1 The Semiconductor 833
 - 20-1-2 Semiconductor Devices 836
 - 20-1-3 Integrated Circuits 839
- 20-2 Manufacture of Silicon Wafers 841
 - 20-2-1 Production of EGS 841
 - 20-2-2 Crystal Growing 843
 - 20-2-3 Wafer Preparation 843
- 20-3 Device Fabrication 844
 - 20-3-1 Outline of Process Sequence 844
 - 20-3-2 Basic Fabrication Techniques 846
 - 20-3-3 Changing the Composition of the Surface 846

- 20-3-4 Deposition of Surface Films 849
- 20-3-5 Lithography 852
- 20-3-6 Etching 855
- 20-3-7 Process Integration 858
- 20-3-8 Packaging 860
- 20-4 Printed Wiring Boards 865
 - 20-4-1 Thin-Film Fabrication Methods 865
 - 20-4-2 Thick-Film Circuits 866
 - 20-4-3 Soldering 867
- 20-5 Microfabrication 868
 - 20-5-1 Techniques of Microfabrication 869
 - 20-5-2 Nanotechnology 872
- 20-6 Summary 873
- Problems 874
- Further Reading 875

Chapter 21

Manufacturing Systems 876

- 21-1 Material Movement 877
 - 21-1-1 Attended Material Movement 878
 - 21-1-2 Mechanized Material Movement 879
 - 21-1-3 Robots 880
- 21-2 Production Organization 883
 - 21-2-1 Production Characteristics 883
 - 21-2-2 Optimum Manufacturing Method 884
 - 21-2-3 Organization for Mass Production 886
 - 21-2-4 Organization for Batch Production 887
 - 21-2-5 Organization of Assembly 891
 - 21-2-6 Scheduling of Assembly 893
- 21-3 Quality Management 894
 - 21-3-1 Quality Assurance 896
 - 21-3-2 Statistical Aspects of Manufacturing 896
 - 21-3-3 Acceptance Control 897
 - 21-3-4 Statistical Process Control 898
- 21-4 Manufacturing Management 904
 - 21-4-1 Company Organization 904
 - 21-4-2 Manufacturing Engineering 906

- 21-5 Summary 906
- Problems 907
- Further Reading 907

Chapter 22

Competitive Aspects of Manufacturing Processes 910

- 22-1 Competition in the Global Economy 912
- 22-2 Manufacturing Costs 913
 - 22-2-1 Cost and Productivity 913
 - 22-2-2 Operating Costs (Direct Costs) 915
 - 22-2-3 Indirect Costs 916
 - 22-2-4 Fixed Costs 917
- 22-3 Competition between Manufacturing Processes 917
- 22-4 Competition between Materials 918
- 22-5 Identifying the Optimum Approach 920
- 22-6 Summary 927
- Problems 928
- Further Reading 929

Appendix A

Conversion Table 931

Appendix B

Approximate Conversion of Hardness Values 933

Appendix C

Solutions to Selected Numerical Problems 935

Index 937