SI EDITION

PHYSICAL METALLURGY PRINCIPLES

Fourth Edition

REZA ABBASCHIAN

LARA ABBASCHIAN

ROBERT E. REED-HILL

Contents

CHAPTER 1 THE STRUCTURE OF METALS 1

1.1 The Structure of Metals, 1 **1.2** Unit Cells, 2 **1.3** The Body-Centered Cubic Structure (BCC), 3 **1.4** Coordination Number of the Body-Centered Cubic Lattice, 4 **1.5** The Face-Centered Cubic Lattice (FCC), 4 **1.6** The Unit Cell of the Hexagonal Closed-Packed (HCP) Lattice, 5 **1.7** Comparison of the Face-Centered Cubic and Close-Packed Hexagonal Structures, 6 **1.8** Coordination Number of the Systems of Closest Packing, 7 **1.9** Anisotropy, 7 **1.10** Textures or Preferred Orientations, 8 **1.11** Miller Indices, 9 **1.12** Crystal Structures of the Metallic Elements, 14 **1.13** The Stereographic Projection, 15 **1.14** Directions that Lie in a Plane, 16 **1.15** Planes of a Zone, 17 **1.16** The Wulff Net, 17 **1.17** Standard Projections, 21 **1.18** The Standard Stereographic Triangle for Cubic Crystals, 24 Problems, 26 References, 28

CHAPTER 2 CHARACTERIZATION TECHNIQUES 29

2.1 The Bragg Law, 30 **2.2** Laue Techniques, 33 **2.3** The Rotating-Crystal Method, 35 **2.4** The Debye-Scherrer or Powder Method, 36 **2.5** The X-Ray Diffractometer, 39 **2.6** The Transmission Electron Microscope, 40 **2.7** Interactions Between the Electrons in an Electron Beam and a Metallic Specimen 46 **2.8** Elastic Scattering, 46 **2.9** Inelastic Scattering, 46 **2.10** Electron Spectrum, 48 **2.11** The Scanning Electron Microscope, 48 **2.12** Topographic Contrast, 50 **2.13** The Picture Element Size, 53 **2.14** The Depth of Focus, 54 **2.15** Microanalysis of Specimens, 55 **2.16** Electron Probe X-Ray Microanalysis, 55 **2.17** The Characteristic X-Rays, 56 **2.18** Auger* Electron Spectroscopy (AES), 58 **2.19** The Scanning Transmission Electron Microscope (STEM), 60 Problems, 60 References 61

CHAPTER 3 CRYSTAL BINDING 62

3.1 The Internal Energy of a Crystal, 62 **3.2** Ionic Crystals, 62 **3.3** The Born Theory of Ionic Crystals, 63 **3.4** Van Der Waals Crystals, 68 **3.5** Dipoles, 68 **3.6** Inert Cases, 69 **3.7** Induced Dipoles, 70 **3.8** The Lattice Energy of an Inert-Gas Solid, 71 **3.9** The Debye Frequency, 72 **3.10** The Zero-Point Energy, 73 **3.11** Dipole-Quadrupole and Quadrupole-Quadrupole Terms, 75 **3.12** Molecular Crystals, 75 **3.13** Refinements to the Born Theory of Ionic Crystals, 75 **3.14** Covalent and Metallic Bonding, 76 Problems 80 References, 81

CHAPTER 4 INTRODUCTION TO DISLOCATIONS 82

4.1 The Discrepancy Between the Theoretical and Observed Yield Stresses of Crystals, 82 **4.2** Dislocations, 85 **4.3** The Burgers Vector, 93 **4.4** Vector Notation for Dislocations, 95 **4.5** Dislocations in the Face-Centered Cubic Lattice, 96 **4.6** Intrinsic and Extrinsic Stacking Faults in Face-Centered Cubic Metals, 101 **4.7** Extended Dislocations in Hexagonal Metals, 102 **4.8** Climb of Edge Dislocations, 102 **4.9** Dislocation Intersections, 104 **4.10** The Stress Field of a Screw Dislocation, 107 **4.11** The Stress Field of an Edge Dislocation, 109 **4.12** The Force on a Dislocation, 111 **4.13** The Strain Energy of a Screw Dislocation, 114 **4.14** The Strain Energy of an Edge Dislocation, 115 Problems, 116 References, 118

CHAPTER 5 DISLOCATIONS AND PLASTIC DEFORMATION 119

5.1 The Frank-Read Source, 119 **5.2** Nucleation of Dislocations, 120 **5.3** Bend Gliding, 123 **5.4** Rotational Slip, 125 **5.5** Slip Planes and Slip Directions, 127 **5.6** Slip Systems, 129 **5.7** Critical Resolved Shear Stress, 129 **5.8** Slip on Equivalent Slip Systems, 133 **5.9** The Dislocation Density, 133 **5.10** Slip Systems in Different Crystal Forms, 133 **5.11** Cross-Slip, 138 **5.12** Slip Bands, 141 **5.13** Double Cross-Slip, 141 **5.14** Extended Dislocations and Cross-Slip, 143 **5.15** Crystal Structure Rotation During Tensile and Compressive Deformation, 144 **5.16** The Notation for the Slip Systems in the Deformation of FCC Crystals, 147 **5.17** Work Hardening, 149 **5.18** Considère's Criterion, 150 **5.19** The Relation Between Dislocation Density and the Stress, 151 **5.20** Taylor's Relation, 153 **5.21** The Orowan Equation, 153 Problems, 154 References, 157

CHAPTER 6 ELEMENTS OF GRAIN BOUNDARIES 158

6.1 Grain Boundaries, 158 **6.2** Dislocation Model of a Small-Angle Grain Boundary, 159 **6.3** The Five Degrees of Freedom of a Grain Boundary, 161 **6.4** The Stress Field of a Grain Boundary, 162 **6.5** Grain-Boundary Energy, 165 **6.6** Low-Energy Dislocation Structures, LEDS, 167 **6.7** Dynamic Recovery, 170 **6.8** Surface Tension of the Grain Boundary, 172 **6.9** Boundaries Between Crystals of Different Phases, 175 **6.10** The Grain Size, 178 **6.11** The Effect of Grain Boundaries on Mechanical Properties: Hall-Petch Relation, 180 **6.12** Grain Size Effects in Nanocrystalline Materials, 182 **6.13** Coincidence Site Boundaries, 185 **6.14** The Density of Coincidence Sites, 186 **6.15** The Ranganathan Relations, 186 **6.16** Examples Involving Twist Boundaries, 187 **6.17** Tilt Boundaries, 189 Problems, 192 References, 193

CHAPTER 7 VACANCIES 194

7.1 Thermal Behavior of Metals, 194 **7.2** Internal Energy, 195 **7.3** Entropy, 196 **7.4** Spontaneous Reactions, 196 **7.5** Gibbs Free Energy, 197

7.6 Statistical Mechanical Definition of Entropy, 199 **7.7** Vacancies, 203 **7.8** Vacancy Motion, 209 **7.9** Interstitial Atoms and Divacancies, 211 Problems, 214 References, 215

CHAPTER 8 ANNEALING 216

8.1 Stored Energy of Cold Work, 216 **8.2** The Relationship of Free Energy to Strain Energy, 217 **8.3** The Release of Stored Energy, 218 **8.4** Recovery, 220 **8.5** Recovery in Single Crystals, 221 **8.6** Polygonization, 223 **8.7** Dislocation Movements in Polygonization, 226 **8.8** Recovery Processes at High and Low Temperatures, 229 **8.9** Recrystallization, 230 **8.10** The Effect of Time and Temperature on Recrystallization, 230 **8.11** Recrystallization Temperature, 232 **8.12** The Effect of Strain on Recrystallization, 233 **8.13** The Rate of Nucleation and the Rate of Nucleus Growth, 234 **8.14** Formation of Nuclei, 235 **8.15** Driving Force for Recrystallization, 237 **8.16** The Recrystallized Grain Size 237 **8.17** Other Variables in Recrystallization, 239 **8.18** Purity of the Metal, 239 **8.19** Initial Grain Size, 240 **8.20** Grain Growth, 240 **8.21**, Geometrical Coalescence, 243 **8.22** Three-Dimensional Changes in Grain Geometry, 244 **8.23** The Grain Growth Law, 245 **8.24** Impurity Atoms in Solid Solution, 249 **8.25** Impurities in the Form of Inclusions, 250 **8.26** The Free-Surface Effects, 253 **8.27** The Limiting Grain Size, 254 **8.28** Preferred Orientation, 256 **8.29** Secondary Recrystallization, 256 **8.30** Strain-Induced Boundary Migration 257 Problems, 258 References, 259

CHAPTER 9 SOLID SOLUTIONS 261

9.1 Solid Solutions, 261 **9.2** Intermediate Phases, 261 **9.3** Interstitial Solid Solutions, 262 **9.4** Solubility of Carbon in Body-Centered Cubic Iron, 263 **9.5** Substitutional Solid Solutions and the Hume-Rothery Rules, 267 **9.6** Interaction of Dislocations and Solute Atoms, 267 **9.7** Dislocation Atmospheres, 268 **9.8** The Formation of a Dislocation Atmosphere, 269 **9.9** The Evaluation of *A*, 270 **9.10** The Drag of Atmospheres on Moving Dislocations, 271 **9.11** The Sharp Yield Point and Lüders Bands, 273 **9.12** The Theory of the Sharp Yield Point, 275 **9.13** Strain Aging, 276 **9.14** The Cottrell-Bilby Theory of Strain Aging, 277 **9.15** Dynamic Strain Aging 282 Problems, 285 References, 286

CHAPTER 10 PHASES 287

10.1 Basic Definitions, 287 **10.2** The Physical Nature of Phase Mixtures, 289 **10.3** Thermodynamics of Solutions, 289 **10.4** Equilibrium Between Two Phases, 292 **10.5** The Number of Phases in an Alloy System, 293 **10.6** Two-Component Systems Containing Two Phases, 303 **10.7** Graphical Determinations of Partial-Molal Free Energies, 304 **10.8** Two-Component Systems with Three Phases in Equilibrium, 306 **10.9** The Phase Rule, 307 **10.10** Ternary Systems, 309 Problems, 310 References, 311

CHAPTER 11 BINARY PHASE DIAGRAMS 312

11.1 Phase Diagrams, 312 **11.2** Isomorphous Alloy Systems, 312 **11.3** The Lever Rule, 314 **11.4** Equilibrium Heating or Cooling of an Isomorphous Alloy, 317 **11.5** The Isomorphous Alloy System from the Point of View of Free Energy, 319 **11.6** Maxima and Minima, 320 **11.7** Superlattices, 322 **11.8** Miscibility Gaps, 326 **11.9** Eutectic Systems, 328 **11.10** The Microstructures of Eutectic Systems, 329 **11.11** The Peritectic Transformation, 334 **11.12** Monotectics, 337 **11.13** Other Three-Phase Reactions, 338 **11.14** Intermediate Phases, 339 **11.15** The Copper-Zinc Phase Diagram, 341 **11.16** Ternary Phase Diagrams, 343 Problems, 346 References, 347

CHAPTER 12 DIFFUSION IN SUBSTITUTIONAL SOLID SOLUTIONS 348

12.1 Diffusion in an Ideal Solution, 348 **12.2** The Kirkendall Effect, 352 **12.3** Pore Formation, 355 **12.4** Darken's Equations, 357 **12.5** Fick's Second Law, 360 **12.6** The Matano Method, 363 **12.7** Determination of the Intrinsic Diffusivities, 366 **12.8** Self-Diffusion in Pure Metals, 368 **12.9** Temperature Dependence of the Diffusion Coefficient, 370 **12.10** Chemical Diffusion at Low-Solute Concentration, 372 **12.11** The Study of Chemical Diffusion Using Radioactive Tracers, 374 **12.12** Diffusion Along Grain Boundaries and Free Surfaces, 377 **12.13** Fick's First Law in Terms of a Mobility and an Effective Force, 380 **12.14** Diffusion in Non-Isomorphic Alloy Systems, 382 Problems, 386 References, 388

CHAPTER 13 INTERSTITIAL DIFFUSION 389

13.1 Measurement of Interstitial Diffusivities, 389 **13.2** The Snoek Effect, 391 **13.3** Experimental Determination of the Relaxation Time, 398 **13.4** Experimental Data, 405 **13.5** Anelastic Measurements at Constant Strain, 405 Problems, 406 References, 407

CHAPTER 14 SOLIDIFICATION OF METALS 408

14.1 The Liquid Phase, 408 **14.2** Nucleation, 411 **14.3** Metallic Glasses, 413 **14.4** Crystal Growth from the Liquid Phase, 420 **14.5** The Heats of Fusion and Vaporization, 421 **14.6** The Nature of the Liquid-Solid Interface, 423 **14.7** Continuous Growth, 425 **14.8** Lateral Growth, 427 **14.9** Stable Interface Freezing, 428 **14.10** Dendritic Growth in Pure Metals, 429 **14.11** Freezing in Alloys with Planar Interface, 432 **14.12** The Scheil Equation, 434 **14.13** Dendritic Freezing in Alloys, 437 **14.14** Freezing of Ingots, 439 **14.15** The Grain Size of Castings, 443 **14.16** Segregation, 443 **14.17** Homogenization 445 **14.18** Inverse Segregation, 450 **14.19** Porosity, 450 **14.20** Eutectic Freezing, 454 Problems, 459 References, 461

CHAPTER 15 NUCLEATION AND GROWTH KINETICS 463

15.1 Nucleation of a Liquid from the Vapor, 463 **15.2** The Becker-Döring Theory, 471 **15.3** Freezing, 473 **15.4** Solid-State Reactions, 475 **15.5** Heterogeneous Nucleation, 478 **15.6** Growth Kinetics, 481 **15.7** Diffusion Controlled Growth, 484 **15.8** Interference of Growing Precipitate Particles, 488 **15.9** Interface Controlled Growth, 488 **15.10** Transformations That Occur on Heating, 492 **15.11** Dissolution of a Precipitate, 493 Problems, 495 References, 497

CHAPTER 16 PRECIPITATION HARDENING 498

16.1 The Significance of the Solvus Curve, 499 **16.2** The Solution Treatment, 500 **16.3** The Aging Treatment, 500 **16.4** Development of Precipitates, 503 **16.5** Aging of Al-Cu Alloys at Temperatures Above 100°C (373 K), 506 **16.6** Precipitation Sequences in Other Aluminum Alloys, 509 **16.7** Homogeneous Versus Heterogeneous Nucleation of Precipitates, 511 **16.8** Interphase Precipitation, 512 **16.9** Theories of Hardening, 515 **16.10** Additional Factors in Precipitation Hardening, 516 Problems, 518 References, 519

CHAPTER 17 DEFORMATION TWINNING AND MARTENSITE REACTIONS 521

17.1 Deformation Twinning, 521 **17.2** Formal Crystallographic Theory of Twinning, 524 **17.3** Twin Boundaries, 530 **17.4** Twin Growth, 531 **17.5** Accommodation of the Twinning Shear, 533 **17.6** The Significance of Twinning in Plastic Deformation, 534 **17.7** The Effect of Twinning on Face-Centered Cubic Stress-Strain Curves, 535 **17.8** Martensite, 537 **17.9** The Bain Distortion, 538 **17.10** The Martensite Transformation in an Indium-Thallium Alloy, 540 **17.11** Reversibility of the Martensite Transformation, 541 **17.12** Athermal Transformation, 541 **17.13** Phenomenological Crystallographic Theory of Martensite Formation, 542 **17.14** Irrational Nature of the Habit Plane, 548 **17.15** The Iron-Nickel Martensitic Transformation, 549 **17.16** Isothermal Formation of Martensite, 551 **17.17** Stabilization, 551 **17.18** Nucleation of Martensite Plates, 552 **17.19** Growth of Martensite Plates, 553 **17.20** The Effect of Stress, 553 **17.21** The Effect of Plastic Deformation, 554 **17.22** Thermoelastic Martensite Transformations, 554 **17.23** Elastic Deformation of Thermoelastic Alloys, 556 **17.24** Stress-Induced Martensite (SIM), 556 **17.25** The Shape-Memory Effect, 557 Problems, 559 References, 560

CHAPTER 18 THE IRON-CARBON ALLOY SYSTEM 562

18.1 The Iron-Carbon Diagram, 562 **18.2** The Proeutectoid Transformations of Austenite, 565 **18.3** The Transformation of Austenite to Pearlite, 566 **18.4** The Growth of Pearlite, 572 **18.5** The Effect of Temperature on the Pearlite

Transformation, 573 **18.6** Forced-Velocity Growth of Pearlite, 575 **18.7** The Effects of Alloying Elements on the Growth of Pearlite, 578 **18.8** The Rate of Nucleation of Pearlite, 581 **18.9** Time-Temperature-Transformation Curves, 583 **18.10** The Bainite Reaction, 584 **18.11** The Complete T-T-T Diagram of an Eutectoid Steel, 591 **18.12** Slowly Cooled Hypoeutectoid Steels, 593 **18.13** Slowly Cooled Hypereutectoid Steels, 595 **18.14** Isothermal Transformation Diagrams for Noneutectoid Steels, 597 Problems, 600 References, 602

CHAPTER 19 THE HARDENING OF STEEL 603

19.1 Continuous Cooling Transformations (CCT), 603 **19.2** Hardenability, 606 **19.3** The Variables that Determine the Hardenability of a Steel, 614 **19.4** Austenitic Grain Size, 614 **19.5** The Effect of Austenitic Grain Size on Hardenability, 615 **19.6** The Influence of Carbon Content on Hardenability, 615 **19.7** The Influence of Alloying Elements on Hardenability, 616 **19.8** The Significance of Hardenability, 621 **19.9** The Martensite Transformation in Steel, 622 **19.10** The Hardness of Iron-Carbon Martensite, 627 **19.11** Dimensional Changes Associated with Transformation of Martensite, 631 **19.12** Quench Cracks, 632 **19.13** Tempering, 633 **19.14** Tempering of a Low-Carbon Steel, 639 **19.15** Spheroidized Cementite, 641 **19.16** The Effect of Tempering on Physical Properties, 643 **19.17** The Interrelation Between Time and Temperature in Tempering, 646 **19.18** Secondary Hardening, 646 Problems, 647 References, 649

CHAPTER 20 SELECTED NONFERROUS ALLOY SYSTEMS 651

20.1 Commercially Pure Copper, 651 **20.2** Copper Alloys, 654 **20.3** Copper Beryllium, 658 **20.4** Other Copper Alloys, 659 **20.5** Aluminum Alloys, 659 **20.6** Aluminum-Lithium Alloys, 660 **20.7** Titanium Alloys, 668 **20.8** Classification of Titanium Alloys, 670 **20.9** The Alpha Alloys, 670 **20.10** The Beta Alloys, 676 **20.11** The Alpha-Beta Alloys, 677 **20.12** Superalloys, 679 20.13 Creep Strength, 680 Problems, 683 References, 684

CHAPTER 21 FAILURE OF METALS 686

21.1 Failure by Easy Glide, 686 **21.2** Rupture by Necking (Multiple Glide), 688 **21.3** The Effect of Twinning, 689 **21.4** Cleavage, 690 **21.5** The Nucleation of Cleavage Cracks, 691 **21.6** Propagation of Cleavage Cracks, 693 **21.7** The Effect of Grain Boundaries, 696 **21.8** The Effect of the State of Stress, 698 **21.9** Ductile Fractures, 700 **21.10** Intercrystalline Brittle Fracture, 705 **21.11** Blue Brittleness, 705 **21.12** Fatigue Failures, 706 **21.13** The Macroscopic Character of Fatigue Failure, 706 **21.14** The Rotating-Beam Fatigue Test, 708 **21.15** Alternating Stress Parameters, 710 **21.16** The Microscopic Aspects of Fatigue Failure, 713 **21.17** Fatigue Crack Growth, 717 **21.18** The Effect of Nonmetallic Inclusions, 720 **21.19** The Effect of Steel

Microstructure on Fatigue, 721 **21.20** Low-Cycle Fatigue, 721 **21.21** The Coffin-Manson Equation, 726 **21.22** Certain Practical Aspects of Fatigue, 727 Problems, 728 References, 729

APPENDICES 731

A ANGLES BETWEEN CRYSTALLOGRAPHIC PLANES IN THE CUBIC SYSTEM* (IN DEGREES), 731

B ANGLES BETWEEN CRYSTALLOGRAPHIC PLANES FOR HEXAGONAL ELEMENTS*, 733

C INDICES OF THE REFLECTING PLANES FOR CUBIC STRUCTURES, 734

D CONVERSION FACTORS AND CONSTANTS, 734

E TWINNING ELEMENTS OF SEVERAL OF THE MORE IMPORTANT TWINNING MODES, 735

F SELECTED VALUES OF INTRINSIC STACKING-FAULT ENERGY γ_I, TWIN-BOUNDARY ENERGY γ_T, GRAIN-BOUNDARY ENERGY γ_G, AND CRYSTAL-VAPOR SURFACE ENERGY γ FOR VARIOUS MATERIALS IN ERGS/CM^2*, 735

LIST OF IMPORTANT SYMBOLS 737

LIST OF GREEK LETTER SYMBOLS 739

INDEX 740