Contents

1 Length-Scale in Solidification Analysis 1
References 5

2 Thermodynamic Concepts—Equilibrium and Nonequilibrium During Solidification 7
2.1 Equilibrium 7
2.2 The Undercooling Requirement 9
2.2.1 Curvature Undercooling 12
2.2.2 Thermal Undercooling 14
2.2.3 Constitutional Undercooling 15
2.2.4 Pressure Undercooling 18
2.2.5 Kinetic Undercooling 19
2.3 Departure from Equilibrium 21
2.3.1 Local Interface Equilibrium 22
2.3.2 Interface Nonequilibrium 23
2.4 Applications 26
References 27

3 Nucleation and Growth Kinetics—Nanoscale Solidification 29
3.1 Nucleation 29
3.1.1 Steady-State Nucleation—Homogeneous Nucleation 30
3.1.2 Steady-State Nucleation—Heterogeneous Nucleation 36
3.1.3 Time-Dependent (Transient) Nucleation in Pure Metals 43
3.1.4 Inoculation and Grain Refining 43
3.1.5 Dynamic Nucleation 45
3.2 Growth Kinetics 48
3.2.1 Types of Interfaces 48
3.2.2 Continuous Growth 52
3.2.3 Lateral Growth 53
3.3 Applications 55
References 58

4 Fundamentals of Transport Phenomena as Applied to Solidification Processing 61
4.1 General Conservation Transport Equations 61
4.2 Flux Laws 64
References 65

5 Diffusive Mass Transport at the Macroscale 67
5.1 Solute Diffusion-Controlled Segregation 67
5.2 Equilibrium Solidification 70
5.3 No Diffusion in Solid, Complete Diffusion in Liquid (the Gulliver–Scheil Model) 72
5.4 No Diffusion in Solid, Limited Diffusion in Liquid 73
5.5 Limited Diffusion in Solid, Complete Diffusion in Liquid 75
5.6 Limited Diffusion in Solid and Liquid 79
5.7 Partial Mixing in Liquid, No Diffusion in Solid 79
5.8 Summary of Diffusion-Controlled Macrosegregation 80
5.9 Zone Melting 81
5.10 Applications 83
References 88

6 Diffusive Energy Transport at the Macroscale 89
6.1 Governing Equation for Diffusive Energy Transport 89
6.2 Boundary Conditions 91
6.3 Analytical Solutions for Steady-State Solidification of Castings 93
6.4 Analytical Solutions for Non-Steady-State Solidification of Castings 94
6.4.1 Resistance in the Mold 97
6.4.2 Resistance at the Mold/Solid Interface 100
6.4.3 The Heat Transfer Coefficient 103
6.4.4 Resistance in the Solid 104
6.5 Thermal Analysis 105
6.5.1 Direct Thermal Analysis 106
6.5.2 Differential Thermal Analysis 106
6.6 Applications 114
References 117

7 Momentum Mass Transport at the Macroscale 119
7.1 Shrinkage Flow 119
7.2 Natural Convection 119
7.3 Surface-Tension-Driven (Marangoni) Convection 122
7.4 Flow Through the Mushy Zone 123
7.4.1 The Hagen–Poiseuille Model 123
7.4.2 The Blake–Kozeny Model 124
7.5 Segregation Controlled by Fluid Flow 124

7.6 Segregation Controlled by Fluid Flow and Solute Diffusion 126
7.7 Macroshrinkage 128
7.7.1 Metal Shrinkage and Feeding 128
7.7.2 Shrinkage Defects 133
References 134

8 Diffusive Mass Transport at the Microscale; Microsolute Redistribution and Microsegregation 135
8.1 Summary of Microsegregation Models 135
8.2 Applications 143
References 144

9 Solidification of Single-Phase Alloys; Cells and Dendrites 145
9.1 Interface Stability 145
9.1.1 Thermal Instability 145
9.1.2 Solutal Instability 147
9.1.3 Thermal, Solutal, and Surface Energy Driven Morphological Instability 150
9.1.4 Influence of Convection on Interface Stability 153
9.2 Morphology of Primary Phases 154
9.3 Analytical Tip Velocity Models for Cells and Dendrites 157
9.3.1 Solute Diffusion-Controlled Growth (Isothermal Growth) of Needle-Like Crystals and Dendrites Tip 157
9.3.2 Thermal Diffusion-Controlled Growth 161
9.3.3 Solutal, Thermal, and Capillary-Controlled Growth 162
9.3.4 Interface Anisotropy and the Dendrite Tip Selection Parameter σ* 169
9.3.5 Effect of Fluid Flow on Dendrite Tip Velocity 170
9.3.6 Multicomponent Alloys 171
9.4 Dendritic Arm Spacing and Coarsening 173
9.4.1 Primary Arm Spacing 173
9.4.2 Secondary Arm Spacing 175
9.4.3 Dendrite Coherency 181
9.5 The Columnar-to-Equiaxed Transition 182
9.6 Applications 189
References 194

10 Solidification of Two-Phase Alloys—Micro-Scale Solidification 197
10.1 Eutectic Solidification 197
10.1.1 Classification of Eutectics 197
10.1.2 Cooperative Eutectics 199
10.1.3 Models for Regular Eutectic Growth 201
10.1.4 Models for Irregular Eutectic Growth 207
10.1.5 Divorced Eutectics 213
10.1.6 Interface Stability of Eutectics 216

10.1.7 Equiaxed Eutectic Solidification 220
10.2 Peritectic Solidification 221
10.2.1 Classification of Peritectics 221
10.2.2 Peritectic Microstructures and Phase Selection 223
10.2.3 Mechanism of Peritectic Solidification 228
10.3 Monotectic Solidification 234
10.3.1 Classification of Monotectics 235
10.3.2 Mechanism of Monotectic Solidification 235
10.4 Applications 240
References 248

11 Solidification of Multicomponent Alloys 251
11.1 Thermodynamics of Multicomponent Alloys 251
11.2 Thermophysical Properties 254
11.2.1 Multicomponent Diffusion 254
11.2.2 Interface Energy 255
11.2.3 Microstructure 255
References 262

12 Microshrinkage 263
12.1 Defect Size and Shape 263
12.2 The Physics of Shrinkage Porosity Formation 267
12.2.1 Pressure in the Mushy Zone 270
12.2.2 Gas Pressure in Pore 272
12.2.3 Gas Evolution in Liquid 273
12.2.4 Pore Nucleation 274
12.2.5 Pore Growth in the Mushy Zone 278
References 280

13 Rapid Solidification and Amorphous Alloys 283
13.1 Rapidly Solidified Crystalline Alloys 283
13.2 Metallic Glasses 288
References 294

14 Semisolid Processing 295
14.1 Phenomenology 295
14.2 Typical Process Routes 299
14.2.1 Semisolid Slurry Processing 299
14.2.2 Forming of the Semisolid Slurry 301
14.3 Material Models/Systems 301
References 303

15 Solidification of Metal Matrix Composites . . . 305
15.1 Solidification in the Presence of Freely Moving Particles . . . 307
15.1.1 Particle Interaction with a Planar Interface . . . 308
15.1.2 Material Properties Models . . . 311
15.1.3 Kinetic Models . . . 312
15.1.4 Microstructure Visualization Models . . . 322
15.1.5 Mechanism of Engulfment (Planar S/L Interface) . . . 323
15.1.6 Particle Interaction with a Cellular/Dendritic Interface . . . 325
15.2 Solidification in the Presence of Stationary Reinforcements; the Infiltration Pressure . . . 326
15.2.1 Surface Energy Considerations . . . 327
15.2.2 Transport Phenomena Considerations . . . 329
15.2.3 Microstructure Effects . . . 331
15.3 Processing of Ex-Situ MMCs by Solidification Techniques . . . 332
15.3.1 Stir Casting . . . 332
15.3.2 Infiltration of Reinforcements . . . 335
15.3.3 Spray Casting . . . 336
15.3.4 Ultrasonic Cavitation . . . 336
15.4 Processing of In-Situ Metal Matrix Composites . . . 338
References . . . 339

16 Multiscale Modeling of Solidification . . . 343
References . . . 344

17 Numerical Macroscale Modeling of Solidification . . . 345
17.1 Problem Formulation . . . 345
17.1.1 The Enthalpy Method . . . 346
17.1.2 The Specific Heat Method . . . 347
17.1.3 The Temperature Recovery Method . . . 347
17.2 Discretization of Governing Equations . . . 348
17.2.1 The Finite Difference Method: Explicit formulation . . . 348
17.2.2 The Finite Difference Method: Implicit Formulation . . . 352
17.2.3 The Finite Difference Method: General Implicit and Explicit Formulation . . . 353
17.2.4 Control-Volume Formulation . . . 353
17.3 Solution of the Discretized Equations . . . 354
17.4 Macrosegregation Modeling . . . 355
17.4.1 A Mixture-Theory Model . . . 355
17.4.2 Effect of Solid Deformation . . . 359
17.5 Macroshrinkage Modeling . . . 360
17.5.1 Thermal Models . . . 360
17.5.2 Thermal/Volume Calculation Models . . . 362
17.5.3 Thermal/Fluid Flow Models . . . 363
17.6 Impact of Macromodeling of Solidification on the Metal Casting Industry . . . 366

17.7 Analysis of Shrinkage Porosity Models and Defect Prevention 369
17.8 Applications 371
References 375

18 Numerical Microscale Modeling of Solidification 379
18.1 Heterogeneous Nucleation Models 380
18.2 Continuum and Volume-Averaged Models 385
18.2.1 Problem Formulation 385
18.2.2 Coupling of Macro-transport and Transformation-Kinetics Codes 388
18.2.3 Dendrite Growth Models 389
18.2.4 Microporosity Models 399
18.3 Phase Field Models 407
18.4 Stochastic Models 410
18.4.1 Monte-Carlo Models 412
18.4.2 Cellular Automaton Models 416
18.4.3 Lattice Boltzmann Models 426
18.5 Molecular Dynamics Models 428
18.6 Applications 430
References 431

19 Solidification of Some Casting Alloys of Commercial Significance 435
19.1 Steel 435
19.1.1 Macrostructure 435
19.1.2 Microstructure 437
19.1.3 Dendrite Arm Spacing 439
19.1.4 Nonmetallic Inclusions 440
19.1.5 Simulation of the Solidification of Steel 441
19.2 Cast Iron 443
19.2.1 The Structure of Liquid Cast Iron 445
19.2.2 Graphite Shape 445
19.2.3 Nucleation and Growth of Austenite Dendrites 447
19.2.4 Nucleation of Graphite 451
19.2.5 Growth of Graphite from the Liquid 454
19.2.6 Eutectic Solidification of Cast Iron 469
19.2.7 The Gray-to-White Structural Transition 480
19.2.8 Thermal Analysis of Cast Iron 484
19.2.9 Simulation of Solidification of Cast Iron 485
19.3 Aluminum–Silicon Alloys 494
19.3.1 Nucleation and Growth of Primary Aluminum Dendrites 494
19.3.2 Eutectic Solidification of Al–Si Alloys 495
19.3.3 Effect of Oxides 500
19.3.4 Ultrasonic Processing 502
19.3.5 Thermal Analysis of Aluminum Alloys 504
19.3.6 Simulation of the Solidification of Aluminum-Based Alloys 505

19.4 Superalloys 509
19.4.1 Microstructure of Superalloys 510
19.4.2 Solidification Processing of Superalloys 514
19.4.3 Simulation of the Solidification of Superalloys 522
19.5 Applications 527
References 528

Appendix 535
Appendix A: Some Solutions of the Diffusion Equations 535
Appendix B: Properties of Selected Materials 538
Appendix C: Selected Phase Diagrams 545
References 549

Index 551

http://www.springer.com/978-3-319-15692-7

Science and Engineering of Casting Solidification
Stefanescu, D.
2015, XVI, 556 p. 300 illus., 100 illus. in color.,
Hardcover
ISBN: 978-3-319-15692-7