ENGINEERING MATERIALS

L. Ratke · P. W. Voorhees

Growth and Coarsening

Ripening in Material Processing

Springer

Table of Contents

Preface V

1. Introduction 1

2. Thermodynamics of alloys 7
2.1 Basic definitions 7
2.2 Single component systems 11
2.3 Binary and multicomponent systems 15
2.4 Applications: Phase diagrams 28
2.4.1 Complete miscibility 28
2.4.2 Eutectic phase diagram 28
2.5 Gibbs-Thomson equation 31
2.5.1 Pure Material 32
2.6 Binary Alloy 35

3. Transport of heat and mass 43
3.1 Diffusive heat transport 43
3.2 Diffusive mass transport 45
3.3 Convective heat and mass transport 50

4. Growth 57
4.1 The general growth problem 57
4.2 Growth of a supercooled sphere 63
4.3 Growth in a supersaturated matrix 65
4.4 Interface Kinetics of first order 67
4.4.1 Interface kinetics in a supersaturated matrix 70
4.4.2 Interface kinetics in a supercooled melt 73
4.5 Interface kinetics of second order 74
4.5.1 Growth rates in second order kinetics 76
4.6 Convective contributions to heat and mass transfer 77

4.6.1 General growth laws at large Peclet numbers 78
4.6.2 Growth of a falling solid sphere 80
4.6.3 Growth of a falling liquid sphere 85
4.6.4 Growth at arbitrary Peclet numbers 89
4.7 Growth with varying supersaturation 92

5. Statistics of growth 97
5.1 Continuity equation and moments 97
5.2 Statistics at constant growth rate 99
5.3 Superposition of growth modes 99
5.4 Constant supercooling or supersaturation 100
5.4.1 Initial value problem - Cauchy problem 101
5.4.2 Scaling solutions 106
5.4.3 Scaling with the inverse square root of time 109
5.4.4 Comments on scaling 110
5.5 Separation ansatz solution for growth 111
5.6 General solution for power law growth 112
5.7 Convective diffusion to dispersed drops 114

6. Coarsening - Basics and Growth Laws 117
6.1 General considerations on coarsening 117
6.2 Ostwald ripening due to curvature supercooling 119
6.3 Ostwald ripening due to solubility changes 122
6.4 Ostwald ripening in interface kinetics or general first order reactions 124
6.5 Coarsening due to a second-order reaction 125
6.6 Coarsening under convective transport 126

7. Ostwald ripening - Wagner analysis 127
7.1 Diffusion driven coarsening 127
7.2 Coarsening with convective transport 143
7.3 Second order reaction coarsening 148

8. Ostwald ripening - Marqusee and Ross type analysis 151
8.1 Interface driven coarsening in a supersaturated matrix . 151
8.2 Diffusive coarsening in a supercooled melt 160

9. Multiparticle diffusion analysis 167
9.1 The Multiparticle Diffusion Problem 168
9.2 Statistically averaged properties 175

9.3 Effective Medium Theories 177
9.3.1 Averaging sphere models 177
9.3.2 Brailsford and Wynblatt approach 186
9.4 Statistical Mechanical Theories 191
9.5 Computer Simulations of Coarsening 195

10. Nucleation, Growth and Coarsening 205
10.1 Nucleation and growth 206
10.1.1 General solution: nucleation and growth 210
10.1.2 Constant nucleation rate density 212
10.2 Nucleation, growth and coarsening 216

Appendix 227

A. Droplet and particle motion 229
A.1 Some basic fluid dynamic equations 229
A.2 Solid sphere moving in a gravity field 235
A.3 Droplet moving in a gravity field 241
A.4 Thermocapillary convection and motion 244

B. Nucleation 253
B.1 Thermodynamics of nucleation 253
B.2 Kinetic theory of nucleation 261
B.2.1 Stationary nucleation rate 263
B.2.2 Time dependent nucleation 267
B.3 Heterogeneous nucleation 268

Bibliography 271

List of Variables 285

Index 295