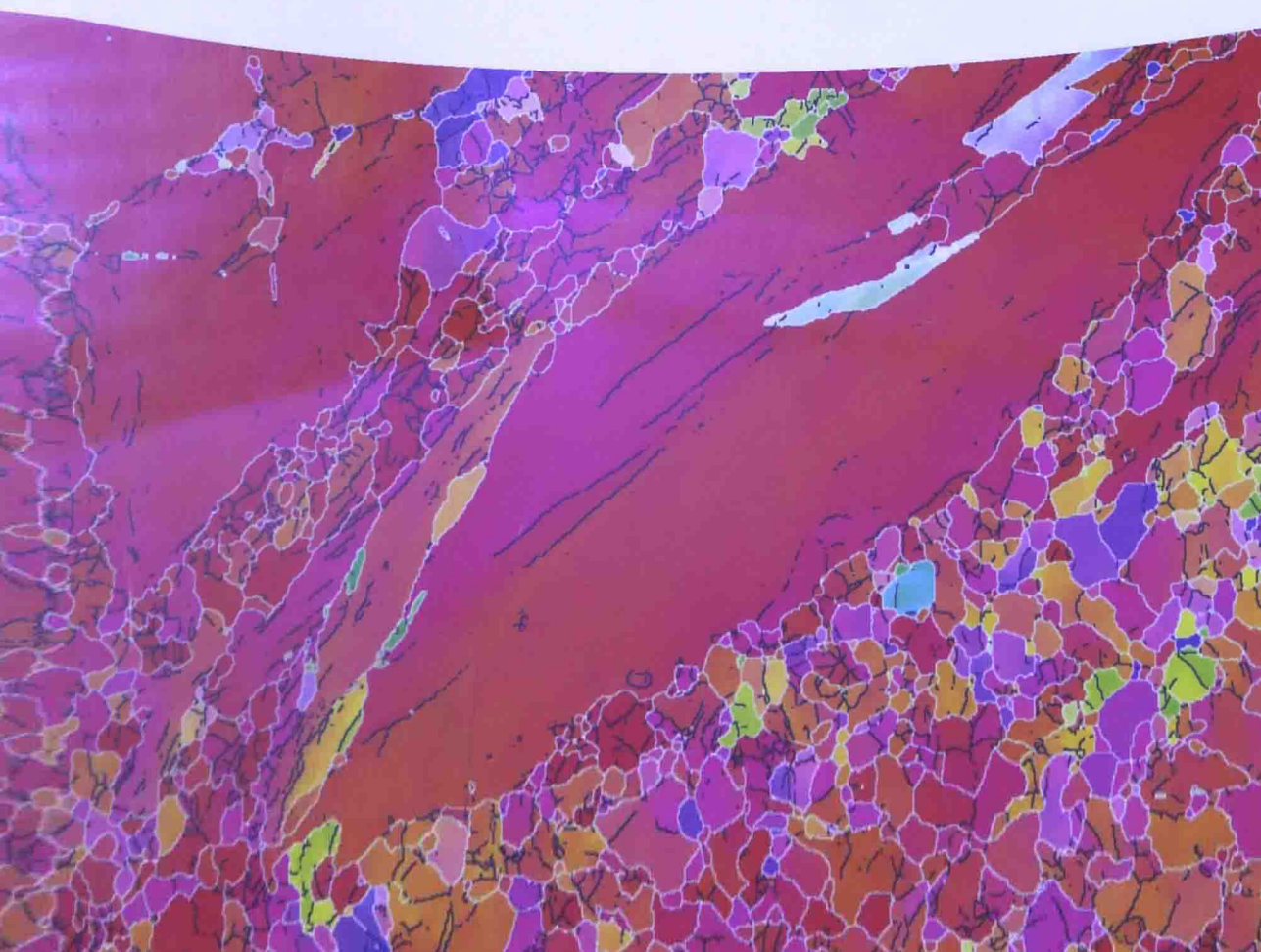


Edited by Dmitri A. Molodov

Microstructural Design of Advanced Engineering Materials



Edited by Dmitri A. Molodov

Microstructural Design of Advanced Engineering Materials



WILEY-VCH
Verlag GmbH & Co. KGaA

Related Titles

Riedel, Ralf / Chen, I-Wei (eds.)

Ceramics Science and Technology

4 Volume Set

2014

ISBN: 978-3-527-31149-1

Plasticity, Failure and Fatigue in Structural Materials-From Macro to Nano

Proceedings of the HaelMughrabi Honorary Symposium

2008

Print ISBN: 978-0-873-39714-8

Pfeiler, W. (ed.)

Alloy Physics

A Comprehensive Reference

2007

Print ISBN: 978-3-527-31321-1, also available in electronic formats

Levitin, V.

High Temperature Strain of Metals and Alloys Physical Fundamentals

2006

Print ISBN: 978-3-527-31338-9, also available in electronic formats

Scheel, H.J., Capper, P. (eds.)

Crystal Growth Technology From Fundamentals and Simulation to Large-scale Production

2008

Print ISBN: 978-3-527-31762-2, also available in electronic formats

Köhler, M., Fritzsche, W.

Nanotechnology An Introduction to Nanostructuring Techniques

2nd Edition

2007

Print ISBN: 978-3-527-31871-1, also available in electronic formats

Herlach, D.M. (ed.)

Phase Transformations in Multicomponent Melts

2009

Print ISBN: 978-3-527-31994-7, also available in electronic formats

Herlach, Dieter M. / Matson, Douglas M. (eds.)

Solidification of Containerless Undercooled Melts

2012

ISBN: 978-3-527-33122-2

Levitin, V., Loskutov, S.

Strained Metallic Surfaces Theory, Nanostructuring and Fatigue Strength

2009

Print ISBN: 978-3-527-32344-9, also available in electronic formats

Dubois, J., Belin-Ferré, E. (eds.)

Complex Metallic Alloys Fundamentals and Applications

2014

Print ISBN: 978-3-527-32523-8, also available in electronic formats

Jackson, K.A.

Kinetic Processes Crystal Growth, Diffusion, and Phase Transitions in Materials

Second Edition

2010

Print ISBN: 978-3-527-32736-2

The Editor

Dmitri A. Molodov

RWTH Aachen

Institut für Metallkunde und Metallphysik

Kopernikusstr. 14

52074 Aachen

Germany

■ All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Print ISBN: 978-3-527-33269-4

ePDF ISBN: 978-3-527-65284-6

ePub ISBN: 978-3-527-65283-9

mobi ISBN: 978-3-527-65282-2

oBook ISBN: 978-3-527-65281-5

Composition Thomson Digital, Noida, India

Printing and Binding Markono Print Media Pte Ltd, Singapore

Cover Design Adam Design, Weinheim

Printed in Singapore

Printed on acid-free paper

Preface

Properties of crystalline engineering materials are directly related to their microstructure, defined as the spatial distribution of elements, phases, defects, and orientations. In view of the dramatically increased specific property material requirements during the past decades, the efforts to understand how the granular microstructure of polycrystals develops and how it can be influenced and predicted became extremely important, since microstructure control is crucial, both for improvement of materials performance and design of advanced materials with tailored properties.

The topic of microstructural design of advanced materials was recently the focus of a special symposium,¹⁾ in honor of Professor Dr rer. nat. Dr h.c. Günter Gottstein (*Günter Gottstein Honorary Symposium on Characterization and Design of Microstructure for Advanced Materials*), which was held in the frame of the MSE 2012 (Materials Science and Engineering) Congress in Darmstadt, Germany, September 25–27, 2012, organized by the Deutsche Gesellschaft für Materialkunde (DGM).

This book represents a collection of manuscripts written by leading scientists in the field of microstructural design of engineering materials, who were invited to deliver keynote lectures at the Günter Gottstein Honorary Symposium. This provided a unique opportunity to bring together experts in various aspects of microstructure design and to address a wide range of topics, which are crucial for predicting and controlling the microstructure evolution, including crystal plasticity due to slip, twinning, and grain boundary motion; nucleation during recrystallization; grain boundary migration under various forces; impact of boundary junctions; interfacial anisotropy and solute segregation, interaction between interfaces and particles, and so on. As obvious from the reviews comprising this book, an interaction between various research approaches – experiment, microstructural modeling, computation, and theory – is indispensable for successful and effective microstructural design of advanced engineering materials.

The book is subdivided into four parts, beginning with the modeling of the basic processes of microstructure development, that is, crystal plasticity, deformation, and

1) Sponsored by the Deutsche Forschungsgemeinschaft (DFG), Deutsche Gesellschaft für Materialkunde (DGM), Aleris Rolled Products Germany GmbH, Hydro Aluminium Deutschland GmbH, ThyssenKrupp VDM GmbH, Wieland-Werke AG.

recrystallization in different metallic materials subjected to various processing routes including severe plastic deformation. The second part addresses grain boundaries and interfaces, their kinetics and thermodynamics, and their effects on microstructure evolution. The third part is dedicated to advanced experimental methods to characterize the microstructure and to elucidate the underlying mechanisms of its development. The final chapters comprise various applications – grain boundary engineering for improving fracture resistance of various metals and alloys and microstructural design of advanced high temperature materials.

The editor is grateful to all authors for their engagement and cooperation as well as the Wiley-VCH editorial team for the enthusiasm and help to prepare and publish this book and in such a way to celebrate Professor Günter Gottstein and his unique contributions to Materials Science.

Aachen, January 2013

Dmitri A. Molodov

List of Contributors

Hamid Assadi

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Matthew Barnett

Deakin University
Institute for Frontier Materials
Pigdons Rd
Geelong, VIC 3217
Australia

Pyuck-Pa Choi

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Martin Diehl

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Julian H. Driver

SMS Centre
Ecole des Mines de Saint Etienne
158 Cours Fauriel
42032 Saint Etienne
France

Philip Eisenlohr

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Yuri Estrin

Monash University
Centre for Advanced Hybrid
Materials
Department of Materials
Engineering
Clayton, VIC 3800
Australia

John G. Fisher

Chonnam National University
School of Materials Science and
Engineering
77 Yongbong-ro, Buk-gu
Gwangju 500-757
Republic of Korea

Roland Fortunier

SMS Centre
Ecole des Mines de Saint Etienne
158 Cours Fauriel
42032 Saint Etienne
France

Martin E. Glicksman

Florida Institute of Technology
Mechanical & Aerospace
Engineering Department
150 West University Blvd.
Melbourne, FL 32901
USA

Shoji Goto

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Günter Gottstein

RWTH Aachen University
Institute of Physical Metallurgy and
Metal Physics (IMM)
Kopernikusstr. 14
52056 Aachen
Germany

Martin Heilmaier

Karlsruher Institut für Technologie
Institut für Angewandte Materialien
Engelbert-Arnold-Str. 4
76131 Karlsruhe
Germany

Michael Herbig

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Jürgen Hirsch

Research & Development Bonn
Hydro Aluminium Rolled
Products GmbH
Georg-von-Boeselager-Str. 21
53117 Bonn
Germany

Bevis Hutchinson

Swerea-KIMAB
Box 7047
164 07 Stockholm
Sweden

Dorte Juul Jensen

Technical University of Denmark
Materials Science and Advanced
Characterization Section
Department of Wind Energy
Risø Campus
4000 Roskilde
Denmark

Sang-Hyun Jung

Korea Advanced Institute of Science
and Technology
Department of Materials Science and
Engineering
291 Daehak-ro, Yuseong-gu
Daejeon 305-701
Republic of Korea

Yang-Il Jung

Korea Atomic Energy Research
Institute
111 Daedeok-daero, 989beon-gil
Yuseong-gu
Daejeon 305-353
Republic of Korea

Suk-Joong L. Kang

Korea Advanced Institute of Science
and Technology
Department of Materials Science and
Engineering
291 Daehak-ro, Yuseong-gu
Daejeon 305-701
Republic of Korea

Reiner Kirchheim

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Aleksander Kostka

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Manja Krüger

Otto-von-Guericke Universität
Magdeburg
Institut für Werkstoff- und
Fügetechnik
Große Steinernetischstr. 6
39104 Magdeburg
Germany

Margarita Kuzmina

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Yujiao Li

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Claire Maurice

SMS Centre
Ecole des Mines de Saint Etienne
158 Cours Fauriel
42032 Saint Etienne
France

Julio Millán

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Yuri Mishin

George Mason University
School of Physics
Astronomy and Computational
Sciences
MSN 3F3
4400 University Drive
Fairfax, VA 22030
USA

Dmitri A. Molodov

RWTH Aachen University
Institute of Physical Metallurgy and
Metal Physics
Kopernikusstr. 14
52056 Aachen
Germany

Debashis Mukherji

Technische Universität
Braunschweig
Institut für Werkstoffe
Langer Kamp 8
38106 Braunschweig
Germany

Dirk Ponge

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Romain Quey

SMS Centre
Ecole des Mines de Saint Etienne
158 Cours Fauriel
42032 Saint Etienne
France

Dierk Raabe

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Paulo R. Rios

Universidade Federal Fluminense
Escola de Engenharia Industrial
Metalúrgica de Volta Redonda
Av. dos Trabalhadores 420
Volta Redonda, RJ 27255-125
Brazil

Anthony D. Rollett

Carnegie Mellon University
Department of Materials Science and
Engineering
5000 Forbes Avenue
Pittsburgh, PA 15213-3890
USA

Joachim Rösler

Technische Universität
Braunschweig
Institut für Werkstoffe
Langer Kamp 8
38106 Braunschweig
Germany

Franz Roters

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Stefanie Sandlöbes

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Lasar S. Shvindlerman

RWTH Aachen University
Institute of Physical Metallurgy and
Metal Physics
Kopernikusstr. 14
52056 Aachen
Germany

and

Russian Academy of Sciences
Institute of Solid State Physics
Academician Ossipyan Str. 2
Chernogolovka
142432 Moscow
Russia

Werner Skrotzki

Dresden University of Technology
Institute of Structural Physics
01062 Dresden
Germany

Paul Van Houtte

Katholieke Universiteit Leuven
Department MTM
Kasteelpark Arenberg 44
3001 Leuven
Belgium

Elena Villa

University of Milan
Department of Mathematics
via Saldini 50
20133 Milano
Italy

Alexei Vinogradov

Togliatti State University
Laboratory of Materials and
Intelligent Diagnostic Systems
14 Belorusskaya St.
445667 Togliatti
Russia

and

Osaka State University
Department of Intelligent Materials
Engineering
Osaka 558-8585
Japan

Tadao Watanabe

Northeastern University
Key Laboratory of Anisotropy and
Texture of Materials
Shenyang 110004
China

Formerly, Tohoku University
Graduate School of Engineering

Permanent address:
4-29-18, Yurigaoka
Natori, Miyagi 981-1245
Japan

Lei Yuan

MPI für Eisenforschung
Max-Planck-Str. 1
40237 Düsseldorf
Germany

Contents

Preface XV

List of Contributors XVII

Part I	Materials Modeling and Simulation: Crystal Plasticity, Deformation, and Recrystallization	1
1	Through-Process Modeling of Materials Fabrication: Philosophy, Current State, and Future Directions	3
	<i>Günter Gottstein</i>	
1.1	Introduction	3
1.2	Microstructure Evolution	5
1.3	Microstructural Processes	6
1.4	Through-Process Modeling	10
1.5	Future Directions	14
	References	16
2	Application of the Generalized Schmid Law in Multiscale Models: Opportunities and Limitations	19
	<i>Paul Van Houtte</i>	
2.1	Introduction	19
2.2	Crystal Plasticity	20
2.2.1	Generalized Schmid Law	22
2.2.2	Calculation of Slip Rates, Lattice Rotation, and Stress from a Prescribed Deformation	23
2.2.3	Taylor Factor	26
2.3	Polycrystal Plasticity Models for Single-Phase Materials	27
2.3.1	Sachs Model	28
2.3.2	Taylor Theory	28
2.3.3	Relaxed Constraints Taylor Theory	29
2.3.4	Grain Interaction Models	30
2.4	Plastic Anisotropy of Polycrystalline Materials	33
2.5	Experimental Validation	34

2.5.1	Prediction of Rolling Textures	34
2.5.2	Prediction of Cup Drawing Textures	36
2.6	Conclusions	37
	References	38
3	Crystal Plasticity Modeling	41
	<i>Franz Roters, Martin Diehl, Philip Eisenlohr, and Dierk Raabe</i>	
3.1	Introduction	41
3.2	Fundamentals	45
3.2.1	Constitutive Models	46
3.2.1.1	Dislocation Slip	47
3.2.1.2	Displacive Transformations	47
3.2.2	Homogenization	48
3.2.3	Boundary Value Solvers	49
3.3	Application Examples	49
3.3.1	Texture and Anisotropy	49
3.3.1.1	Prediction of Texture Evolution	49
3.3.1.2	Prediction of Earing Behavior	50
3.3.1.3	Optimization of Earing Behavior	51
3.3.2	Effective Material Properties	55
3.3.2.1	Direct Transfer of Microstructures	55
3.3.2.2	Representative Volume Elements	57
3.3.2.3	The <i>Virtual Laboratory</i>	59
3.4	Conclusions and Outlook	61
	References	62
4	Modeling of Severe Plastic Deformation: Time-Proven Recipes and New Results	69
	<i>Yuri Estrin and Alexei Vinogradov</i>	
4.1	Introduction	69
4.2	One-Internal Variable Models	70
4.3	Two-Internal Variable Models	77
4.4	Three-Internal Variable Models	81
4.5	Numerical Simulations of SPD Processes	82
4.6	Concluding Remarks	86
	References	87
5	Plastic Anisotropy in Magnesium Alloys – Phenomena and Modeling	91
	<i>Bevis Hutchinson and Matthew Barnett</i>	
5.1	Deformation Modes and Textures	91
5.2	Anisotropy of Stress and Strain	92
5.3	Modeling Anisotropic Stress and Strain	103
5.4	Concluding Remarks	114
	References	115

6	Application of Stochastic Geometry to Nucleation and Growth Transformations	119
	<i>Paulo R. Rios and Elena Villa</i>	
6.1	Introduction	119
6.2	Mathematical Background and Basic Notation	121
6.2.1	Modeling Birth-and-Growth Processes	121
6.2.2	Mean Densities Associated to a Birth-and-Growth Process	123
6.2.3	Causal Cone	124
6.3	Revisiting JMAK	126
6.4	Nucleation in Clusters	130
6.4.1	The Matérn Cluster Process	130
6.4.2	Evaluation of the Integral in Eq. (6.17)	131
6.4.3	Numerical Examples	133
6.4.3.1	Influence of Cluster Radius	133
6.4.3.2	Influence of Number of Nuclei per Cluster	135
6.5	Nucleation on Lower Dimensional Surfaces	136
6.5.1	Derivation of General Expressions for Surface and Bulk Nucleation	136
6.5.1.1	Surface Nucleation	136
6.5.1.2	Bulk Nucleation	137
6.5.2	Numerical Examples	138
6.5.2.1	Surface Nucleation	138
6.5.2.2	Bulk Nucleation	138
6.5.2.3	Simultaneous Bulk and Surface Nucleation	140
6.6	Analytical Expressions for Transformations Nucleated on Random Planes	141
6.6.1	General Results for Nucleation on Random Planes	141
6.6.2	Behavior at the Origin as a Model for the Behavior in an “Unbounded” Specimen	142
6.6.3	Nucleation on Random Parallel Planes Located Within a Specimen of Finite Thickness	143
6.6.4	Nucleation on Random Parallel Planes Located Within an “Unbounded Specimens”	143
6.6.5	Computer Simulation Results	145
6.7	Random Velocity	145
6.7.1	Time-Dependent, Random Velocity	145
6.7.2	Particular Cases	147
6.7.3	Computer Simulation	148
6.8	Simultaneous and Sequential Transformations	150
6.8.1	Simultaneous Transformations	151
6.8.2	Sequential Transformations	152
6.8.3	Application to Recrystallization of an IF Steel	153
6.9	Final Remarks	157
	References	157

7 Implementation of Anisotropic Grain Boundary Properties in Mesoscopic Simulations 161

Anthony D. Rollett

- 7.1 Introduction 161
- 7.2 Overview of Simulation Methods 161
- 7.3 Anisotropy of Grain Boundaries 162
 - 7.3.1 Energy 162
 - 7.3.2 Mobility 163
- 7.4 Simulation Approaches 164
 - 7.4.1 Potts Model 164
 - 7.4.2 Cellular Automata 169
 - 7.4.3 Phase Field 170
 - 7.4.4 Cusps in Grain Boundary Energy 174
 - 7.4.5 Level Set 174
 - 7.4.6 Vertex 175
 - 7.4.7 Moving Finite Element 176
 - 7.4.8 Particle Pinning of Boundaries 179
- 7.5 Summary 180
- References 180

Part II Interfacial Phenomena and their Role in Microstructure Control 187

8 Grain Boundary Junctions: Their Effect on Interfacial Phenomena 189

Lasar S. Shvindlerman and Günter Gottstein

- 8.1 Introduction 189
- 8.2 Experimental Measurement of Grain Boundary Triple Line Energy 190
- 8.3 Impact of Triple Line Tension on the Thermodynamics and Kinetics in Solids 192
 - 8.3.1 Grain Boundary Triple Line Contribution to the Driving Force for Grain Growth 192
 - 8.3.2 Effect of the Triple Junction Line Tension on the Zener Force 193
 - 8.3.3 Effect of Triple Junction Line Tension on the Gibbs–Thompson Relation 195
- 8.4 Why do Crystalline Nanoparticles Agglomerate with Low Misorientations? 196
- 8.5 Concluding Remarks 198
- References 199

9 Plastic Deformation by Grain Boundary Motion: Experiments and Simulations 201

Dmitri A. Molodov and Yuri Mishin

- 9.1 Introduction 201
- 9.2 What is the Coupled Grain Boundary Motion? 202
- 9.3 Computer Simulation Methodology 204

9.4	Experimental Methodology	206
9.5	Multiplicity of Coupling Factors	208
9.6	Dynamics of Coupled GB Motion	212
9.7	Coupled Motion of Asymmetrical Grain Boundaries	216
9.8	Coupled Grain Boundary Motion and Grain Rotation	221
9.9	Concluding Remarks	227
	References	229
10	Grain Boundary Migration Induced by a Magnetic Field: Fundamentals and Implications for Microstructure Evolution	235
	<i>Dmitri A. Molodov</i>	
10.1	Introduction	235
10.2	Driving Forces for Grain Boundary Migration	236
10.3	Magnetically Driven Grain Boundary Motion in Bicrystals	237
10.3.1	Specimens and Applied Methods to Measure Grain Boundary Migration	237
10.3.2	Measurements of Absolute Grain Boundary Mobility	239
10.3.3	Misorientation Dependence of Grain Boundary Mobility	243
10.3.4	Effect of Boundary Plane Inclination on Tilt Boundary Mobility	245
10.4	Selective Grain Growth in Locally Deformed Zn Single Crystals under a Magnetic Driving Force	246
10.5	Impact of a Magnetic Driving Force on Texture and Grain Structure Development in Magnetically Anisotropic Polycrystals	248
10.5.1	Texture Evolution during Grain Growth	248
10.5.2	Microstructure Evolution and Growth Kinetics	253
10.6	Magnetic Field Influence on Texture and Microstructure Evolution in Polycrystals Due to Enhanced Grain Boundary Motion	258
10.7	Concluding Remarks	261
	References	262
11	Interface Segregation in Advanced Steels Studied at the Atomic Scale	267
	<i>Dierk Raabe, Dirk Ponge, Reiner Kirchheim, Hamid Assadi, Yujiao Li, Shoji Goto, Aleksander Kostka, Michael Herbig, Stefanie Sandlöbes, Margarita Kuzmina, Julio Millán, Lei Yuan, and Pyuck-Pa Choi</i>	
11.1	Motivation for Analyzing Grain and Phase Boundaries in High-Strength Steels	267
11.2	Theory of Equilibrium Grain Boundary Segregation	271
11.2.1	Gibbs Adsorption Isotherm Applied to Grain Boundaries	271
11.2.2	Langmuir–McLean Isotherm Equations for Grain Boundary Segregation	272
11.2.3	Phase-Field Modeling of Grain Boundary Segregation and Phase Transformation at Grain Boundaries	274
11.2.4	Interface Complexions at Grain Boundaries	278

11.3	Atom Probe Tomography and Correlated Electron Microscopy on Interfaces in Steels	280
11.4	Atomic-Scale Experimental Observation of Grain Boundary Segregation in the Ferrite Phase of Pearlitic Steel	282
11.5	Phase Transformation and Nucleation on Chemically Decorated Grain Boundaries	288
11.5.1	Introduction to Phase Transformation at Grain Boundaries	288
11.5.2	Grain Boundary Segregation and Associated Local Phase Transformation in Martensitic Fe-C Steels	290
11.6	Conclusions and Outlook	295
	References	295
12	Interface Structure-Dependent Grain Growth Behavior in Polycrystals	299
	<i>Suk-Joong L. Kang, Yang-Il Jung, Sang-Hyun Jung, and John G. Fisher</i>	
12.1	Introduction	299
12.2	Fundamentals: Equilibrium Shape of the Interface	300
12.2.1	Equilibrium Crystal Shape	300
12.2.2	Equilibrium Boundary Shape	301
12.3	Grain Growth in Solid-Liquid Two-Phase Systems	302
12.3.1	Growth Mechanisms and Kinetics of a Single Crystal in a Liquid	302
12.3.1.1	Diffusion-Controlled Crystal Growth	302
12.3.1.2	Interface Reaction-Controlled Crystal Growth	303
12.3.1.3	Mixed Controlled Growth of a Faceted Crystal	306
12.3.2	Grain Growth Behavior	307
12.3.2.1	Stationary Grain Growth in Systems with Spherical Grains	308
12.3.2.2	Nonstationary Grain Growth in Systems with Faceted Grains	309
12.4	Grain Growth in Solid-State Single-Phase Systems	312
12.4.1	Migration Mechanisms and Kinetics of the Grain Boundary	312
12.4.2	Grain Growth Behavior	315
12.5	Concluding Remarks	317
	References	318
13	Capillary-Mediated Interface Energy Fields: Deterministic Dendritic Branching	323
	<i>Martin E. Glicksman</i>	
13.1	Introduction	323
13.2	Capillary Energy Fields	324
13.2.1	Background	324
13.2.2	Melting Experiments	325
13.2.3	Self-Similar Melting	326
13.2.4	Influence of Capillarity on Melting	327
13.3	Capillarity-Mediated Branching	329