

Contents

Preface XIX

List of Contributors XXI

Part One Introduction and Overview

1	Nanostructured Materials: An Overview	3
	<i>Carl C. Koch</i>	
1.1	Introduction	3
1.2	Processing	6
1.3	Characterization	11
1.4	Properties	12
1.4.1	Mechanical Properties	12
1.4.2	Magnetic and Other Properties	18
	References	19
2	Bulk Nanostructured Materials by SPD Processing: Techniques, Microstructures and Properties	21
	<i>Ruslan Z. Valiev and Airat A. Nazarov</i>	
2.1	Introduction	21
2.2	Developing SPD Techniques for Grain Refinement	22
2.2.1	The Principles of SPD Techniques	22
2.2.2	Continuous ECA Pressing	28
2.2.3	Combined SPD Processing	31
2.3	The New SPD Processing of Bulk Nanocrystalline Materials	33
2.3.1	SPD Consolidation	33
2.3.2	SPD-induced Nanocrystallization	34
2.4	Structural Features and Enhanced Properties in SPD-produced Nanomaterials	37
2.5	Using SPD-produced Nanostructured Metals	42
2.6	Conclusions	45
	Acknowledgements	45
	References	46

3	Nonmetallic Bulk Nanomaterials	49
	<i>Dieter Vollath and Dorothée V. Szabó</i>	
3.1	Introduction	49
3.2	Optical Properties	51
3.3	Metallic and Semiconducting Nanoparticles in Transparent Matrices	62
3.4	Magnetic Properties of Bulk Nanomaterials	66
3.4.1	Superparamagnetic Nanocomposites	66
3.4.2	Magnetic Refrigeration	74
3.4.3	Exchange-coupled Magnetic Nanocomposites	75
3.5	Electrical Conductivity	81
	References	84
Part Two	Fundamentals	
4	Deformation Mechanisms of Nanostructured Materials	89
	<i>Yuntian T. Zhu, Bing Q. Han, and Enrique J. Lavernia</i>	
4.1	Introduction	89
4.2	Deformation Mechanisms of Nanostructured Materials	91
4.2.1	Slip of Full Dislocations	92
4.2.2	Slip of Partial Dislocations and Deformation Twinning	93
4.2.2.1	MD Simulations and Experimental Observations	93
4.2.2.2	Analytical Dislocation Models	97
4.2.2.3	Wide Stacking Faults	102
4.2.2.4	Effect of Generalized Planar Fault Energy	102
4.2.3	Grain-boundary Sliding and Grain Rotations	104
4.3	Summary	105
	References	106
5	Modeling of Strength and Strain Hardening of Bulk Nanostructured Materials	109
	<i>Michael J. Zehetbauer and Yuri Estrin</i>	
5.1	Introduction	109
5.2	Modeling of Strength and Strain Hardening of Ultrafine-grained and Nanocrystalline Materials	110
5.2.1	Modeling of Hardening of Equilibrated Nanostructures	110
5.2.2	Modeling of Strength and Structure Evolution during Nanostructuring by Severe Plastic Deformation: SPD models	114
5.2.2.1	Constitutive Models for Strain Hardening at Large Strains	114
5.2.2.2	Application of Large-strain Models to SPD Processes	119
5.3	Summary and Outlook	134
	References	135

6	Finite-element Method Simulation of Severe Plastic-deformation Methods	137
	<i>Hyoungh Seop Kim</i>	
6.1	Introduction	137
6.2	Characteristics of ECAP and Main Factors Affecting Plastic Deformation	139
6.3	Plasticity and Calculation Theories	141
6.4	Simulation Results	143
6.4.1	Two-dimensional vs. Three-dimensional Simulations	143
6.4.2	Benchmark Testing of ECAP Simulations [81] in NANOSPD3	144
6.4.3	Mesh-size Sensitivity	146
6.4.4	Influence of Die-channel Angle	147
6.4.5	Influence of Die-corner Angle	147
6.4.6	Effect of Friction	149
6.4.7	Effect of Backpressure	151
6.4.8	Effects of Material Properties: Strain Hardening and Strain-rate Sensitivity	153
6.5	Multiscale Modeling: Dislocation-cell Modeling [82]	156
6.6	HPT Simulation [84]	158
6.7	Conclusions	160
	Acknowledgements	160
	References	161
7	MD Simulation of Deformation Mechanisms in Nanocrystalline Materials	165
	<i>Dieter Wolf and Vesselin Yamakov</i>	
7.1	Introduction	165
7.2	Dislocation Plasticity for Larger Grain Sizes and the Existence of d_c	167
7.2.1	Columnar Simulation Model for Al	168
7.2.2	Length-scale Effects in the Nucleation of Dislocations from the Grain Boundaries and the Existence of d_c	169
7.2.3	Deformation Twinning in Nanocrystalline Al	171
7.2.4	Experimental Validation of Key Predictions	174
7.3	Grain-boundary-based Deformation Mechanisms for the Smallest Grain Sizes ($d < d_c$)	176
7.3.1	Simulation of Low-temperature Deformation	176
7.3.2	Simulation of Grain-boundary Diffusion Creep	180
7.3.3	Geometrically Necessary Coupling between Grain-boundary Diffusion Creep and Grain-boundary Sliding	182
7.3.4	Discussion	183
7.4	Crossover from “Normal” to “Inverse” Hall–Petch Behavior	185
7.4.1	Grain Boundaries as Dislocation Sources	185
7.4.2	Crossover in the Mechanical Behavior	188

7.4.3	Effect of the Stacking-fault Energy	192
7.5	Discussion and Conclusions	196
	Acknowledgements	197
	References	197

Part Three Processing

8	ECAP: Processing Fundamentals and Recent Progresses	203
	<i>Zenji Horita</i>	
8.1	Principle of ECAP	203
8.2	Shearing Characteristic	204
8.3	Microstructural Evolution	205
8.4	Effect of Channel Angles on Microstructures	207
8.4.1	The Effect of Φ	207
8.4.2	The Effect of Ψ	208
8.5	Pressing Speed	209
8.6	ECAP Temperature	210
8.7	Applied Load	212
8.8	Temperature Measurement during ECAP	212
8.9	Sample Size	214
	References	215
9	High-pressure Torsion – Features and Applications	217
	<i>Reinhard Pippan</i>	
9.1	Introduction	217
9.2	The Equivalent Strain in Torsion	217
9.2.1	Idealized and Real HPT	219
9.3	The Homogeneity of the Deformation	222
9.3.1	The Radial Distribution	222
9.3.2	The Axial Homogeneity	224
9.4	Advantages and Disadvantages of the HPT Process	226
9.5	Upscaling of the HPT Deformation and the Possibility of Large-scale Industrial Production	228
9.6	Some General Remarks on the Evolution of Microstructure	229
	Acknowledgements	232
	References	232
10	Fabrication of Bulk Nanostructured Materials by Accumulative Roll Bonding (ARB)	235
	<i>Nobuhiro Tsuji</i>	
10.1	Introduction	235
10.2	ARB Process	235
10.3	Microstructure of ARB-processed Materials	240

10.4	Mechanical Properties of the ARB-processed Materials	243
10.5	Conclusions	252
	Acknowledgement	252
	References	252
11	Bulk Nanomaterials from Friction Stir Processing: Features and Properties	255
	<i>Rajiv S. Mishra</i>	
11.1	Introduction	255
11.2	Temperature Distribution	257
11.3	Microstructural Evolution	259
11.3.1	Nugget Zone	260
11.3.2	Shape of Nugget Zone	260
11.3.3	Grain Size	260
11.3.4	Recrystallization Mechanisms	263
11.4	Superplasticity in FSP Ultrafine Grained Materials	264
11.5	FSP for Surface Composite Fabrication and Microstructural Homogenization	266
11.5.1	Localized Surface Modification	266
11.5.2	Processing of Powder Metallurgy Alloys	267
	Acknowledgement	269
	References	270
12	Bulk Nanostructured Metals from Ball Milling and Consolidatio	273
	<i>Bing Q. Han, Jichun Ye, A. Piers Newbery, Yuntian T. Zhu, Julie M. Schoenung, and Enrique J. Lavernia</i>	
12.1	Introduction	273
12.2	Mechanisms of Nanostructure Formation	274
12.3	Ball Milling of Metal Matrix Composites	277
12.4	Consolidation of Ball-milled Powders	279
12.5	Mechanical Properties of Bulk Nanostructured Metallic Materials	282
12.6	Summary	288
	Acknowledgements	289
	References	289
13	Bulk Nanostructured Materials from Amorphous Solids	293
	<i>Gerhard Wilde</i>	
13.1	Introduction	293
13.2	Amorphization and Devitrification	296
13.3	Thermally Induced Nanocrystallization	299
13.3.1	Phase Separation of Glasses	302
13.4	BNM Formation by Plastic Deformation	304

13.5	Properties of BNM from Amorphous Precursors – Selected Examples	306
13.6	Summary and Outlook	308
	Acknowledgements	308
	References	309
14	Continuous SPD Techniques, and Post-SPD Processing	311
	<i>Igor V. Alexandrov</i>	
14.1	Introduction	311
14.2	Continuous SPD Techniques	312
14.2.1	ECAP-Conform Process	312
14.2.2	Equal-channel Angular Drawing (ECAD) Process	313
14.2.3	Conshearing Process	314
14.2.4	Continuous Confined Strip Shearing (C2S2) Process	315
14.3	Post-SPD Processing	316
14.3.1	ECAP plus Forging or Cold Rolling	316
14.3.2	ECAP plus Additional Thermomechanical Treatment	321
14.4	Conclusions	323
	References	323

Part Four Characterization

15	Transmission Electron Microscopy of Bulk Nanostructured Metals	327
	<i>Xiaozhou Liao and Xiaoxu Huang</i>	
15.1	Investigation of Deformation Mechanisms of Nanostructured Metals	327
15.2	Nanostructured Metals Produced by Severe Plastic Deformation	334
15.2.1	Structural Morphology	334
15.2.2	Boundary Spacing	336
15.2.3	Boundary Misorientation	337
15.2.4	Interior Dislocation Density	340
15.2.5	Summary	340
	Acknowledgment	340
	References	341
16	Bulk Nanostructured Intermetallic Alloys Studied by Transmission Electron Microscopy	343
	<i>Thomas Waitz, Christian Rentenberger, and H. Peter Karnthaler</i>	
16.1	Introduction	343
16.2	TEM Analysis of Lattice Defects in Nanostructured Materials: Possible Pitfalls	344
16.3	Evolution of Nanostructures by SPD	346
16.4	Local Phase Analysis	349

16.4.1	SPD-induced Order–Disorder Transition	349
16.4.2	Thermally Induced Crystalline–Crystalline Phase Transformation in Nanograins	351
16.4.3	Amorphous–Crystalline Phase Transformation	352
16.5	Local Texture Analysis by SAED, HRTEM and Dark-field Images	355
16.6	Summary	357
	Acknowledgments	358
	References	358
17	Microstructure of Bulk Nanomaterials Determined by X-Ray Line-profile Analysis	361
	<i>Tamás Ungár, Erhard Schafner, and Jenő Gubicza</i>	
17.1	Introduction	361
17.2	General Concept and the Basic Ideas of X-ray Line-profile Analysis	361
17.3	Basic Principles of X-ray Line-profile Analysis	363
17.3.1	Strain Anisotropy	364
17.3.2	Breadth Methods	365
17.3.3	Whole-profile Fitting Methods	366
17.4	Interpretation of Crystallite Size in Bulk Materials in Terms of Subgrains	367
17.5	Dislocation Structure of Bulk Nanomaterials Determined by X-ray Line-profile Analysis	369
17.5.1	Characteristic Parameters of the Dislocation Structure from Line Profiles	369
17.5.2	Dislocation Structure in Cubic Nanomaterials	372
17.5.3	Dislocations in Hexagonal Nanomaterials	375
17.6	Vacancies and X-ray Line-profile Analysis	377
17.7	Stacking Faults and Twinning in Nanostructured Materials Determined by X-ray Line-profile Analysis	381
17.8	Conclusions	382
	Acknowledgements	382
	References	383
18	Texture Evolution in Equal-channel Angular Extrusion	387
	<i>Irene J. Beyerlein and László S. Tóth</i>	
18.1	Introduction	387
18.2	Background	388
18.2.1	Macroscopic Deformation in ECAE	388
18.2.1.1	Simple Shear Model	388
18.2.1.2	Finite-element Modeling	389
18.2.1.3	Analytical Flow Models	390
18.2.1.4	Multiple Passes	392

18.2.2	Crystal Plasticity and Polycrystal Modeling	393
18.2.2.1	Crystal Structure	393
18.2.2.2	Texture Measurement and Presentation	393
18.2.2.3	Texture Characterization	394
18.2.2.4	Polycrystal Modeling	399
18.2.2.5	Comparing Measurement and Prediction	400
18.3	Texture Results	400
18.3.1	Cubic Textures	400
18.3.1.1	Influence of Die Angle Φ	400
18.3.1.2	Influence of Route and Pass Number	401
18.3.2	HCP Textures	403
18.3.3	Influence of Microstructure	405
18.3.3.1	Influence of Initial Texture	405
18.3.3.2	Stacking-fault Energy/Twinning in Cubic Materials	406
18.3.3.3	Influence of Deformation Mechanisms in hcp Materials	407
18.3.3.4	ECAE of Single Crystals	409
18.3.4	Effect of Temperature	410
18.4	Model Performance	411
18.4.1	Macroscale	411
18.4.2	Mesoscale	412
18.4.3	Microscale	413
18.4.4	Factors Affecting Comparisons Between Experiment and Prediction	414
18.5	Additional Features	414
18.5.1	Heterogeneity	414
18.5.2	Texture Strength	415
18.5.3	Influence on Grain Refinement	416
18.5.4	Influence on Mechanical Properties	416
	References	417

Part Five Properties

19	Mechanical Properties of Bulk Nanostructured Metals	425
	<i>Yinmin M. Wang and Evan Ma</i>	
19.1	Introduction	425
19.2	Elastic Properties	426
19.3	Hardness and Strength	427
19.4	Strain-hardening Behavior	430
19.5	Strain-rate Sensitivity	431
19.6	Tensile Ductility	436
19.6.1	Bimodal and/or Multimodal Microstructures	440
19.6.2	Growth Twins	442
19.6.3	Deformation at Low Temperature and/or High Strain Rates	444
19.6.4	Taking Advantage of Elevated Strain-rate Sensitivity	445

19.6.5	Other Possible Approaches	445
19.7	Temperature Dependence	446
19.8	Deformation Modes	447
19.9	Concluding Remarks	449
	Acknowledgements	450
	References	450
20	Superplasticity of Bulk Nanostructured Materials	455
	<i>Terence G. Langdon</i>	
20.1	Principles of Superplasticity	455
20.2	Achieving Superplasticity after SPD Processing	457
20.3	Achieving a Superplastic-forming Capability	461
20.4	Cavitation in Superplasticity after SPD Processing	463
20.5	Future Prospects for Superplasticity in Nanostructured Materials	466
	References	467
21	Fracture and Crack Growth in Bulk Nanostructured Materials	469
	<i>Ruth Schwaiger, Benedikt Moser, and Timothy Hanlon</i>	
21.1	Introduction	469
21.2	Fracture Toughness	470
21.3	Fracture Mechanisms	473
21.4	Fatigue Crack Growth	476
21.5	Conclusion	478
	References	478
22	Fatigue Properties of Bulk Nanostructured Materials	481
	<i>Heinz-Werner Höppel, Hael Mughrabi, and Alexej Vinogradov</i>	
22.1	Introduction and Motivation and Motivation	481
22.2	Fatigue Life of UFG Materials	483
22.3	Cyclic Deformation Behavior and Damage Mechanisms	488
22.4	Modeling	494
22.5	Criteria for Optimizing the Cyclic Deformation Behavior	496
	References	498
23	Diffusion in Nanocrystalline Metallic Materials	501
	<i>Wolfgang Sprengel and Roland Würschum</i>	
23.1	Introduction	501
23.2	Modelling	502
23.3	Diffusion Measurements	503
23.3.1	Overview	503
23.3.2	Structural Relaxation and Grain Growth	506
23.3.3	Different Types of Interfaces	507
23.3.4	Intergranular Amorphous Phases	508

23.3.5	Intergranular Melting	510
23.4	Atomistic Simulations	512
23.5	Comparison with Diffusion-mediated Processes of Deformation and Induced Magnetic Anisotropy	512
	References	515
24	Creep Behavior of Bulk Nanostructured Materials – Time-dependent Deformation and Deformation Kinetics	519
	<i>Wolfgang Blum, Philip Eisenlohr, and Vaclav Sklenička</i>	
24.1	Introduction	519
24.2	Deformation Resistance in Creep	521
24.2.1	Nanocrystalline Ni	521
24.2.2	Fine-grained Al	522
24.2.3	Ultrafine-grained Cu	525
24.3	Creep Response to Changes in Deformation Conditions	526
24.3.1	Stress Changes	527
24.3.2	Temperature Changes	528
24.4	Creep Resistance at Saturation	530
24.5	Creep Life	532
24.6	Microstructural Interpretation of Grain-size Effects	533
24.7	Conclusions	534
	Acknowledgements	534
	References	535
25	Structural Properties of Bulk Nanostructured Ceramics	539
	<i>Alla V. Sergueeva, Dongtao T. Jiang, Katherine E. Thomson, Dustin M. Hulbert, and Amiya K. Mukherjee</i>	
25.1	Introduction	539
25.2	Highly Creep Resistant Ceramics	539
25.2.1	Nano-nanoceramic Composites	541
25.2.2	Creep Resistance	543
25.3	Superplasticity in Ceramics	546
25.3.1	Low-temperature Superplasticity	547
25.3.2	Effect of the Processing Route	550
25.3.3	SPS Accelerated Superplasticity	551
25.4	Nanocomposites with Enhanced Fracture Toughness	552
25.4.1	Fiber Toughening	555
25.4.2	Ductile-phase Toughening	560
25.4.3	Transformation Toughening	560
25.4.4	Microcrack Toughening	562
25.4.5	Future Perspectives	562
25.5	Concluding Remarks	563
	Acknowledgements	564
	References	564

Part Six Applications**26 Bulk Nanostructured Multiphase Ferrous and Nonferrous Alloys 571**
Sergey Dobatkin and Xavier Sauvage

- 26.1 Introduction 571
- 26.2 Bulk Nanostructured Multiphase Ferrous Alloys 571
 - 26.2.1 Introduction 571
 - 26.2.2 Low-carbon Ferritic–Pearlitic Steels 572
 - 26.2.2.1 Cold SPD Processing of Low-carbon Steels 572
 - 26.2.2.2 Warm SPD of Low-carbon Steels 576
 - 26.2.2.3 Formation of Submicrocrystalline Structure by Conventional Processes 577
 - 26.2.3 Low-carbon Martensitic and Ferritic–Martensitic Steels 577
 - 26.2.3.1 Low-carbon Martensitic Steels 577
 - 26.2.3.2 Low-carbon Ferritic–Martensitic Steels 578
 - 26.2.4 High-carbon Pearlitic Steels 579
 - 26.2.5 Austenitic and Austenitic–Ferritic Stainless Steels 581
 - 26.2.5.1 Austenitic Stainless Steels 581
 - 26.2.5.2 Austenitic–Ferritic Stainless Steels 584
 - 26.2.6 Summary 584
- 26.3 Bulk Nanostructured Multiphase Nonferrous Alloys 584
 - 26.3.1 Introduction 584
 - 26.3.2 Cast and Wrought Alloys 585
 - 26.3.2.1 Cast and Wrought Magnesium Alloys 585
 - 26.3.2.2 Cast and Wrought Aluminum Alloys 587
 - 26.3.2.3 Cast and Wrought Copper Alloys 589
 - 26.3.3 Age-hardenable Alloys 589
 - 26.3.3.1 Age-hardenable Magnesium Alloys 589
 - 26.3.3.2 Age-hardenable Aluminum Alloys 590
 - 26.3.3.3 Age-hardenable Copper Alloys 590
 - 26.3.4 Eutectic and Eutectoid Alloys 592
 - 26.3.5 Intermetallics 593
 - 26.3.5.1 Ni–Ti Alloys 593
 - 26.3.5.2 Ni–Al, Ti–Al and Cu–Au Ordered Alloys 595
 - 26.3.6 Composite Materials 595
 - 26.3.7 Final Remarks 596
- 26.4 Summary 596
- References 597

27 Bulk Nanocrystalline and Amorphous Magnetic Materials 605
Roland Grössinger and Reiko Sato Turtelli

- 27.1 Introduction 605
- 27.2 Soft Magnetic Materials 606
 - 27.2.1 Rapidly Solidified Crystalline Materials 606

27.2.2	Amorphous Materials or Rapidly Quenched Glasses	607
27.2.3	Bulk Amorphous Alloys	608
27.2.4	Nanocrystalline Soft Magnetic Materials	609
27.3	Hard Magnetic Materials	612
27.3.1	Nanocrystalline Hard Magnetic Materials	612
27.3.1.1	Nanocomposite Magnets	614
27.3.1.2	Single-phase Nanocrystalline Magnets	621
27.3.2	Nd-(Fe,Co)-Al – a Hard Magnetic Amorphous System?	621
27.3.2.1	Magnetic Properties of Melt-spun Nd ₆₀ Fe ₃₀ Al ₁₀ and Nd ₆₀ Fe ₂₀ Co ₁₀ Al ₁₀ Alloys at 300 K	622
27.3.2.2	Temperature Dependence of Magnetic Properties of Melt-spun Nd ₆₀ Fe ₃₀ Al ₁₀ and Nd ₆₀ Fe ₂₀ Co ₁₀ Al ₁₀ Alloys	623
27.3.2.3	Temperature Dependence of the Magnetic After-effect	625
27.3.3	Industrial Nanocrystalline Hard Magnetic Material	625
27.4	Magnetostrictive Materials	626
27.5	Magnetoelectric Materials	627
27.5.1	Single-phase Materials	627
27.5.2	Magnetoelectric Composites	627
27.6	Summary	628
	References	629

28 Niche Applications of Bulk Nanostructured Materials Processed by Severe Plastic Deformation 635

Yuri Estrin and Michael J. Zehetbauer

28.1	Introduction	635
28.2	Downscaling of Severe Plastic Deformation	635
28.3	Enhanced Reaction Kinetics	638
28.3.1	Plasma Nitriding of Steels	638
28.3.2	Accelerated Hydrogenation Kinetics of Magnesium Alloys	638
28.4	Biomedical Applications of Ultrafine-grained Materials	643
28.5	Corrosion/Biocorrosion in SPD-processed Materials	645
28.6	Summary	646
	References	647

29 Bulk Materials with a Nanostructured Surface and Coarse-grained Interior 649

Ke Lu and Leon Shaw

29.1	Introduction	649
29.2	Processing and Structure Characterization	651
29.2.1	Deformation Field	651
29.2.2	Residual Stresses	653
29.2.3	Surface Roughness	655
29.2.4	Grain Size and Grain-refinement Mechanism	655
29.3	Properties and Performance	660

29.3.1	Hardness and Strength	660
29.3.2	Fatigue Resistance	663
29.3.3	Wear and Friction	665
29.3.4	Diffusion and Surface Chemical Reaction	666
29.4	Perspectives	668
	Acknowledgments	669
	References	670
30	Commercializing Bulk Nanostructured Metals and Alloys	673
	<i>Terry C. Lowe</i>	
30.1	The Innovation Process	673
30.2	The Technology: Nanostructured Metals	676
30.3	Market drivers	677
30.4	Competition from Other Materials	679
30.4.1	Appropriability: Ability of Innovators to Capture Profit	679
30.5	Maturity of the Bulk Nanostructuring Metals Process Design Paradigm	681
30.6	The Need for Complementary Assets	682
30.7	Impact on the Metals Industry	683
30.8	Conclusions	684
	References	685
	Subject Index	687

