

Contents

1 Present State of Electron Backscatter Diffraction and Prospective Developments	1
Robert A. Schwarzer, David P. Field, Brent L. Adams, Mukul Kumar, and Adam J. Schwartz	
1.1 Introduction	1
1.2 Generation and Interpretation of Electron Backscatter Diffraction Patterns	2
1.3 Experimental Set-Up of an EBSD System	3
1.4 The Components of an Automated EBSD System	4
1.4.1 The Pattern Acquisition Device	4
1.4.2 Mechanical Stage and Digital Beam Scanning	5
1.5 Spatial Resolution	7
1.6 SEM Specifications for Good EBSD Performance	9
1.7 The Radon or Hough Transformation for Band Localization	11
1.8 Indexing	12
1.9 Fast EBSD	13
1.10 Ion Blocking Patterns	15
1.11 Conclusions	19
2 Dynamical Simulation of Electron Backscatter Diffraction Patterns	21
Aimo Winkelmann	
2.1 Introduction	21
2.2 Model of Electron Backscatter Diffraction	21
2.3 Dynamical Electron Diffraction in EBSD	22
2.3.1 Dynamical Electron Diffraction in EBSD	22
2.3.2 Dynamical Electron Diffraction in EBSD	23
2.3.3 Dynamical Electron Diffraction in EBSD	24
2.4 Applications	25
2.4.1 A Real-Space View of EBSD	25
2.4.2 Full Scale Simulation of EBSD Patterns	27
2.4.3 The Influence of the Energy Spectrum of the Backscattered Electrons	28
2.4.4 Dynamical Effects of Anisotropic Backscattering	30
2.5 Summary	32

3	Representations of Texture	35
	Jeremy K. Mason and Christopher A. Schuh	
3.1	Introduction	35
3.2	Rotations and Orientations	36
3.2.1	Defining a Rotation	36
3.2.2	Defining an Orientation	37
3.3	Pole Figures	38
3.4	Discrete Orientations	40
3.4.1	Axis-Angle Parameters	41
3.4.2	Rodrigues Vectors	42
3.4.3	Quaternions	42
3.4.4	Euler Angles	45
3.5	Orientation Distribution Functions	46
3.5.1	Circular Harmonics	46
3.5.2	Spherical Harmonics	47
3.5.3	Hyperspherical Harmonics	48
3.5.4	Generalized Spherical Harmonics	49
3.5.5	Symmetrized Harmonics	49
3.6	Conclusion	50
4	Energy Filtering in EBSD	53
	Alwyn Eades, Andrew Deal, Abhishek Bhattacharyya, and Tejpal Hooghan	
4.1	Introduction	53
4.2	Background	53
4.3	Energy Filters	54
4.4	Operating the Filter	56
4.5	Early Results	57
4.6	Patterns at Different Energies	60
4.7	Localization of the Signal	61
4.8	Future Energy Filters in EBSD	62
4.9	Summary and Conclusions	62
5	Spherical Kikuchi Maps and Other Rarities	65
	Austin P. Day	
5.1	Introduction	65
5.2	Electron Backscatter Patterns	65
5.3	Spherical Kikuchi Maps	65
5.4	EBSP Detectors	65
5.5	EBSP Imaging and Uniformity	68
5.6	EBSP Simulation	68
5.7	Spherical Kikuchi Maps from EBSPs	68
5.8	Kikuchi Band Profiles	72
5.9	Spherical Kikuchi Map Inversion	74
5.10	Uses for Spherical Kikuchi Maps	75
5.11	Colour Orientation Contrast Images	76
5.12	STEM in the SEM	76
5.13	Unusual Features in EBSPs	77

6	Application of Electron Backscatter Diffraction to Phase Identification	81
	Bassem El-Dasher and Andrew Deal	
6.1	Introduction	81
6.2	Considerations for Phase ID with EBSD	82
6.3	Case Studies	84
6.3.1	Simultaneous EBSD/EDS Phase Discrimination	85
6.3.2	Distinguishing γ and γ' in Ni Superalloys	86
6.3.3	Volume Fraction Determination in a Multiphase Alloy	89
7	Phase Identification Through Symmetry Determination in EBSD Patterns	97
	David J. Dingley and S.I. Wright	
7.1	Introduction	97
7.2	Basis of the Phase Identification Method	97
7.3	Determination of the Crystal Unit Cell	98
7.4	Discovering the Lattice Symmetry	100
7.5	Re-Indexing the Pattern According to the Discovered Crystal Class	101
7.6	Examples	102
7.6.1	Case 1, A Cubic Crystal	102
7.6.2	Case 2, A Hexagonal Crystal	104
7.6.3	Case 3, A Trigonal Crystal	104
7.7	Discussion	106
8	Three-Dimensional Orientation Microscopy by Serial Sectioning and EBSD-Based Orientation Mapping in a FIB-SEM	109
	Stefan Zaeferrer and Stuart I. Wright	
8.1	Introduction	109
8.2	The Geometrical Set-Up for 3D Characterisation in a FIB-SEM	110
8.3	Automatic 3D Orientation Microscopy	113
8.4	Software for 3D Data Analysis	113
8.5	Application Examples	114
8.5.1	The 3D Microstructure and Crystallography of Pearlite Colonies	114
8.5.2	Microstructure of “Nanocrystalline” NiCo Deposits	115
8.6	Discussion	119
8.6.1	Accuracy and Application Limits	119
8.6.2	Materials Issues	120
8.7	Conclusions	120

9	Collection, Processing, and Analysis of Three-Dimensional EBSD Data Sets	123
	Michael A. Groeber, David J. Rowenhorst, and Michael D. Uchic	
9.1	Introduction	123
9.2	Data Collection	123
9.3	Processing Strategies	124
9.3.1	Registration and Alignment of Sections	124
9.3.2	Segmentation of Grains	126
9.3.3	Clean-Up Routines	127
9.4	Analysis Capabilities	129
9.4.1	Morphological Descriptors	129
9.4.2	Crystallographic Descriptors	133
9.5	Summary	135
10	3D Reconstruction of Digital Microstructures	139
	Stephen D. Sintay, Michael A. Groeber, and Anthony D. Rollett	
10.1	Motivation	139
10.2	Background	139
10.2.1	2D–3D Inference	139
10.2.2	3D Polycrystal Microstructure Generation	140
10.3	Data Collection and Analysis	140
10.3.1	Data Sources	140
10.3.2	Identifying Features	141
10.3.3	Statistical Description of Features	141
10.4	Methods for 3D Structure Inference	141
10.4.1	Monte Carlo-Based Histogram Fitting	143
10.4.2	Observation-Based Domain Constraint	145
10.5	Generation of 3D Structure	147
10.5.1	Packing of Ellipsoids	147
10.5.2	Relaxation of Boundaries	149
10.6	Quality Analysis	149
10.6.1	Size Distribution Comparison	149
10.6.2	Shape Distribution Comparison	149
10.6.3	Neighborhood Comparison	151
10.6.4	Boundary Structure Comparison	151
10.7	Thoughts on Current Conditions and Future Work	151
11	Direct 3D Simulation of Plastic Flow from EBSD Data	155
	Nathan R. Barton, Joel V. Bernier, Ricardo A. Lebensohn, and Anthony D. Rollett	
11.1	Introduction	155
11.2	Material and Microstructural Model	156
11.2.1	Three-Dimensional Microstructure Generation	157
11.2.2	Micromechanical Model	158
11.2.3	Finite Element Model	159
11.3	Simulation Results	159
11.4	Directions for Further Computational Development	162
11.5	Conclusions	165

12	First-Order Microstructure Sensitive Design Based on Volume Fractions and Elementary Bounds	169
	Surya R. Kalidindi, David T. Fullwood, and Brent L. Adams	
12.1	Introduction	169
12.2	Quantification of Microstructure	170
12.3	Microstructure Sensitive Design Framework	170
12.4	Property Closures	172
13	Second-Order Microstructure Sensitive Design Using 2-Point Spatial Correlations	177
	David T. Fullwood, Surya R. Kalidindi, and Brent L. Adams	
13.1	Introduction	177
13.2	Definition and Properties of the 2-Point Correlation Functions	178
13.2.1	Boundary Conditions	179
13.2.2	Properties of the 2-Point Functions	179
13.2.3	Visualization of the 2-Point Functions	179
13.2.4	Metrics from 2-Point Correlations	180
13.2.5	Collecting 2-Point Correlations from Material Samples	180
13.3	Structure Property Relations	181
13.3.1	Localization Tensors	182
13.3.2	Effective Tensors	184
13.4	Microstructure Design	186
14	Combinatorial Materials Science and EBSD: A High Throughput Experimentation Tool	189
	Krishna Rajan	
14.1	Introduction	189
14.2	Introduction to Combinatorial Methods	189
14.2.1	High Throughput EBSD Screening	190
14.2.2	Informatics and Data	194
14.3	Summary	196
15	Grain Boundary Networks	201
	Bryan W. Reed and Christopher A. Schuh	
15.1	Introduction	201
15.2	Measurement and Classification of Local Network Elements	202
15.2.1	General Definitions for Single Boundaries	202
15.2.2	Structures with More than One Boundary	203
15.3	Geometry of the Network Structure	204
15.3.1	Percolation Measures of the Grain Boundary Network	205
15.3.2	Crystallographic Constraints	206
15.4	Microstructure-Property Connections	208
15.4.1	Composite Averaging vs. Percolation Theory	209
15.4.2	Crystallographic Correlations	211
15.5	Conclusions and Future Outlook	212

16	Measurement of the Five-Parameter Grain Boundary Distribution from Planar Sections	215
	Gregory S. Rohrer and Valerie Randle	
16.1	Introduction: Grain Boundary Planes and Properties	215
16.2	Serial Sectioning	216
16.3	Single-Surface Trace Analysis	217
16.4	Five-Parameter Stereological Analysis	218
16.4.1	Parameterization and Discretization of the Space of Grain Boundary Types	218
16.4.2	Measurement of the Grain Boundary Characterization Distribution	219
16.4.3	Performance of the Stereological Analysis	221
16.4.4	Comparison GBCDs Measured Stereologically and by Serial Sectioning in the Dual Beam FIB	223
16.5	Examples of Five-Parameter Analyses	224
17	Strain Mapping Using Electron Backscatter Diffraction	231
	Angus J. Wilkinson, David J. Dingley, and Graham Meaden	
17.1	Introduction	231
17.1.1	The Need for Local Strain Assessment	231
17.1.2	Competing Strain Mapping Techniques	231
17.1.3	Review of Applications of EBSD to Analysis of Elastic Strains	232
17.2	Cross-Correlation-Based Analysis of EBSD Patterns	234
17.2.1	Geometry: Linking Pattern Shifts to Strain	234
17.2.2	Pattern Shift Measurement	235
17.2.3	Sensitivity Analysis	237
17.2.4	Illustrative Applications	239
17.3	Concluding Remarks	247
18	Mapping and Assessing Plastic Deformation Using EBSD	251
	Luke N. Brewer, David P. Field, and Colin C. Merriman	
18.1	Plastic Deformation Effects on the EBSD Pattern and Orientation Map	251
18.2	Pattern Rotation Approaches	253
18.2.1	Mapping Orientations and Misorientations	253
18.2.2	Average Misorientation Approaches	255
18.2.3	Measurement and Calculation of GND Densities	258
19	Analysis of Deformation Structures in FCC Materials Using EBSD and TEM Techniques	263
	Oleg V. Mishin, Andrew Godfrey, and Dorte Juul Jensen	
19.1	Introduction	263
19.2	Orientation Noise in EBSD Data	265
19.2.1	A Quantitative Description of Orientation Noise	265
19.2.2	Postprocessing Orientation Filtering Operations	266
19.3	Quantitative TEM–EBSD Comparison	268
19.4	Heterogeneity in Microstructural Refinement	271

19.4.1	Analysis of Local Heterogeneity	271
19.4.2	Potential for Analysis of Large-Scale Heterogeneities	272
19.5	Summary and Conclusions	273
20	Application of EBSD Methods to Severe Plastic Deformation (SPD) and Related Processing Methods	277
	Terry R. McNelley, Alexandre P. Zhilyaev, Srinivasan Swaminathan, Jianqing Su, and E. Sarath Menon	
20.1	Introduction	277
20.2	Microstructures During the Initial ECAP Pass	278
20.3	Microstructures Developed by Machining	282
20.4	Grain Refinement During FSP	284
20.5	Conclusions	288
21	Applications of EBSD to Microstructural Control in Friction Stir Welding/Processing	291
	Sergey Mironov, Yutaka S. Sato, and Hiroyuki Kokawa	
21.1	Introduction	291
21.2	Brief Explanations of FSW/P Terminology	292
21.3	Microstructural Evolution	292
21.4	Material Flow	296
21.5	Structure-Properties Relationship	298
21.6	Summary and Future Outlook	299
22	Characterization of Shear Localization and Shock Damage with EBSD	301
	John F. Bingert, Veronica Livescu, and Ellen K. Cerrera	
22.1	Introduction	301
22.2	Shear Localization	302
22.2.1	Constrained Shear in Pure Fe—Shear Zone Geometry	302
22.2.2	Constrained Shear in Pure Fe—Texture Development	306
22.2.3	Effect of Morphology on Grain Instability in Cu	307
22.3	Shock Loading Damage in Tantalum	309
22.3.1	Effect of Shock Duration on Incipient Spall Structure	310
22.3.2	Effect of Pressure on Incipient Spall Structure	313
22.4	Conclusions	313
23	Texture Separation for α/β Titanium Alloys	317
	Ayman A. Salem	
23.1	Introduction	317
23.2	Microstructure of α/β Titanium Alloys	317
23.3	Texture of Ti-6Al-4V	318
23.3.1	Separation of Primary and Secondary Alpha Texture	319
23.3.2	EBSD + BSE Imaging Technique	319
23.3.3	EBSD or XRD + Heat Treatment Technique	320
23.4	Texture Separation Using EBSD + EDS Technique	320
23.4.1	Texture Separation Using EBSD + EDS Technique	320
23.4.2	Microstructure Observations	321
23.4.3	Chemical Composition Maps (EDS)	321
23.5	Industrial Application: Controlling Texture During Hot-Rolling of Ti-6Al-4V	322

23.5.1	Microstructure Evolution	323
23.5.2	Overall Texture Evolution	323
23.5.3	Primary-Alpha (α_p) Textures	324
23.5.4	Secondary-Alpha (α_s) Texture	325
23.6	Industrial Application: Controlling Texture During Hot-Rolling of Ti-6Al-4V	326
24	A Review of In Situ EBSD Studies	329
	Stuart I. Wright and Matthew M. Nowell	
24.1	Introduction	329
24.2	In Situ Postmortem Experiments	330
24.3	Deformation Stage Experiments	331
24.4	Heating Stage Experiments	332
24.4.1	Phase Transformation	332
24.4.2	Recrystallization and Grain Growth	333
24.5	Combined Heating and Tensile Stage Experiments	335
24.6	Conclusions	335
25	Electron Backscatter Diffraction in Low Vacuum Conditions	339
	Bassem S. El-Dasher and Sharon G. Torres	
25.1	Introduction	339
25.2	Considerations for Low Vacuum EBSD	340
25.3	Example Applications	341
25.3.1	Microstructural Analysis of AlN-TiB ₂ Ceramic Composite	341
25.3.2	Characterization of CaHPO ₄ ·2H ₂ O Single Crystals	342
26	EBSD in the Earth Sciences: Applications, Common Practice, and Challenges	345
	David J. Prior, Elisabetta Mariani, and John Wheeler	
26.1	Development of EBSD in Earth Sciences	345
26.2	Current Practice, Capabilities, and Limitations	346
26.2.1	Range of Materials and Preparation	346
26.2.2	Speed of Data Collection	347
26.2.3	Spatial Resolution	347
26.2.4	Misindexing	348
26.2.5	Polyphase Samples	350
26.3	Application of EBSD in Earth Sciences	351
26.3.1	Rock Deformation and Solid Earth Geophysics	352
26.3.2	Metamorphic Processes	355
26.3.3	Meteorites	356
26.3.4	Other Areas	356
26.4	Conclusions	357

27	Orientation Imaging Microscopy in Research on High Temperature Oxidation	361
	Bae-Kyun Kim and Jerzy A. Szpunar	
27.1	Introduction	361
27.2	High Temperature Oxidation	362
27.3	Experimental Procedure	363
27.3.1	Oxidation of Samples and Oxide Formation	363
27.3.2	Sample Preparation and Geometry in OIM	364
27.3.3	Microstructure and Texture Measurement	365
27.3.4	Oxidation of Low Carbon Steel	365
27.4	Results and Discussion	368
27.4.1	Grain Growth in Iron Oxide	368
27.4.2	Effect of the Oxidation Process on Microstructure	371
27.4.3	Oxidation of Pure Iron	373
27.5	Cracks and Defects	384
27.6	Conclusion	390
	Index	395