
Contents

Preface.....	xiii
About the Authors.....	xvii

PART I Fundamental Issues

Chapter 1	Introduction.....	3
1.1	The Classical Approach to Texture.....	3
1.2	The Modern Approach to Texture: Microtexture.....	7
1.2.1	Applications of Microtexture.....	8
1.2.2	Electron Backscatter Diffraction.....	11
1.2.3	Orientation Microscopy and Orientation Mapping.....	12
1.3	A Guide to the Book.....	13
Chapter 2	Descriptors of Orientation.....	15
2.1	Introduction.....	15
2.2	Crystal Structures and Crystal Symmetries.....	15
2.3	Transformation between Coordinate Systems: The Rotation Matrix.....	19
2.3.1	Coordinate Systems.....	19
2.3.2	The Rotation (Orientation) Matrix.....	23
2.3.3	Crystallographically Related Solutions.....	24
2.4	The “Ideal Orientation” (Miller or Miller–Bravais Indices) Notation.....	27
2.5	The Reference Sphere, Pole Figure, and Inverse Pole Figure.....	29
2.5.1	The Pole Figure.....	31
2.5.2	The Inverse Pole Figure.....	32
2.6	The Euler Angles and Euler Space.....	33
2.6.1	The Euler Angles.....	33
2.6.2	The Euler Space.....	36
2.7	The Angle/Axis of Rotation and Cylindrical Angle/Axis Space.....	39
2.7.1	Angle/Axis of Rotation.....	39
2.7.2	Angle/Axis Description of Misorientation.....	41
2.7.3	The Cylindrical Angle/Axis Space.....	43
2.8	The Rodrigues Vector and Rodrigues Space.....	44
2.8.1	The Rodrigues Vector.....	44
2.8.2	The Fundamental Zone.....	46
2.8.3	Properties of Rodrigues Space.....	47

2.9	Quaternions	48
2.10	Summation.....	52
Chapter 3	Application of Diffraction to Texture Analysis.....	53
3.1	Introduction	53
3.2	Diffraction of Radiation and Bragg's Law	53
3.3	Structure Factor	61
3.4	Laue and Debye–Scherrer Methods	64
3.5	Absorption and Depth of Penetration.....	67
3.6	Characteristics of Radiations Used for Texture Analysis.....	68
3.6.1	X-Rays	68
3.6.2	Neutrons	69
3.6.3	Electrons.....	72
3.7	Summation.....	73
PART II Macrotecture Analysis		
Chapter 4	Macrotecture Measurements.....	77
4.1	Introduction	77
4.2	Principle of Pole Figure Measurement.....	77
4.3	X-Ray Diffraction Methods.....	81
4.3.1	Generation of X-Rays.....	82
4.3.2	Pole Figure Diffractometry in the Texture Goniometer.....	88
4.3.3	Principles of Pole Figure Scanning	92
4.3.4	X-Ray Detectors	94
4.3.5	Energy-Dispersive Diffractometry.....	99
4.3.6	Correction and Normalization of Pole Figure Data.....	102
4.3.7	Inverse Pole Figures	106
4.4	Neutron Diffraction Methods	107
4.4.1	Pole Figure Measurement by Neutron Diffraction.....	107
4.4.2	Time-of-Flight Measurements.....	110
4.5	Texture Measurements in Low-Symmetry and Multiphase Materials	113
4.5.1	Peak Separation.....	113
4.5.2	Multiphase Materials.....	116
4.6	Sample Preparation.....	117
4.7	Summation.....	121
Chapter 5	Evaluation and Representation of Macrotecture Data	122
5.1	Introduction	122
5.2	Pole Figure and Inverse Pole Figure.....	123

5.2.1	Normalization and Contouring of Pole Figures	123
5.2.2	Representation of Orientations in the Inverse Pole Figure	125
5.3	Determination of the Orientation Distribution Function from Pole Figure Data	125
5.3.1	The Orientation Distribution Function.....	125
5.3.2	The Series Expansion Method	128
5.3.3	Truncation Error and Ghost Correction	132
5.3.4	Direct Methods.....	140
5.3.5	Comparison of Series Expansion and Direct Methods.....	143
5.3.6	Texture Parameters.....	144
5.4	Representation and Display of Texture in Euler Space	144
5.4.1	Properties of Euler Space	145
5.4.2	Representation and Display of Textures.....	146
5.5	Examples of Typical Textures in Metals	150
5.5.1	Deformation Textures of fcc Metals.....	150
5.5.2	Deformation Textures of bcc Metals.....	155
5.5.3	Deformation Textures of Hexagonal Metals	159
5.5.4	Recrystallization Textures of fcc Metals.....	163
5.5.5	Recrystallization Textures of bcc Metals.....	167
5.5.6	Recrystallization Textures of Hexagonal Metals	171
5.6	Summation.....	172

PART III Microtexture Analysis

Chapter 6	Diffraction Techniques in TEM and SEM.....	177
6.1	Introduction	177
6.1.1	Description of Bragg Diffraction in Reciprocal Space	178
6.1.2	Forms of Electron Diffraction—Overview.....	181
6.2	Diffraction in TEM	183
6.2.1	Selected Area Diffraction Patterns (SADP) and Ewald Construction	183
6.2.2	Debye–Scherrer Ring Patterns (DSP).....	189
6.2.3	Convergent Beam Electron Diffraction Patterns (CBEDP).....	192
6.2.4	Spot Diffraction with Electron Beam Precession (Precession Electron Diffraction, PED)	195
6.2.5	Conical Scanning	196
6.2.6	Transmission Kikuchi Diffraction Patterns (TKP).....	198
6.3	Diffraction in SEM.....	203
6.3.1	Backscatter Kikuchi Patterns (BKP) or Electron Backscatter Diffraction (EBSD) Patterns	205

6.3.2	Physics of Backscatter Kikuchi Pattern Formation—Dynamical Theory of Electron Diffraction	206
6.3.3	Physical Spatial Resolution of EBSD	219
6.3.4	Electron Channeling Techniques	221
6.3.5	Micro-Kossel Technique	227
6.4	Summation.....	230
Note	231
Chapter 7	Procedures for Orientation Determination from Electron Diffraction Patterns.....	232
7.1	Introduction	232
7.1.1	Coordinate Systems.....	233
7.1.2	Calculation of the Reciprocal Lattice.....	235
7.2	Extraction of Lattice Plane (Reflector) Positions from Diffraction Patterns	237
7.2.1	Manual Determination of Diffraction Plane Vectors.....	237
7.2.2	Automatic Kikuchi Pattern Analysis: The Hough Transform for EBSD Pattern Analysis	239
7.2.3	The Hough Transform for TKP.....	241
7.2.4	Extraction of Diffraction Vectors from Spot Patterns.....	243
7.3	Indexing and Orientation Calculation	244
7.3.1	Serial Indexing	245
7.3.2	Parallel Indexing	246
7.4	Pattern Matching and Dictionary Indexing.....	248
7.4.1	Introduction	248
7.4.2	Template Matching for Spot Pattern Indexing in TEM	249
7.4.3	Dictionary Indexing for EBSD Pattern Analysis.....	252
7.4.4	Pseudo-Symmetries.....	255
7.4.5	Cross-Correlation EBSD for the Measurement of Elastic Strain Fields	259
7.5	Summation.....	262
Note	263
Chapter 8	Practice of Orientation Measurement and Orientation Microscopy.....	264
8.1	Introduction	264
8.2	EBSD-Based Orientation Microscopy in the SEM	264
8.2.1	Specimen Requirements.....	266
8.2.2	EBSD Specimen Preparation	268
8.2.3	Microscope Parameters	272
8.2.4	Specimen/Microscope Geometry	275

8.2.5	EBSD Detector	277
8.2.6	Diffraction Pattern Enhancement	280
8.2.7	Software	281
8.2.8	Calibration of an EBSD System	282
8.2.9	Lateral Resolution	288
8.2.10	Angular Resolution	290
8.2.11	In-Situ Investigations of Texture Formation Processes by EBSD	292
8.3	Techniques of TEM Orientation Microscopy.....	293
8.3.1	Technical Aspects of TEM-Based Orientation Microscopy	294
8.3.2	Calibration of Patterns	295
8.3.3	Camera Considerations	296
8.3.4	Sample Preparation	296
8.3.5	Spatial and Angular Resolution	298
8.4	Summation.....	300
Chapter 9	Orientation Microscopy and Orientation Mapping.....	301
9.1	Introduction	301
9.2	Historical Evolution of Orientation Microscopy in SEM and TEM.....	301
9.3	EBSD-Based Orientation Microscopy	303
9.3.1	Measurement Strategies	305
9.3.2	Data Storage	307
9.4	Orientation Mapping and its Applications	308
9.4.1	Spatial Distribution of Microtexture Components...	309
9.4.2	True Grain Size/Shape Distributions	312
9.4.3	Phase Maps.....	313
9.4.4	Deformation Maps.....	315
9.4.5	Quantification of Plastic Strain Fields by Cross-Correlation EBSD	320
9.4.6	Cross-Correlation EBSD for the Measurement of Elastic Strain Fields	322
9.4.7	Measurement of the Macroscopic Crystallographic Texture.....	323
9.4.8	Analysis of Data Using MTEX	329
9.5	Orientation Microscopy in the TEM.....	333
9.5.1	Semi-Automatic TEM ORM.....	333
9.5.2	STEM Techniques	334
9.6	When Using TEM- or SEM-ORM Techniques?	336
9.6.1	Orientation Microscopy on Highly Deformed Metals	337
9.6.2	Other Cases Requiring High Spatial Resolution.....	340
9.6.3	Cases Requiring High Angular Resolution or Precision of Structure Analysis	341
9.7	Summation.....	344

Chapter 10	Evaluation and Representation of Microtexture Data	346
10.1	Introduction	346
10.1.1	Statistical Distribution of Orientation and Misorientation Data	347
10.1.2	Orientation and Misorientation Data Related to the Microstructure	348
10.2	Representation of Orientations in a Pole Figure or Inverse Pole Figure	349
10.2.1	Individual Orientations	349
10.2.2	Density Distributions	351
10.3	Representation of Orientations in Euler Space	353
10.3.1	Individual Orientations	354
10.3.2	Continuous Distributions	355
10.3.3	Statistical Relevance of Single-Grain Orientation Measurements	357
10.4	Representation of Orientations in Rodrigues Space	362
10.5	General Representation of Misorientation Data	367
10.5.1	Representations Based on the Angle/Axis Descriptor	367
10.5.2	Intragrain Misorientations	372
10.6	Representation of Misorientations in Three-Dimensional Spaces	373
10.6.1	Representation of Misorientations in Euler Space	373
10.6.2	Representation of Misorientations in the Cylindrical Angle/Axis Space	375
10.6.3	Representation of Misorientations in Rodrigues Space	376
10.7	Normalization and Evaluation of the Misorientation Distribution Function	379
10.8	Use of Orientation Data for Ensuing Microstructure Modeling	384
10.9	Summation	386
Chapter 11	Crystallographic Analysis of Interfaces, Surfaces, and Connectivity	387
11.1	Introduction	387
11.2	Description of Grain Boundaries	389
11.2.1	Characterization of the Grain Boundary Structure	390
11.2.2	Small- and Large-Angle Grain Boundaries	392
11.2.3	Distinction of Grain Boundaries by the CSL Model	395
11.2.4	Refining the CSL Model: The DSC Model	400

11.2.5	Generalization of CSL Lattices: The O-Lattice Theory	401
11.2.6	The Importance of the Boundary Plane.....	402
11.2.7	Five-Parameter Grain Boundary Description	406
11.3	Crystallographic Analysis of Grain Boundaries and Surfaces	409
11.3.1	Stereo-Photogrammetry for Observation of Free Surfaces.....	410
11.3.2	Sectioning Technique Principles.....	412
11.3.3	Stereological Analysis.....	415
11.4	Three-Dimensional EBSD Orientation Measurements.....	419
11.4.1	3D EBSD Techniques.....	420
11.4.2	3D EBSD Data Processing.....	422
11.4.3	Large Volume 3D EBSD Techniques.....	423
11.5	Orientation Connectivity and Spatial Distribution.....	429
11.6	Summation.....	431
Chapter 12	Orientation Relationships between Phases and Texture Formation during Phase Transformations.....	432
12.1	Introduction	432
12.2	Orientation Relationships between Different Phases	432
12.2.1	Introduction to Orientation Relationships between Different Phases.....	432
12.2.2	Orientation Relationships in Steels	436
12.2.3	Orientation Relationships in Other Materials	443
12.3	Texture Formation, Variant Selection, Reconstruction of Texture and Microstructure of Austenite	444
12.4	Summation.....	446
Chapter 13	Synchrotron Radiation, Nondiffraction Techniques, and Comparisons between Methods	448
13.1	Introduction	448
13.2	Texture Analysis by Synchrotron Radiation.....	448
13.2.1	Individual Orientations from Laue Patterns.....	449
13.2.2	Local Textures from Debye–Scherrer Patterns in Polycrystalline Regions.....	452
13.3	Texture Analysis by Nondiffraction Techniques.....	459
13.3.1	Ultrasonic Velocity.....	460
13.3.2	Optical Methods.....	461
13.4	Summation: Comparison and Assessment of the Experimental Methods for Texture Analysis	465
13.4.1	Comparison of Different Techniques and Their Fields of Application	466
13.4.2	Overview on the Evolution of EBSD Applications in Literature.....	473

Addendum: Spherical Indexing of EBSD Patterns	475
Appendix I: Miller and Miller–Bravais Indices	477
Appendix II: Crystallographically Related Operations.....	479
Appendix III: Crystallographically Related Solutions for the Four S-texture Variants.....	481
Appendix IV: Spherical Projection and the Stereographic, Equal-Area, and Gnomonic Projections.....	483
Appendix V: Indexing a Pole Figure.....	489
Appendix VI: X-ray Counters and Pulse Height Analysis.....	491
Glossary of Terms.....	495
References.....	503
General Bibliography	551
Index.....	555