

Contents

Preface *xiii*

Part I Introduction 1

- 1 Introduction and Overview 3**
Hang Z. Yu, Nihan Tuncer, and Zhili Feng
- 1.1 Overview and History of Metal Additive Manufacturing 4
- 1.2 Liquid-State Bonding Versus Solid-State Bonding 7
 - 1.2.1 Liquid-State Bonding 7
 - 1.2.2 Solid-State Bonding 8
- 1.3 Nonbeam-Based, Solid-State Metal Additive Manufacturing 9
 - 1.3.1 Deformation-Based Metal Additive Manufacturing 9
 - 1.3.2 Sintering-Based Metal Additive Manufacturing 11
- 1.4 Additive Manufacturing Categorization Based on the Relationship Between Shape Forming and Consolidation 12
- 1.5 Organization of the Book 14
- References 15

Part II Cold Spray Additive Manufacturing 19

- 2 Impact-Induced Bonding: Physical Processes and Bonding Mechanisms 21**
David Veyssset and Mostafa Hassani
- 2.1 Introduction 21
- 2.2 Fundamentals of Impact Bonding 23
 - 2.2.1 Plate Impacts and Explosive Welding 23
 - 2.2.1.1 The Shock Equations of State 23
 - 2.2.1.2 Limiting Conditions for Explosive Welding 24
 - 2.2.2 Laser Impact Bonding 30
- 2.3 Bonding Mechanisms in Cold Spray 32
 - 2.3.1 Proposed Mechanisms 32

2.3.1.1	The Role of Jetting and Impact Pressure in Particle Bonding	32
2.3.1.2	The Limiting Case of Impact Melting	33
2.3.1.3	Adiabatic Shear Instability	36
2.3.1.4	Dissimilar Materials Impact	40
2.3.2	Influence of Particle Characteristics	41
2.3.2.1	Particle Temperature	41
2.3.2.2	Particle Size	42
2.3.2.3	Surface Oxide and Hydroxide Effects	42
	References	43

3 Microstructures and Microstructural Evolution in Cold-Sprayed Materials 49

Luke N. Brewer and Lorena I. Perez-Andrade

3.1	Introduction	49
3.2	Defect Structures	50
3.2.1	Vacancies	51
3.2.2	Dislocation Structure	52
3.2.3	Grain Structure	55
3.2.4	Precipitate Structure	56
3.2.5	Porosity	60
3.3	Microstructural Evolution of Thermally Treated Cold-Sprayed Materials	61
3.3.1	Recovery, Recrystallization, and Grain Growth	62
3.3.2	Precipitation	65
3.3.3	Heat Treatment of Feedstock Powders and its Impact on Microstructure	66
3.4	Conclusions	67
	Acknowledgements	67
	References	68

4 Mechanical Properties of Cold Spray Deposits 75

Sara Bagherifard and Mario Guagliano

4.1	Introduction	75
4.2	Mechanical Properties	76
4.2.1	Adhesive Strength	77
4.2.1.1	Adhesive Strength Test Methods	77
4.2.1.2	The Effect of Process Parameters on Adhesive Strength	80
4.2.1.3	The effect of Pre-/Post-treatments on Adhesive Strength	80
4.2.2	Cohesive Strength	83
4.2.2.1	Cohesive Strength Test methods	84
4.2.2.2	Cohesive Strength Under Static Loading	84
4.2.2.3	Cohesive Strength Under Fatigue Loading	86
4.2.2.4	Anisotropy in Cohesive Strength	90

4.2.3	Summary and Future Perspectives	91
	References	94
5	Cold Spray in Practical and Potential Applications	101
	<i>Jingjie Wei, Yong He, Phuong Vo, and Yu Zou</i>	
5.1	Introduction	101
5.1.1	The Cold Spray Process	101
5.1.2	Cold Spray Additive Manufacturing (CSAM)	103
5.2	Materials	103
5.2.1	Cu and Cu Alloys	103
5.2.1.1	2Cu–Ga and Cu–In–Ga	107
5.2.1.2	Cu–Sn	107
5.2.1.3	Cu–W	107
5.2.2	Al and Al Alloys	108
5.2.3	Ni and Ni Alloys	110
5.2.4	Stainless Steels	111
5.2.5	Body Center Cubic (BCC) Metals	112
5.2.5.1	Tantalum	112
5.2.5.2	Niobium	114
5.2.6	Hexagonal Close-Packed (HCP) Metals	114
5.2.6.1	Titanium	114
5.2.6.2	Magnesium	116
5.2.7	Metal Mixes and Metal Matrix Composite (MMC)	116
5.2.7.1	Metal Mixes	117
5.2.7.2	Metal Matrix Composite	117
5.2.8	Multicomponent and High Entropy Alloys	120
5.2.8.1	MCrAlY Multicomponent Alloy	120
5.2.8.2	High Entropy Alloy (HEA)	120
5.2.9	Multimaterials	121
5.3	Perspective and Challenges	122
	References	124
	Part III Additive Friction Stir Deposition	133
6	Process Fundamentals of Additive Friction Stir Deposition	135
	<i>David Garcia and Hang Z. Yu</i>	
6.1	Additive Friction Stir Deposition – Macroscopic Process Overview	136
6.2	Thermo-Mechanical Processing Evolution	139
6.3	Heat Generation and Heat Transfer	142
6.3.1	Heat Generation and Heat Transfer Mechanisms	142
6.3.2	Peak Temperature and Material Dependence	143
6.4	Material Flow and Deformation	146
	References	149

7	Dynamic Microstructure Evolution in Additive Friction Stir Deposition	153
	<i>Robert J. Griffiths and Hunter A. Rauch</i>	
7.1	Introduction to Microstructure Evolution in Additive Friction Stir Deposition	154
7.2	Dynamic Microstructure Evolution in Single-Phase Materials	155
7.2.1	Stacking Fault Energy and Dislocation Mobility	155
7.2.2	Dynamic Recovery	157
7.2.3	Continuous Dynamic Recrystallization	157
7.2.4	Discontinuous Dynamic Recrystallization	159
7.2.5	Static and Post-Dynamic Recrystallization	160
7.2.6	Heterogeneous Deposits and Metadynamic Recrystallization	161
7.3	Dynamic Microstructure Evolution in Multiple-Phase Materials	162
7.3.1	Thermal Evolution During Additive Friction Stir Deposition	162
7.3.2	Evolution of Secondary Phases at Low Temperature	164
7.3.3	Evolution of Secondary Phases at High Temperature	166
7.3.4	Evolution of Secondary Phases After Deformation	168
7.3.5	Mapping Secondary Phase Evolution to Processing Space	168
7.4	Effects of Material Transport on Microstructure Evolution	170
7.4.1	Mechanisms of Material Transport	170
7.4.2	Material Transport for the Homogenization of Mixtures	172
7.4.3	Densification of Material Through Material Transport	173
7.4.4	Material Transport and Spatial Variance in Thermomechanical Conditions	174
7.5	The Study of Microstructure Evolution in Additive Friction Stir Deposition	175
7.5.1	Contemporary Approaches	175
7.5.2	Novel Approaches	177
	Acknowledgement	177
	References	177
8	Mechanical Properties of Additive Friction Stir Deposits	181
	<i>Dustin Avery and Mackenzie Perry</i>	
8.1	Introduction	181
8.2	Magnesium-Based Alloys	184
8.2.1	WE43	184
8.2.2	AZ31	187
8.3	Aluminum-Based Alloys	189
8.3.1	5xxx	190
8.3.2	2xxx	192
8.3.3	6xxx	193
8.3.4	7xxx	195
8.3.5	Cast Al Alloys	197

8.4	Other Alloys Systems	197
8.4.1	Nickel-Based Alloys	197
8.4.2	Copper-Based Alloys	198
8.4.3	Titanium-Based Alloys	198
8.4.4	Steel Alloys	199
8.4.5	High-Entropy Alloys	199
8.4.6	Metal Matrix Composites	200
8.5	Repair	200
8.6	Summary and Future Perspectives	201
8.6.1	Anisotropy	201
8.6.2	Graphite Lubricant	202
8.6.3	Multimaterial or Designed Feedstock	202
8.6.4	Effect of Process Parameters on Mechanical Properties	202
8.6.5	Active Cooling/Heating	202
8.6.6	Heat Treatment	202
8.6.7	High-Temperature Materials – Tool Wear	203
8.6.8	Unique Possibilities	203
8.6.9	Modeling	203
	References	203

9 Potential Industrial Applications of Additive Friction Stir Deposition 209

Hang Z. Yu, Rajiv S. Mishra, Chase D. Cox, and Zhili Feng

9.1	Large-Scale Metal Additive Manufacturing	209
9.2	Selective Area Cladding	211
9.3	Recycling and Upcycling	214
9.4	Structural Repair	220
9.5	Underwater Deposition	224
	Acknowledgment	227
	References	227

Part IV Ultrasonic Additive Manufacturing 231

10 Process Fundamentals of Ultrasonic Additive Manufacturing 233

Austin Ward

10.1	Process Overview	233
10.1.1	Process Parameters	234
10.2	Temperature Rise and Thermal Modeling	235
10.2.1	Heat Generation During Welding	235
10.2.2	Sonotrode Contact Stress	237
10.2.3	Coefficient of Friction	238
10.2.4	Temperature Profile	239
10.3	Feedstock Bonding Mechanisms	241

10.3.1	Oxide Breakdown	241
10.3.2	Asperity Deformation	243
10.3.3	Diffusional Bonding Processes	246
10.3.4	Liquid-Phase Bonding	247
10.4	Dissimilar Metal Consolidation	247
10.4.1	Mechanical and Thermal Modeling	247
10.4.2	Dissimilar Metal Junction Growth	248
10.4.3	Interdiffusion	249
10.5	Acoustic Softening and Strain Normality	251
10.5.1	Cyclic Strain Ratcheting	253
10.6	Summary	254
	Acknowledgments	255
	References	255
11	Ultrasonic Additive Manufacturing: Microstructural and Mechanical Characterization	259
	<i>Tianyang (Tyler) Han, Leon M. Headings, and Marcelo J. Dapino</i>	
11.1	Introduction	259
11.2	Microstructure Analysis of UAM Builds	259
11.2.1	Similar Material Joining with UAM	260
11.2.2	Dissimilar Material Joining with UAM	262
11.2.2.1	Al-Ceramic Weld	262
11.2.2.2	Ni-Steel Weld	263
11.3	Hardness Analysis of UAM Builds	266
11.4	Mechanical Characterization of UAM Builds	267
11.4.1	Design of a Custom Shear Testing Method	268
11.4.2	Validation of the Shear Test	268
11.4.3	Finite element Modeling of the Shear Test	270
11.4.4	Application of the Shear Test to UAM Samples	273
11.5	Conclusions	275
	References	275
12	Industrial Applications of Ultrasonic Additive Manufacturing	279
	<i>Mark Norfolk</i>	
12.1	Early Years	279
12.2	Increased Power → Increased Capability	281
12.3	Modern Applications	282
12.3.1	Electrification	282
12.3.2	Thermal Management	286
12.3.3	Embedded Electronics	288
12.3.3.1	SmartPlate	290
12.3.3.2	SensePipe	291
12.4	Future Applications	292
	References	292

Part V Sintering-Based Processes 295

- 13 Principles of Solid-State Sintering 297**
Basil J. Paudel, Albert C. To, and Amir Mostafaei
 - 13.1 Introduction 297
 - 13.2 Basic Terminology 298
 - 13.2.1 Sintering 298
 - 13.2.2 Relative Density/Green Density 299
 - 13.2.3 Coordination Number 299
 - 13.2.4 Surface Tension/Surface Energy 300
 - 13.2.5 Wetting Angle/Dihedral Angle 300
 - 13.2.6 Neck Growth/Shrinkage/Densification 301
 - 13.3 Sintering Stress 302
 - 13.3.1 Two Particle Model 302
 - 13.3.1.1 Case I: Without Shrinkage 303
 - 13.3.1.2 Case II: With Shrinkage 303
 - 13.3.2 Driving Force 303
 - 13.3.3 Interfacial Activity/Thermodynamics 304
 - 13.4 Mass Transport Mechanisms 306
 - 13.4.1 Grain Boundary Diffusion 306
 - 13.4.2 Lattice/Volume Diffusion 306
 - 13.4.3 Viscous Flow 306
 - 13.4.4 Surface Diffusion 307
 - 13.4.5 Evaporation/Condensation 307
 - 13.4.6 Gas Diffusion 307
 - 13.5 Sintering Stages 307
 - 13.6 Sintering Simulation 308
 - 13.7 Concluding Remarks, Challenges, and Future Works 309
 - References 310
- 14 Material Extrusion Additive Manufacturing 313**
Alexander C. Barbati and Aaron Preston
 - 14.1 Introduction 313
 - 14.2 Hierarchy of MEAM Parts and Feedstock Behavior 316
 - 14.3 Feedstock Attributes 325
 - 14.4 Extrusion Control 327
 - 14.5 Toolpathing: Strength and Quality 331
 - 14.6 Conclusions 335
 - Acknowledgments 336
 - References 336
- 15 Binder Jetting-based Metal Printing 339**
Marco Mariani, Nora Lecis, and Amir Mostafaei
 - 15.1 Introduction to Binder Jetting 339
 - 15.2 Printing Phase 341

15.2.1	Particulate Feedstock	341
15.2.1.1	Feedstock Materials	342
15.2.1.2	Feedstock Morphology and Size Distribution	343
15.2.2	Binder Selection	344
15.2.3	Powder Spreading and Binder Deposition System Configurations	345
15.3	Thermal Treatments	346
15.3.1	Curing	346
15.3.2	Debinding	347
15.3.3	Sintering	348
15.3.4	Additional Treatments	349
15.4	Future Developments	350
15.5	Conclusion	352
	References	352
16	Sintering-based Metal Additive Manufacturing Methods for Magnetic Materials	361
	<i>H. Wang, A. M. Elliot, and M. P. Paranthaman</i>	
16.1	Introduction	361
16.2	Background	362
16.3	Additive Manufacturing Methods	369
16.4	Applications	372
16.5	Summary	374
	Acknowledgments	375
	References	375
17	Future Perspectives	379
	<i>Hang Z. Yu, Nihan Tuncer, and Zhili Feng</i>	
17.1	Enhancing the Understanding of Process Fundamentals	379
17.2	Expanding the Printable Material Library	381
17.3	Embracing Artificial Intelligence for Quality Control and Process Prediction	381
	References	383
	Index	385