

METAL ADDITIVE MANUFACTURING

**Ehsan Toyserkani, Dyuti Sarker, Osezua Obehi Ibadode,
Farzad Liravi, Paola Russo, Katayoon Taherkhani**

*University of Waterloo
Waterloo, Ontario
Canada*

WILEY

Contents

Preface	xv
Abbreviations	xvii
1 Additive Manufacturing Process Classification, Applications, Trends, Opportunities, and Challenges	1
1.1 Additive Manufacturing: A Long-Term Game Changer	1
1.2 AM Standard Definition and Classification	4
1.3 Why Metal Additive Manufacturing?	5
1.4 Market Size: Current and Future Estimation	11
1.5 Applications of Metal AM	12
1.5.1 <i>Medical and Dental</i>	14
1.5.2 <i>Aerospace and Defense</i>	15
1.5.3 <i>Communication</i>	17
1.5.4 <i>Energy and Resources</i>	18
1.5.5 <i>Automotive</i>	19
1.5.6 <i>Industrial Tooling and Other Applications</i>	20
1.6 Economic/Environmental Benefits and Societal Impact	20
1.7 AM Trends, Challenges, and Opportunities	23
1.8 Looking Ahead	27
References	28
2 Basics of Metal Additive Manufacturing	31
2.1 Introduction	31
2.2 Main Metal Additive Manufacturing Processes	32
2.2.1 <i>Powder Bed Fusion (PBF)</i>	32
2.2.2 <i>Directed Energy Deposition (DED)</i>	41
2.2.3 <i>Binder Jetting (BJ)</i>	49
2.2.4 <i>Emerging Metal AM Processes</i>	55
2.3 Main Process Parameters for Metal DED, PBF, and BJ	62

2.3.1	<i>Main Output Parameters</i>	64
2.3.2	<i>Combined Thermal Energy Source Parameters PBF and DED</i>	65
2.3.3	<i>Beam Scanning Strategies and Parameters for PBF and DED</i>	68
2.3.4	<i>Powder Properties for PBF, DED, and BJ</i>	71
2.3.5	<i>Wire Properties for DED</i>	76
2.3.6	<i>Layer Thickness for PBF, DED, and BJ</i>	77
2.3.7	<i>Ambient Parameters for PBF, DED, and BJ</i>	79
2.3.8	<i>Geometry-Specific Parameters (PBF)</i>	80
2.3.9	<i>Support Structures for PBF</i>	82
2.3.10	<i>Binder Properties for BJ</i>	82
2.3.11	<i>Binder Saturation for BJ</i>	84
2.4	Materials	85
2.4.1	<i>Ferrous Alloys</i>	86
2.4.2	<i>Titanium Alloys</i>	86
2.4.3	<i>Nickel Alloys</i>	86
2.4.4	<i>Aluminum Alloys</i>	86
	References	87
3	Main Sub-Systems for Metal AM Machines	91
3.1	Introduction	91
3.2	System Setup of AM Machines	92
3.2.1	<i>Laser Powder Bed Fusion (LPBF)</i>	92
3.2.2	<i>Laser Directed Energy Deposition (LDED) with Blown Powder Known as Laser Powder-Fed (LPF)</i>	92
3.2.3	<i>Binder Jetting (BJ)</i>	93
3.3	Laser Basics: Important Parameters Needed to be Known for AM	93
3.3.1	<i>Laser Theory</i>	93
3.3.2	<i>Laser Components</i>	100
3.3.3	<i>Continuous Vs. Pulsed Laser</i>	101
3.3.4	<i>Laser Types</i>	102
3.3.5	<i>Laser Beam Properties</i>	109
3.4	Electron Beam Basics	114
3.4.1	<i>Comparisons and Contrasts between Laser and Electron Beams</i>	114
3.4.2	<i>Electron Beam Powder Bed Fusion Setup</i>	114
3.4.3	<i>Electron Beam Mechanism</i>	116
3.4.4	<i>Vacuum Chambers</i>	119
3.5	Powder Feeders and Delivery Nozzles Technology	121
3.5.1	<i>Classification of Powder Feeders</i>	121
3.5.2	<i>Powder Delivery Nozzles for DED</i>	125
3.5.3	<i>Powder Bed Delivery and Spreading Mechanisms</i>	128
3.5.4	<i>Wire Feed System</i>	129
3.5.5	<i>Positioning Devices and Scanners in Laser-Based AM</i>	130
3.5.6	<i>Print-Head in Binder Jetting</i>	131
3.6	CAD File Formats	133
3.6.1	<i>CAD/CAM Software</i>	134
3.7	Summary	134
	References	134

4	Directed Energy Deposition (DED): Physics and Modeling of Laser/Electron Beam Material Processing and DED	137
4.1	Introduction	137
4.2	Laser Material Interaction and the Associated Significant Parameters to Laser AM	140
4.2.1	<i>Continuous Versus Pulsed/Modulated Lasers</i>	141
4.2.2	<i>Absorption, Reflection, and Transmission Factors</i>	143
4.2.3	<i>Dependencies of Absorption Factor to Wavelength and Temperature</i>	144
4.2.4	<i>Angle of Incidence</i>	144
4.2.5	<i>Surface Roughness Effects</i>	147
4.2.6	<i>Scattering Effects</i>	147
4.3	E-beam Material Interaction	148
4.4	Power Density and Interaction Time for Various Heat Source-based Material Processing	149
4.5	Physical Phenomena and Governing Equations During DED	150
4.5.1	<i>Absorption</i>	150
4.5.2	<i>Heat Conduction</i>	151
4.5.3	<i>Surface Convection and Radiation</i>	152
4.5.4	<i>Fluid Dynamics</i>	153
4.5.5	<i>Phase Transformation</i>	156
4.5.6	<i>Rapid Solidification</i>	158
4.5.7	<i>Thermal Stresses</i>	158
4.5.8	<i>Flow Field in DED with Injected Powder</i>	159
4.6	Modeling of DED	161
4.6.1	<i>Analytical Modeling: Basics, Simplified Equations, and Assumptions</i>	161
4.6.2	<i>Numerical Models for DED</i>	165
4.6.3	<i>Experimental-based Models: Basics and Approaches</i>	166
4.7	Case Studies on Common Modeling Platforms for DED	168
4.7.1	<i>Lumped Analytical Model for Powder-Fed LDED</i>	168
4.7.2	<i>Comprehensive Analytical Model for Powder-Fed LDED (PF-LDED)</i>	172
4.7.3	<i>Numerical Modeling of LDED: Heat Transfer Model</i>	184
4.7.4	<i>Modeling of Wire-Fed E-beam DED (WF-EDED)</i>	193
4.7.5	<i>A Stochastic Model for Powder-Fed LDED</i>	195
4.8	Summary	200
	References	200
5	Powder Bed Fusion Processes: Physics and Modeling	203
5.1	Introduction and Notes to Readers	203
5.2	Physics of Laser Powder bed Fusion (LPBF)	204
5.2.1	<i>Heat Transfer in LPBF: Governing Equations and Assumptions</i>	205
5.2.2	<i>Fluid Flow in the Melt Pool of LPBF: Governing Equations and Assumptions</i>	215
5.2.3	<i>Vaporization and Material Expulsion: Governing Equations and Assumptions</i>	218
5.2.4	<i>Thermal Residual Stresses: Governing Equations and Assumptions</i>	219
5.2.5	<i>Numerical Modeling of LPBF</i>	220
5.2.6	<i>Case Studies on Common LPBF Modeling Platforms</i>	222

5.3	Physics and Modeling of Electron Beam Additive Manufacturing	228
5.3.1	<i>Electron Beam Additive Manufacturing Parameters</i>	228
5.3.2	<i>Emissions in Electron Beam Sources</i>	230
5.3.3	<i>Mathematical Description of Free Electron Current</i>	231
5.3.4	<i>Modeling of Electron Beam Powder Bed Fusion (EB-PBF)</i>	233
5.3.5	<i>Case Studies</i>	245
5.3.6	<i>Summary</i>	249
	References	251
6	Binder Jetting and Material Jetting: Physics and Modeling	255
6.1	Introduction	255
6.2	Physics and Governing Equations	257
6.2.1	<i>Droplet Formation</i>	257
6.2.2	<i>Droplet–Substrate Interaction</i>	263
6.2.3	<i>Binder Imbibition</i>	265
6.3	Numerical Modeling	270
6.3.1	<i>Level-Set Model</i>	270
6.3.2	<i>Lattice Boltzmann Method</i>	274
6.4	Summary	277
	References	277
7	Material Extrusion: Physics and Modeling	279
7.1	Introduction	279
7.2	Analytical Modeling of ME	281
7.2.1	<i>Heat Transfer and Outlet Temperature</i>	281
7.2.2	<i>Flow Dynamics and Drop Pressure</i>	283
7.2.3	<i>Die Swell</i>	288
7.2.4	<i>Deposition and Healing</i>	289
7.3	Numerical Modeling of ME	291
7.4	Summary	296
	References	296
8	Material Design and Considerations for Metal Additive Manufacturing	297
8.1	Historical Background on Materials	297
8.2	Materials Science: Structure–Property Relationship	298
8.3	Manufacturing of Metallic Materials	299
8.4	Solidification of Metals: Equilibrium	301
8.5	Solidification in Additive Manufacturing: Non-Equilibrium	302
8.6	Equilibrium Solidification: Theory and Mechanism	304
8.6.1	<i>Cooling Curve and Phase Diagram</i>	304
8.7	Non-Equilibrium Solidification: Theory and Mechanism	307
8.8	Solute Redistribution and Microsegregation	308
8.9	Constitutional Supercooling	312
8.10	Nucleation and Growth Kinetics	314
8.10.1	<i>Nucleation</i>	315
8.10.2	<i>Growth Behavior</i>	319

8.11	Solidification Microstructure in Pure Metals and Alloys	321
8.12	Directional Solidification in AM	324
8.13	Factors Affecting Solidification in AM	325
	8.13.1 <i>Cooling Rate</i>	325
	8.13.2 <i>Temperature Gradient and Solidification Rate</i>	326
	8.13.3 <i>Process Parameters</i>	329
	8.13.4 <i>Solidification Temperature Span</i>	329
	8.13.5 <i>Gas Interactions</i>	330
8.14	Solidification Defects	330
	8.14.1 <i>Porosity</i>	330
	8.14.2 <i>Balling</i>	332
	8.14.3 <i>Cracking</i>	335
	8.14.4 <i>Lamellar Tearing</i>	337
8.15	Post Solidification Phase Transformation	337
	8.15.1 <i>Ferrous Alloys/Steels</i>	337
	8.15.2 <i>Al Alloys</i>	338
	8.15.3 <i>Nickel Alloys/Superalloys</i>	341
	8.15.4 <i>Titanium Alloys</i>	350
8.16	Phases after Post-Process Heat Treatment	357
	8.16.1 <i>Ferrous Alloys</i>	357
	8.16.2 <i>Al Alloys</i>	357
	8.16.3 <i>Ni Alloys</i>	357
	8.16.4 <i>Ti Alloys</i>	358
8.17	Mechanical Properties	358
	8.17.1 <i>Hardness</i>	359
	8.17.2 <i>Tensile Strength and Static Strength</i>	363
	8.17.3 <i>Fatigue Behavior of AM-Manufactured Alloys</i>	365
8.18	Summary	371
	References	375
9	Additive Manufacturing of Metal Matrix Composites	383
9.1	Introduction	383
9.2	Conventional Manufacturing Techniques for Metal Matrix Composites (MMCs)	384
9.3	Additive Manufacturing of Metal Matrix Composites (MMCs)	385
9.4	AM Challenges and Opportunities	386
9.5	Preparation of Composite Materials: Mechanical Mixing	387
9.6	Different Categories of MMCs	389
9.7	Additive Manufacturing of Ferrous Matrix Composites	390
	9.7.1 <i>316 SS-TiC Composite</i>	390
	9.7.2 <i>316 SS-TiB₂ Composite</i>	392
	9.7.3 <i>H13-TiB₂ Composite</i>	392
	9.7.4 <i>H13-TiC Composite</i>	393
	9.7.5 <i>Ferrous-WC Composite</i>	393
	9.7.6 <i>Ferrous-VC Composites</i>	394

9.8	Additive Manufacturing of Titanium-Matrix Composites (TMCs)	395
9.8.1	<i>Ti–TiC Composite</i>	396
9.8.2	<i>Ti–TiB Composites</i>	396
9.8.3	<i>Ti–Hydroxyapatite (Ti–HA) Composites</i>	399
9.8.4	<i>Ti-6Al-4V-Metallic Glass (MG) Composites</i>	400
9.8.5	<i>Ti-6Al-4V + B₄C Pre-alloyed Composites</i>	401
9.8.6	<i>Ti-6Al-4V + Mo Composite</i>	402
9.8.7	<i>Structure and Properties of Different TMCs</i>	403
9.9	Additive Manufacturing of Aluminum Matrix Composites	403
9.9.1	<i>Al–Fe₂O₃ Composite</i>	405
9.9.2	<i>AlSi₁₀Mg–SiC Composite</i>	405
9.9.3	<i>AlSi₁₀Mg–TiC Composite</i>	406
9.9.4	<i>2024Al–TiB₂ Composite</i>	406
9.9.5	<i>AlSi₁₀Mg–TiB₂ Composite</i>	407
9.9.6	<i>AA7075–TiB₂ Composite</i>	407
9.10	Additive Manufacturing of Nickel Matrix Composites	407
9.10.1	<i>Inconel 625–TiC Composites</i>	408
9.10.2	<i>Inconel 625–TiB₂ Composite</i>	409
9.11	Factors Affecting Composite Property	409
9.11.1	<i>Mixing of Matrix and Reinforcing Elements</i>	409
9.11.2	<i>Size of Reinforcing Elements</i>	410
9.11.3	<i>Decomposition Temperature</i>	411
9.11.4	<i>Viscosity and Pore Formation</i>	411
9.11.5	<i>Volume of Reinforcing Elements and Pore Formation</i>	412
9.11.6	<i>Buoyancy Effects and Surface Tension Forces</i>	412
9.12	Summary	414
	References	417
10	Design for Metal Additive Manufacturing	421
10.1	Design Frameworks for Additive Manufacturing	421
10.1.1	<i>Integrated Topological and Functional Optimization DfAM</i>	422
10.1.2	<i>Additive Manufacturing-Enabled Design Framework</i>	422
10.1.3	<i>Product Design Framework for AM with Integration of Topology Optimization</i>	424
10.1.4	<i>Multifunctional Optimization Methodology for DfAM</i>	427
10.1.5	<i>AM Process Model for Product Family Design</i>	427
10.2	Design Rules and Guidelines	427
10.2.1	<i>Laser Powder Bed Fusion (LPBF)</i>	427
10.2.2	<i>Electron Beam Powder Bed Fusion (EB-PBF)</i>	431
10.2.3	<i>Binder Jetting</i>	433
10.2.4	<i>Technologies Compared</i>	434
10.3	Topology Optimization for Additive Manufacturing	434
10.3.1	<i>Structural Optimization</i>	435
10.3.2	<i>Topology Optimization</i>	436
10.3.3	<i>Design-Dependent Topology Optimization</i>	444
10.3.4	<i>Efforts in AM-Constrained Topology Optimization</i>	450

10.4	Lattice Structure Design	458
10.4.1	<i>Unit Cell</i>	458
10.4.2	<i>Lattice Framework</i>	459
10.4.3	<i>Uniform Lattice</i>	460
10.4.4	<i>Conformal Lattices</i>	462
10.4.5	<i>Irregular/Randomized Lattices</i>	462
10.4.6	<i>Design Workflows for Lattice Structures</i>	463
10.5	Design for Support Structures	473
10.5.1	<i>Principles that Should Guide Support Structure Design</i>	474
10.5.2	<i>Build Orientation Optimization</i>	474
10.5.3	<i>Support Structure Optimization</i>	476
10.6	Design Case Studies	483
10.6.1	<i>Redesign of an Aerospace Bracket to be Made by LPBF</i>	484
10.6.2	<i>Design and Development of a Structural Member in a Suspension Assembly Using EB Powder Bed Fusion</i>	487
10.6.3	<i>Binder Jetting of the Framework of a Partial Metal Denture</i>	488
10.6.4	<i>Redesign of a Crank and Connecting Rod</i>	490
10.6.5	<i>Redesign of a Mechanical Assembly</i>	492
10.6.6	<i>Solid-Lattice Hip Prosthesis Design</i>	498
10.7	Summary	501
	References	501
11	Monitoring and Quality Assurance for Metal Additive Manufacturing	507
11.1	Why are Closed-Loop and Quality Assurance Platforms Essential?	507
11.2	In-Situ Sensing Devices and Setups	509
11.2.1	<i>Types of Sensors Used in Metal AM</i>	509
11.2.2	<i>Mounting Strategies for In-line Monitoring Sensors in Metal AM Setups</i>	521
11.3	Commercially Available Sensors	522
11.3.1	<i>LPBF Commercial Sensors</i>	522
11.3.2	<i>LDED Commercial Sensors</i>	525
11.4	Signal/Data Conditioning, Methodologies, and Classic Controllers for Monitoring, Control, and Quality Assurance in Metal AM Processes	526
11.4.1	<i>Signal/Data Conditioning and Controllers for Melt Pool Geometrical Analysis</i>	526
11.4.2	<i>Signal/Data Conditioning and Methodologies for Temperature Monitoring and Analysis</i>	531
11.4.3	<i>Signal/Data Conditioning and Methodologies for the Detection of Porosity</i>	532
11.4.4	<i>Signal/Data Conditioning and Methodologies for Detection of Crack and Delamination</i>	537
11.4.5	<i>Signal/Data Conditioning and Methodologies for Detection of Plasma Plume and Spatters</i>	538
11.5	Machine Learning for Data Analytics and Quality Assurance in Metal AM	539
11.5.1	<i>Supervised Learning</i>	539
11.5.2	<i>Unsupervised Learning</i>	549

11.6	Case Study	553
	11.6.1 <i>Design of Experiments</i>	554
	11.6.2 <i>In-Situ Sensors and Quality Assurance Algorithm</i>	555
	11.6.3 <i>Correlation Between CT Scan and Analyzed Data</i>	560
11.7	Summary	563
	References	565
12	Safety	577
12.1	Introduction	577
12.2	Overview of Hazards	578
12.3	AM Process Hazards	578
12.4	Laser Safety in Additive Manufacturing	579
	12.4.1 <i>Laser Categorization</i>	579
	12.4.2 <i>Laser Hazards</i>	581
	12.4.3 <i>Eye Protection</i>	584
	12.4.4 <i>Laser Protective Eyewear Requirements</i>	584
12.5	Electron Beam Safety	585
12.6	Powder Hazards	585
	12.6.1 <i>Combustibility</i>	586
12.7	Human Health Hazards	587
12.8	Comprehensive Steps to AM Safety Management	587
	12.8.1 <i>Engineering Controls</i>	587
	12.8.2 <i>Personal Protective Equipment</i>	588
	12.8.3 <i>AM Guidelines and Standards</i>	588
12.9	Summary	589
	References	590
	Index	591