

Contents

Preface	<i>ix</i>
Acronyms	<i>xiii</i>

1	Introduction to Additive Manufacturing	1
1.1	Evolution of Manufacturing	1
1.2	Concept of AM	3
1.3	Advantages over Conventional Manufacturing Techniques	6
1.4	Laser-Based AM	7
1.4.1	Laser-Based Directed Energy Deposition	7
1.4.1.1	Machine Design	9
1.4.1.2	Process Parameters	9
1.4.2	Laser Powder Bed Fusion	10
1.4.2.1	Process Parameters	11
1.4.3	Estimation of Energy Input in LAM Processes	13
1.4.4	Multi-Step LAM Techniques	15
	References	16
2	Multiscale Computational Approaches to LAM	19
2.1	Computational Science	19
2.1.1	Computational Material Science	20
2.2	Multiscale Modeling	21
2.2.1	Nano-Micro-Scale Modeling	21
2.2.1.1	Molecular Dynamics and Density Functional Theory	21
2.2.1.2	Monte Carlo Method	22
2.2.2	Meso-Macro Scale Modeling	23
2.2.2.1	Kinetic Monte Carlo Method	24
2.2.2.2	Cellular Automata	25
2.2.2.3	Phase-Field Method	29
2.2.2.4	Finite Element Method	30
2.3	Integrated Computational Materials Engineering (ICME)	33
	References	34

3	Laser Matter Interaction in LAM	37
3.1	Introduction	37
3.1.1	Physical Phenomena in LAM	38
3.2	Components of Mathematical Models in Metal AM	40
3.3	Feedstock	40
3.3.1	Powder Bed Morphology in LPBF	40
3.3.1.1	Discrete Element Method	41
3.3.1.2	Powder Spreading Mechanism	44
3.3.2	Powder Stream Generation in LDED	48
3.3.2.1	Turbulent Gas Flow and Discrete Phase Model	49
3.3.2.2	Powder Stream Characteristics	52
3.3.3	Laser-Feedstock Interaction	54
3.4	Thermo-Fluidic Model in LAM	60
3.4.1	Laser Heat Source	61
3.4.2	Radiative and Convective Cooling	61
3.4.3	Recoil Pressure and Evaporative Cooling	61
3.4.4	Surface Tension	62
3.4.5	Free Surface Tracking Methods	63
3.5	Melt Hydrodynamics in LPBF	65
3.5.1	Thermo-Fluidic Anatomy of a Single Track	65
3.5.2	Conduction Mode LPBF	68
3.5.3	Keyhole Mode LPBF	68
3.5.4	Energy Coupling Mechanism	71
3.6	Melt Hydrodynamics in LDED	74
3.7	Multi-Layer, Multi-Track Approach	79
3.8	Computational Cost	82
3.9	Computationally Efficient Approach	83
3.10	Guidelines for Experimental Validation	89
	References	89
4	Thermokinetics, Microstructural Evolution, and Material Response	101
4.1	Thermokinetics in LAM	101
4.2	Solidification	104
4.2.1	Nucleation	104
4.2.1.1	Heterogeneous Nucleation Assisted by Inoculants	104
4.2.1.2	Homogeneous Nucleation	107
4.2.1.3	Nucleation Influenced by Acoustic Cavitation	110
4.2.2	Solidification Variables	115
4.2.2.1	Thermal Gradient	115
4.2.2.2	Solidification Rate	116
4.2.3	Growth and Orientation	116
4.2.4	Solidification Modes	121
4.2.5	Spatial Variation of Thermokinetic Parameters	124
4.2.5.1	Dependence on the Curvature of the Trailing Boundary	126

4.2.5.2	Solidification Rate and Thermal Gradient	128
4.2.5.3	Morphology Factor and Cooling Rate Variation	128
4.2.5.4	Columnar-to-Equiaxed Transition	131
4.3	Thermal Cycles in LAM Processes	134
4.3.1	Thermal Cycles in LPBF	134
4.3.1.1	Thermal Cycles During Layer Fabrication	137
4.3.1.2	Thermal Cycles During Fabrication of Multiple Layers	138
4.3.2	Thermal Cycles in LDED	139
4.3.2.1	Thermal Cycles During the Deposition of a Layer	141
4.3.2.2	Thermal Cycles During Fabrication of Multiple Layers	141
4.4	Phase Transformations in LAM	142
4.4.1	Thermal Cycle-Driven Phase Evolution	143
4.4.2	Process-Driven Phase Transformations	148
4.4.2.1	Isothermal Effect	148
4.4.2.2	Process Parameters	149
4.5	Effect of Process Parameters	151
4.5.1	Laser Beam Attributes	151
4.5.1.1	Laser Beam Diameter	153
4.5.1.2	Laser Power	154
4.5.1.3	Laser Speed	156
4.5.2	Laser Process Attributes	161
4.5.2.1	Scanning Strategy	161
4.5.2.2	Preheating the Substrate	164
4.5.2.3	Build Orientation	166
4.5.2.4	Interlayer Duration	167
4.5.2.5	Feed Rate	169
4.6	Effect of Melting Modes	170
4.7	Laser Operation Modes	173
4.8	Material Response	178
4.8.1	Mechanical Response	179
4.8.1.1	Elastic Modulus	192
4.8.1.2	Fatigue	193
4.8.1.3	Creep	194
4.8.1.4	Wear	195
4.8.2	Electrochemical Response	196
	References	200
5	Residual Stress in LAM	223
5.1	Introduction	223
5.2	Thermo-Mechanical Model: Mathematical Framework	225
5.2.1	Elasto-Plastic Mechanical Model	226
5.2.2	Stress-Strain Behavior	227
5.2.2.1	Elastic Region	227
5.2.2.2	Yield Stress	227
5.2.2.3	Plastic Region	227

5.2.2.4	Bauschinger Effect and Kinematic Hardening	228
5.2.3	Basic Elements of Elastic-Plastic Theory	229
5.2.3.1	Stress	229
5.2.3.2	Strain	230
5.2.3.3	Equation of Motion	231
5.2.3.4	Criterion for Initial Yielding	231
5.2.3.5	Flow Rule	231
5.2.3.6	Isotropic Strain Hardening	232
5.2.3.7	Viscoplasticity and Thermal Softening	232
5.2.3.8	Kinematic Hardening	232
5.2.3.9	Consistency Condition	233
5.2.3.10	Elastic-Plastic Stress-Strain Relation	233
5.3	Thermal Elastic-Plastic Formulation	234
5.3.1	Macro-Scale Approaches	237
5.4	Evolution of Residual Stress in LAM	237
5.4.1	Thermo-Mechanical Anatomy of a Single Track	238
5.4.2	Thermo-Mechanical Anatomy of a Single Layer	241
5.4.3	Stress Evolution at Component Scale	241
5.4.4	Experimental Validation of Residual Stress	242
5.4.5	Integrated Experimental and Numerical Approach for the Mitigation of Residual Stress	246
5.4.5.1	Role of the Scanning Strategy	246
5.4.5.2	Role of Preheating	250
5.4.5.3	Real-Time Control and Miscellaneous Approaches	251
	References	253
6	Surface Roughness in LAM	261
6.1	Introduction	261
6.2	Surface Roughness Characteristics in LAM	262
6.3	Surface Defects in LAM	265
6.4	Post-LAM Surface Finishing	269
	References	272
	Index	277