
Contents

Preface.....xvii

Acknowledgments.....xix

Authors.....xxi

Glossaryxxv

Chapter 1 Introduction to Additive Manufacturing and 3D Printing Technology 1

1.1 Development of Additive Manufacturing 1

1.2 Major Trends Shaping the Evaluation of 3D Printing 2

1.3 Technology Improvement 3

1.4 Active 3D Printing Market 4

1.5 3D Printing Processes 5

 1.5.1 Material Extrusion..... 6

 1.5.1.1 Fused Deposition Modeling (FDM) 6

 1.5.2 Vat Photopolymerization..... 7

 1.5.2.1 Stereolithography (SLA)..... 8

 1.5.2.2 Digital Light Processing (DLP)..... 8

 1.5.3 Powder Bed Fusion 8

 1.5.3.1 Powder Bed Fusion (Polymers)..... 8

 1.5.3.2 Powder Bed Fusion (Metals)..... 10

 1.5.4 Material Jetting 11

 1.5.4.1 Material Jetting (MJ)..... 12

 1.5.4.2 Drop on Demand (DOD) 12

 1.5.5 Binder Jetting 12

 1.5.5.1 Sand Binder Jetting..... 13

 1.5.5.2 Metal Binder Jetting 14

 1.5.6 Sheet Lamination 14

 1.5.6.1 Materials Used in Sheet Lamination 14

 1.5.7 Directed Energy Deposition..... 15

1.6 Classification of Additive Manufacturing Systems 17

 1.6.1 Liquid-Based 17

 1.6.2 Solid-Based 17

 1.6.3 Powder-Based 18

1.7 Advantages and Limitations..... 18

1.8 Additive vs. Conventional Manufacturing Processes..... 18

1.9 Applications..... 19

1.10 Exercises..... 19

1.11 Multiple-Choice Questions..... 21

Chapter 2	CAD for Additive Manufacturing	25
2.1	Introduction	25
2.2	Preparation of CAD Models: The STL File	25
2.2.1	STL File Format, Binary/ASCII.....	26
2.2.1.1	Format Specifications	28
2.2.1.2	STL ASCII Format	29
2.2.1.3	STL Binary Format	30
2.2.2	Creating STL Files from a CAD System	30
2.2.3	Calculation of Each Slice Profile	32
2.2.4	Technology-Specific Elements	37
2.3	Problems with STL Files	39
2.4	STL File Manipulation	41
2.4.1	Viewers	42
2.4.2	STL Manipulation on the AM Machine	43
2.5	Beyond the STL File.....	44
2.5.1	Direct Slicing of the CAD Model	44
2.5.2	Color Models	45
2.5.3	Multiple Materials	45
2.5.4	Use of STL for Machining	45
2.6	Additional Software to Assist AM	46
2.6.1	Survey of Software Functions	46
2.6.2	AM Process Simulations Using Finite Element Analysis	47
2.7	The Additive Manufacturing File Format	49
2.8	Solved Example	50
2.9	Exercises.....	51
2.10	Multiple-Choice Questions.....	52
Chapter 3	Liquid-Based Additive Manufacturing Systems	55
3.1	3D Systems Stereolithography Apparatus (SLA).....	55
3.2	Stratasys PolyJet	59
3.2.1	Fused Deposition Modeling from Stratasys.....	60
3.2.2	Material Jetting Machines.....	61
3.3	3D Systems' Multi-Jet Printing System (MJP)	62
3.4	EnvisionTEC's Perfactory	63
3.5	CMET's Solid Object Ultraviolet-Laser Printer (SOUP)	65
3.6	EnvisionTEC's Bioplotter	66
3.7	RegenHU's 3D Bioprinting	67
3.8	Rapid Freeze Prototyping.....	69
3.9	FDM 3D Printing for Zygomatic Implant Placement Mock Surgery for Prosthodontic Dentistry: A Case Study	70
3.9.1	Zygomatic Implant	70
3.9.2	Conclusion	72

3.10	Exercises	72
3.11	Multiple-Choice Questions.....	72
Chapter 4	Solid-Based Additive Manufacturing Systems	75
4.1	Stratasys Fused Deposition Modeling (FDM)	75
4.2	Solidscape's BenchTop System.....	75
4.3	Mcor Technologies' Selective Deposition Lamination (SDL).....	77
4.4	Cubic Technologies' Laminated Object Manufacturing (LOM)	80
4.4.1	Working Process.....	82
4.4.2	Applications.....	83
4.5	Ultrasonic Consolidation.....	83
4.6	Exercises.....	86
4.7	Multiple-Choice Questions.....	86
Chapter 5	Powder-Based Additive Manufacturing Systems	89
5.1	3D Systems' Selective Laser Sintering (SLS)	89
5.1.1	Technology	89
5.1.2	Materials.....	90
5.1.3	Powder Production	91
5.1.4	Sintering Mechanisms	91
5.1.5	Advantage.....	91
5.1.6	Application	92
5.2	3D Systems' ColorJet Printing (CJP) Technology.....	92
5.2.1	Technology	92
5.3	EOS's EOSINT System	93
5.3.1	About EOS (Electro Optical Systems)	93
5.3.2	EOSINT M 280 System	93
5.4	Optomec's Laser Engineered Net Shaping (LENS) and Aerosol Jet System.....	95
5.4.1	About Optomec	95
5.4.2	Laser Engineered Net Shaping (LENS).....	95
5.4.3	How the LENS System Works	95
5.5	Arcam's Electron Beam Melting (EBM).....	95
5.6	Concept Laser's LaserCUSING.....	97
5.6.1	Concept Laser's Patented LaserCUSING 3D-Printing Technology.....	97
5.6.2	Working of LaserCUSING 3D-Printing Technology	98
5.6.3	Additional Features of LaserCUSING 3D-Printing Technology	100
5.6.4	Advantages of LaserCUSING 3D-Printing Technology	100
5.7	SLM Solutions' Selective Laser Melting (SLM)	100

5.8	Exercises.....	102
5.9	Multiple-Choice Questions.....	102
Chapter 6	Materials in Additive Manufacturing.....	107
6.1	Choosing Materials for Manufacturing.....	107
6.1.1	Application.....	107
6.1.2	Aesthetics.....	108
6.1.3	Function.....	108
6.1.4	Certifications.....	108
6.1.4.1	Nylon.....	108
6.1.4.2	ABS (Acrylonitrile Butadiene Styrene)....	109
6.1.4.3	Resin.....	109
6.1.4.4	PLA (Polylactic Acid).....	110
6.1.4.5	Gold and Silver.....	110
6.1.4.6	Stainless Steel.....	111
6.1.4.7	Titanium.....	111
6.1.4.8	Ceramics.....	111
6.1.4.9	PET/PETG.....	112
6.1.4.10	HIPS (High Impact Polystyrene).....	112
6.1.4.11	Thermoplastics.....	113
6.1.4.12	Thermosets (Resins).....	114
6.1.4.13	Metals.....	114
6.2	Multiple Materials.....	114
6.2.1	Multi-Material and Composite Additive Manufacturing Methods.....	115
6.2.1.1	Stereolithography Methods.....	115
6.2.1.2	Binder Jetting Methods.....	115
6.2.1.3	Extrusion-Based Printing Methods.....	116
6.2.1.4	Material Jetting Printing Methods.....	118
6.3	Metal AM Processes and Materials.....	119
6.3.1	Powder-Bed Systems.....	120
6.3.2	Powder-Fed Systems.....	120
6.3.3	Direct Metal Laser Sintering (DMLS) Materials....	121
6.3.4	Selective Laser Sintering (SLS) Materials.....	123
6.3.5	Stereolithography (SLA) Materials.....	124
6.4	Composite Materials.....	127
6.4.1	Generic Composite Materials.....	128
6.4.2	Composite Materials for 3D Printing Processes.....	129
6.5	Biomaterials, Hierarchical Materials, and Biomimetics.....	129
6.5.1	Biomaterials.....	129
6.5.1.1	Biomedical.....	130
6.5.2	Hierarchical Materials and Biomimetics.....	130
6.5.3	Biomimetics.....	133
6.5.3.1	Definition of Biomimetic Material.....	135
6.5.3.2	History of Biomimetic Materials.....	135

- 6.6 Ceramics and Bio-Ceramics..... 137
 - 6.6.1 Ceramics..... 137
 - 6.6.2 Bio-Ceramics..... 138
- 6.7 Shape-Memory Materials, 4D Printing, and Bio-Active Materials..... 139
 - 6.7.1 Shape-Memory Materials..... 139
 - 6.7.1.1 How Does Shape-Memory Work..... 140
 - 6.7.1.2 Shape-Memory Alloys..... 141
 - 6.7.1.3 Shape-Memory Polymers 142
 - 6.7.1.4 Shape-Memory Composites..... 146
 - 6.7.1.5 Shape-Memory Hybrids..... 146
 - 6.7.2 4D Printing and Bio-Active Materials 150
- 6.8 Advanced AM Materials 151
- 6.9 Support Materials 152
 - 6.9.1 Build Material Supports 153
 - 6.9.1.1 Materials as Their Own Support 153
 - 6.9.2 Quick Removal: Breakaway Supports..... 154
 - 6.9.3 Best Quality: Soluble Supports 155
 - 6.9.4 Supporting with the Original Material..... 156
 - 6.9.5 Supporting with PVA Filament 156
 - 6.9.6 Supporting with PVA+ Filament 156
- 6.10 Exercises..... 156
- 6.11 Multiple-Choice Questions..... 157

Chapter 7 Applications and Examples 159

- 7.1 Application–Material Relationship 159
 - 7.1.1 Polymer..... 159
 - 7.1.2 Metal..... 161
- 7.2 Finishing Processes 162
 - 7.2.1 Plating..... 163
 - 7.2.2 Sanding..... 163
 - 7.2.3 Bead Blasting 164
 - 7.2.4 Shot Peening..... 164
 - 7.2.5 Heat Treatments 164
 - 7.2.6 Vibratory Systems 165
 - 7.2.7 Tumbling 165
 - 7.2.8 Vapor Smoothing..... 166
 - 7.2.9 Solvent Dipping..... 166
 - 7.2.10 Epoxy Coating 166
 - 7.2.11 Epoxy Infiltration 166
 - 7.2.12 Painting 167
- 7.3 Applications in Design 167
 - 7.3.1 CAD Model Verification 167
 - 7.3.2 Visualizing Objects 167
 - 7.3.3 Proof of Concept 167

7.4	Applications in Engineering, Analysis, and Planning.....	168
7.4.1	Scaling	168
7.4.2	Form and Fit	168
7.4.3	Flow Analysis.....	168
7.4.4	Pre-Production Parts	168
7.5	Applications in Manufacturing and Tooling	168
7.5.1	Direct Soft Tooling	168
7.5.2	Indirect Soft Tooling	168
7.5.3	Direct Hard Tooling	169
7.5.4	Indirect Hard Tooling.....	169
7.6	Aerospace Industry.....	169
7.6.1	The Benefits of 3D Printing for Aerospace and Defense	170
7.6.1.1	Low-Volume Production	170
7.6.1.2	Weight Reduction.....	170
7.6.1.3	Material Efficiency	170
7.6.1.4	Consolidation of the Part	171
7.6.1.5	Maintenance and Repair.....	171
7.7	Automotive Industry	171
7.7.1	The Benefits of 3D Printing for Automotive	172
7.7.1.1	Faster Product Development.....	172
7.7.1.2	Greater Design Flexibility	172
7.7.1.3	Customization.....	172
7.7.1.4	Create Complex Geometries.....	172
7.8	Jewelry Industry	172
7.8.1	Investment Casting	173
7.8.2	Direct Printing.....	176
7.9	Coin Industry.....	178
7.10	Tableware Industry	180
7.11	Geographic Information System (GIS) Applications	180
7.12	Arts and Architecture.....	182
7.12.1	Benefits of 3D Printing for Architects	183
7.13	Construction	183
7.14	Fashion and Textiles	184
7.15	Weapons	186
7.16	Musical Instruments	186
7.17	Food.....	187
7.18	Movies	188
7.19	Design and Development of a Prosthetic Hand through 3D Printing: Case Study	189
7.19.1	Conclusion.....	194
7.19.1.1	Prototype Assessment.....	194
7.20	Exercises.....	195
7.21	Multiple-Choice Questions.....	196

Chapter 8 Additive Manufacturing Equipment 199

8.1 Process Equipment—Design and Process Parameters..... 199

8.1.1 Seven Distinct AM Processes 199

8.1.1.1 Powder Bed Fusion 199

8.1.1.2 Directed Energy Deposition 200

8.1.1.3 Binder Jetting..... 200

8.1.1.4 Sheet Lamination 200

8.1.1.5 Material Extrusion..... 200

8.1.1.6 Material Jetting..... 201

8.1.1.7 Vat Photopolymerization 201

8.1.2 Designing for 3D Printing 201

8.2 Governing Bonding Mechanism 201

8.2.1 Overview of the Bonding Process 202

8.2.2 Bond Mechanisms 204

8.3 Common Faults and Troubleshooting 204

8.3.1 The Printer Is Working but Nothing Is Printing 205

8.3.1.1 The Problem—Out of Filament..... 205

8.3.1.2 The Cause 205

8.3.1.3 The Solution..... 205

8.3.2 Nozzle Is Too Close to the Print Bed 205

8.3.2.1 The Problem..... 205

8.3.2.2 The Cause 206

8.3.2.3 The Solution..... 206

8.3.3 Over-Extrusion 206

8.3.3.1 The Problem—Print Looks Droopy
and Stringy..... 206

8.3.3.2 The Cause 207

8.3.3.3 The Solution..... 207

8.3.4 Incomplete and Messy Infill..... 207

8.3.4.1 The Problem..... 207

8.3.4.2 The Cause 208

8.3.4.3 The Solution..... 208

8.3.5 Warping..... 208

8.3.5.1 The Problem—Bending..... 208

8.3.5.2 The Cause 208

8.3.5.3 The Solution..... 208

8.3.6 Messy First Layer..... 209

8.3.6.1 The Problem..... 209

8.3.6.2 The Cause 209

8.3.6.3 The Solution..... 210

8.3.7 Elephant’s Foot..... 210

8.3.7.1 The Problem..... 210

8.3.7.2 The Cause 210

8.3.7.3 The Solution..... 210

8.3.8	Print Looks Deformed and Melted	211
8.3.8.1	The Problem.....	211
8.3.8.2	The Cause	211
8.3.8.3	The Solution.....	211
8.3.9	Snapped Filament.....	211
8.3.9.1	The Problem.....	211
8.3.9.2	The Cause	212
8.3.9.3	The Solution.....	212
8.3.10	Getting Cracks in Tall Objects	213
8.3.10.1	The Problem.....	213
8.3.10.2	The Cause	213
8.3.10.3	The Solution.....	213
8.4	Process Design	213
8.4.1	Creation End Evaluation of Support Structure.....	214
8.4.2	Additive Manufacturing Preparation	214
8.4.3	Validation of Build Time and Cost	215
8.4.4	Additive Manufacturing Simulation.....	215
8.5	Low Cost, Rapid Deployment Wireless Patient Monitoring System Developed with Additive Manufacturing Equipment: Case Study	216
8.5.1	Conclusion	219
8.6	Exercises.....	219
8.7	Multiple-Choice Questions.....	220

Chapter 9	Post-Processing	221
9.1	Introduction	221
9.2	Support Material Removal	221
9.2.1	Natural Support Post-Processing.....	222
9.2.2	Synthetic Support Removal	223
9.2.2.1	Supports Made from the Build Material.....	224
9.2.2.2	Supports Made from Secondary Materials	225
9.3	Surface Texture Improvements.....	226
9.4	Accuracy Improvements.....	226
9.4.1	Sources of Inaccuracy	226
9.4.2	Model Pre-Processing to Compensate for Inaccuracy	227
9.4.3	Machining Strategy	228
9.4.3.1	Adaptive Raster Milling	228
9.4.3.2	Sharp Edge Contour Machining.....	230
9.4.3.3	Hole Drilling.....	232
9.5	Esthetic Improvements	232
9.6	Preparation for Use as a Pattern	233
9.6.1	Investment Casting Patterns	233

9.6.2	Sand Casting Patterns.....	234
9.6.3	Other Pattern Replication Methods.....	235
9.7	Property Enhancements Using Non-Thermal Techniques	236
9.8	Property Enhancements Using Thermal Techniques	237
9.9	Exercises	240
9.10	Multiple-Choice Questions.....	240
Chapter 10	Product Quality	243
10.1	Building the Part	243
10.1.1	Powder Reclamation.....	243
10.2	Post-Processing and Finishing.....	244
10.3	Bulk Deposit Defects.....	247
10.4	Dimensional Accuracy, Shrinkage, and Distortion	254
10.5	Inspection, Quality, and Testing of AM Metal Parts	255
10.5.1	Nondestructive Test Methods.....	255
10.5.2	Destructive Test Methods.....	258
10.5.3	Form, Fit, Function, and Proof Testing	261
10.6	Standards and Certification	262
10.7	Key Takeaway Points.....	264
10.8	Overview of 4D Printing	264
10.8.1	A Definition of 4D Printing.....	264
10.8.1.1	The Difference between 4D and 3D Printing	265
10.8.2	Potential Applications for 4D Printing.....	265
10.9	Exercises.....	265
10.10	Multiple-Choice Questions.....	266
	Interview Preparedness.....	267
	References	275
	Index.....	279