
Contents

| | | |
|----------|---|----------|
| 1 | Introduction and Basic Principles | 1 |
| 1.1 | What Is Additive Manufacturing? | 1 |
| 1.2 | What Are AM Parts Used for? | 3 |
| 1.3 | The Generic AM Process | 4 |
| 1.3.1 | Step 1: CAD | 4 |
| 1.3.2 | Step 2: Conversion to STL | 4 |
| 1.3.3 | Step 3: Transfer to AM Machine and STL File Manipulation | 5 |
| 1.3.4 | Step 4: Machine Setup | 5 |
| 1.3.5 | Step 5: Build | 5 |
| 1.3.6 | Step 6: Removal | 6 |
| 1.3.7 | Step 7: Post-processing | 6 |
| 1.3.8 | Step 8: Application | 6 |
| 1.4 | Why Use the Term Additive Manufacturing? | 7 |
| 1.4.1 | Automated Fabrication (Autofab) | 7 |
| 1.4.2 | Freeform Fabrication or Solid Freeform Fabrication | 7 |
| 1.4.3 | Additive Manufacturing or Layer-Based Manufacturing | 7 |
| 1.4.4 | Stereolithography or 3D Printing | 8 |
| 1.4.5 | Rapid Prototyping | 8 |
| 1.5 | The Benefits of AM | 9 |
| 1.6 | Distinction Between AM and CNC Machining | 10 |
| 1.6.1 | Material | 10 |
| 1.6.2 | Speed | 10 |
| 1.6.3 | Complexity | 11 |
| 1.6.4 | Accuracy | 11 |
| 1.6.5 | Geometry | 12 |
| 1.6.6 | Programming | 12 |
| 1.7 | Example AM Parts | 12 |
| 1.8 | Other Related Technologies | 14 |
| 1.8.1 | Reverse Engineering Technology | 14 |
| 1.8.2 | Computer-Aided Engineering | 15 |

| | | |
|----------|---|-----------|
| 1.8.3 | Haptic-Based CAD | 16 |
| 1.9 | About this Book | 17 |
| 1.10 | Exercises | 17 |
| | References | 18 |
| 2 | Development of Additive Manufacturing Technology | 19 |
| 2.1 | Introduction | 19 |
| 2.2 | Computers | 20 |
| 2.3 | Computer-Aided Design Technology | 22 |
| 2.4 | Other Associated Technologies | 26 |
| 2.4.1 | Lasers | 26 |
| 2.4.2 | Printing Technologies | 26 |
| 2.4.3 | Programmable Logic Controllers | 27 |
| 2.4.4 | Materials | 27 |
| 2.4.5 | Computer Numerically Controlled Machining | 28 |
| 2.5 | The Use of Layers | 28 |
| 2.6 | Classification of AM Processes | 30 |
| 2.6.1 | Liquid Polymer Systems | 31 |
| 2.6.2 | Discrete Particle Systems | 32 |
| 2.6.3 | Molten Material Systems | 33 |
| 2.6.4 | Solid Sheet Systems | 34 |
| 2.6.5 | New AM Classification Schemes | 34 |
| 2.7 | Metal Systems | 35 |
| 2.8 | Hybrid Systems | 36 |
| 2.9 | Milestones in AM Development | 37 |
| 2.10 | AM Around the World | 39 |
| 2.11 | The Future? Rapid Prototyping Develops into Direct Digital Manufacturing | 40 |
| 2.12 | Exercises | 41 |
| | References | 41 |
| 3 | Generalized Additive Manufacturing Process Chain | 43 |
| 3.1 | Introduction | 43 |
| 3.2 | The Eight Steps in Additive Manufacture | 44 |
| 3.2.1 | Step 1: Conceptualization and CAD | 44 |
| 3.2.2 | Step 2: Conversion to STL/AMF | 45 |
| 3.2.3 | Step 3: Transfer to AM Machine and STL File Manipulation | 47 |
| 3.2.4 | Step 4: Machine Setup | 47 |
| 3.2.5 | Step 5: Build | 48 |
| 3.2.6 | Step 6: Removal and Cleanup | 48 |
| 3.2.7 | Step 7: Post-Processing | 49 |
| 3.2.8 | Step 8: Application | 49 |
| 3.3 | Variations from One AM Machine to Another | 50 |
| 3.3.1 | Photopolymer-Based Systems | 51 |

| | | |
|----------|---|-----------|
| 3.3.2 | Powder-Based Systems | 51 |
| 3.3.3 | Molten Material Systems | 51 |
| 3.3.4 | Solid Sheets | 52 |
| 3.4 | Metal Systems | 52 |
| 3.4.1 | The Use of Substrates | 53 |
| 3.4.2 | Energy Density | 53 |
| 3.4.3 | Weight | 53 |
| 3.4.4 | Accuracy | 53 |
| 3.4.5 | Speed | 54 |
| 3.5 | Maintenance of Equipment | 54 |
| 3.6 | Materials Handling Issues | 54 |
| 3.7 | Design for AM | 55 |
| 3.7.1 | Part Orientation | 55 |
| 3.7.2 | Removal of Supports | 56 |
| 3.7.3 | Hollowing Out Parts | 57 |
| 3.7.4 | Inclusion of Undercuts and Other Manufacturing Constraining Features | 57 |
| 3.7.5 | Interlocking Features | 57 |
| 3.7.6 | Reduction of Part Count in an Assembly | 58 |
| 3.7.7 | Identification Markings/Numbers | 58 |
| 3.8 | Application Areas That Don't Involve Conventional CAD Modeling | 59 |
| 3.8.1 | Medical Modeling | 59 |
| 3.8.2 | Reverse Engineering Data | 59 |
| 3.8.3 | Architectural Modeling | 60 |
| 3.9 | Further Discussion | 60 |
| 3.9.1 | Exercises | 61 |
| | References | 61 |
| 4 | Vat Photopolymerization Processes | 63 |
| 4.1 | Introduction | 63 |
| 4.2 | Vat Photopolymerization Materials | 65 |
| 4.2.1 | UV-Curable Photopolymers | 66 |
| 4.2.2 | Overview of Photopolymer Chemistry | 67 |
| 4.2.3 | Resin Formulations and Reaction Mechanisms | 70 |
| 4.3 | Reaction Rates | 73 |
| 4.4 | Laser Scan Vat Photopolymerization | 74 |
| 4.5 | Photopolymerization Process Modeling | 74 |
| 4.5.1 | Irradiance and Exposure | 75 |
| 4.5.2 | Laser-Resin Interaction | 78 |
| 4.5.3 | Photospeed | 80 |
| 4.5.4 | Time Scales | 81 |
| 4.6 | Vector Scan VP Machines | 82 |
| 4.7 | Scan Patterns | 84 |
| 4.7.1 | Layer-Based Build Phenomena and Errors | 84 |

| | | |
|----------|--|------------|
| 4.7.2 | WEAVE | 86 |
| 4.7.3 | STAR-WEAVE | 88 |
| 4.7.4 | ACES Scan Pattern | 90 |
| 4.8 | Vector Scan Micro-Vat Photopolymerization | 94 |
| 4.9 | Mask Projection VP Technologies and Processes | 95 |
| 4.9.1 | Mask Projection VP Technology | 95 |
| 4.9.2 | Commercial MPVP Systems | 96 |
| 4.9.3 | MPVP Modeling | 98 |
| 4.10 | Two-Photon Vat Photopolymerization | 99 |
| 4.11 | Process Benefits and Drawbacks | 101 |
| 4.12 | Summary | 102 |
| 4.13 | Exercises | 102 |
| | References | 103 |
| 5 | Powder Bed Fusion Processes | 107 |
| 5.1 | Introduction | 107 |
| 5.2 | Materials | 109 |
| 5.2.1 | Polymers and Composites | 109 |
| 5.2.2 | Metals and Composites | 110 |
| 5.2.3 | Ceramics and Ceramic Composites | 112 |
| 5.3 | Powder Fusion Mechanisms | 112 |
| 5.3.1 | Solid-State Sintering | 112 |
| 5.3.2 | Chemically Induced Sintering | 115 |
| 5.3.3 | LPS and Partial Melting | 116 |
| 5.3.4 | Full Melting | 120 |
| 5.3.5 | Part Fabrication | 121 |
| 5.4 | Process Parameters and Modeling | 122 |
| 5.4.1 | Process Parameters | 123 |
| 5.4.2 | Applied Energy Correlations and Scan Patterns | 125 |
| 5.5 | Powder Handling | 127 |
| 5.5.1 | Powder Handling Challenges | 127 |
| 5.5.2 | Powder Handling Systems | 128 |
| 5.5.3 | Powder Recycling | 129 |
| 5.6 | PBF Process Variants and Commercial Machines | 131 |
| 5.6.1 | Polymer Laser Sintering | 131 |
| 5.6.2 | Laser-Based Systems for Metals and Ceramics | 134 |
| 5.6.3 | Electron Beam Melting | 136 |
| 5.6.4 | Line-Wise and Layer-Wise PBF Processes for Polymers | 140 |
| 5.7 | Process Benefits and Drawbacks | 143 |
| 5.8 | Conclusions | 144 |
| 5.9 | Exercises | 144 |
| | References | 145 |

| | | |
|----------|---|-----|
| 6 | Extrusion-Based Systems | 147 |
| 6.1 | Introduction | 147 |
| 6.2 | Basic Principles | 148 |
| 6.2.1 | Material Loading | 149 |
| 6.2.2 | Liquification | 149 |
| 6.2.3 | Extrusion | 149 |
| 6.2.4 | Solidification | 153 |
| 6.2.5 | Positional Control | 154 |
| 6.2.6 | Bonding | 155 |
| 6.2.7 | Support Generation | 156 |
| 6.3 | Plotting and Path Control | 157 |
| 6.4 | Fused Deposition Modeling from Stratasys | 160 |
| 6.4.1 | FDM Machine Types | 161 |
| 6.5 | Materials | 163 |
| 6.6 | Limitations of FDM | 164 |
| 6.7 | Bioextrusion | 166 |
| 6.7.1 | Gel Formation | 166 |
| 6.7.2 | Melt Extrusion | 166 |
| 6.7.3 | Scaffold Architectures | 168 |
| 6.8 | Other Systems | 168 |
| 6.8.1 | Contour Crafting | 169 |
| 6.8.2 | Nonplanar Systems | 169 |
| 6.8.3 | FDM of Ceramics | 171 |
| 6.8.4 | Reprap and Fab@home | 171 |
| 6.9 | Exercises | 172 |
| | References | 173 |
| 7 | Material Jetting | 175 |
| 7.1 | Evolution of Printing as an Additive Manufacturing Process | 175 |
| 7.2 | Materials for Material Jetting | 176 |
| 7.2.1 | Polymers | 177 |
| 7.2.2 | Ceramics | 180 |
| 7.2.3 | Metals | 181 |
| 7.2.4 | Solution- and Dispersion-Based Deposition | 183 |
| 7.3 | Material Processing Fundamentals | 184 |
| 7.3.1 | Technical Challenges of MJ | 184 |
| 7.3.2 | Droplet Formation Technologies | 186 |
| 7.3.3 | Continuous Mode | 187 |
| 7.3.4 | DOD Mode | 188 |
| 7.3.5 | Other Droplet Formation Methods | 190 |
| 7.4 | MJ Process Modeling | 191 |
| 7.5 | Material Jetting Machines | 195 |
| 7.6 | Process Benefits and Drawbacks | 198 |
| 7.7 | Summary | 198 |
| 7.8 | Exercises | 199 |
| | References | 200 |

| | | |
|-----------|---|-----|
| 8 | Binder Jetting | 205 |
| 8.1 | Introduction | 205 |
| 8.2 | Materials | 207 |
| | 8.2.1 Commercially Available Materials | 207 |
| | 8.2.2 Ceramic Materials in Research | 208 |
| 8.3 | Process Variations | 210 |
| 8.4 | BJ Machines | 212 |
| 8.5 | Process Benefits and Drawbacks | 216 |
| 8.6 | Summary | 217 |
| 8.7 | Exercises | 217 |
| | References | 218 |
| 9 | Sheet Lamination Processes | 219 |
| 9.1 | Introduction | 219 |
| | 9.1.1 Gluing or Adhesive Bonding | 219 |
| | 9.1.2 Bond-Then-Form Processes | 220 |
| | 9.1.3 Form-Then-Bond Processes | 222 |
| 9.2 | Materials | 224 |
| 9.3 | Material Processing Fundamentals | 225 |
| | 9.3.1 Thermal Bonding | 226 |
| | 9.3.2 Sheet Metal Clamping | 227 |
| 9.4 | Ultrasonic Additive Manufacturing | 228 |
| | 9.4.1 UAM Bond Quality | 229 |
| | 9.4.2 Ultrasonic Metal Welding Process Fundamentals | 230 |
| | 9.4.3 UAM Process Parameters and Process Optimization | 233 |
| | 9.4.4 Microstructures and Mechanical Properties of UAM Parts | 235 |
| | 9.4.5 UAM Applications | 239 |
| 9.5 | Conclusions | 242 |
| 9.6 | Exercises | 243 |
| | References | 243 |
| 10 | Directed Energy Deposition Processes | 245 |
| 10.1 | Introduction | 245 |
| 10.2 | General DED Process Description | 247 |
| 10.3 | Material Delivery | 249 |
| | 10.3.1 Powder Feeding | 249 |
| | 10.3.2 Wire Feeding | 251 |
| 10.4 | DED Systems | 252 |
| | 10.4.1 Laser Based Metal Deposition Processes | 252 |
| | 10.4.2 Electron Beam Based Metal Deposition Processes | 256 |
| | 10.4.3 Other DED Processes | 257 |
| 10.5 | Process Parameters | 257 |
| 10.6 | Typical Materials and Microstructure | 258 |

| | | |
|-----------|--|------------|
| 10.7 | Processing–Structure–Properties Relationships | 261 |
| 10.8 | DED Benefits and Drawbacks | 266 |
| 10.9 | Exercises | 267 |
| | References | 268 |
| 11 | Direct Write Technologies | 269 |
| 11.1 | Direct Write Technologies | 269 |
| 11.2 | Background | 269 |
| 11.3 | Ink-Based DW | 270 |
| | 11.3.1 Nozzle Dispensing Processes | 271 |
| | 11.3.2 Quill-Type Processes | 273 |
| | 11.3.3 Inkjet Printing Processes | 275 |
| | 11.3.4 Aerosol DW | 276 |
| 11.4 | Laser Transfer DW | 277 |
| 11.5 | Thermal Spray DW | 280 |
| 11.6 | Beam Deposition DW | 282 |
| | 11.6.1 Laser CVD | 282 |
| | 11.6.2 Focused Ion Beam CVD | 284 |
| | 11.6.3 Electron Beam CVD | 284 |
| 11.7 | Liquid-Phase Direct Deposition | 285 |
| 11.8 | Beam Tracing Approaches to Additive/Subtractive DW | 286 |
| | 11.8.1 Electron Beam Tracing | 286 |
| | 11.8.2 Focused Ion Beam Tracing | 287 |
| | 11.8.3 Laser Beam Tracing | 287 |
| 11.9 | Hybrid Technologies | 287 |
| 11.10 | Applications of Direct Write Technologies | 288 |
| | 11.10.1 Exercises | 290 |
| | References | 290 |
| 12 | The Impact of Low-Cost AM Systems | 293 |
| 12.1 | Introduction | 293 |
| 12.2 | Intellectual Property | 294 |
| 12.3 | Disruptive Innovation | 296 |
| | 12.3.1 Disruptive Business Opportunities | 296 |
| | 12.3.2 Media Attention | 297 |
| 12.4 | The Maker Movement | 299 |
| 12.5 | The Future of Low-Cost AM | 301 |
| 12.6 | Exercises | 301 |
| | References | 301 |
| 13 | Guidelines for Process Selection | 303 |
| 13.1 | Introduction | 303 |
| 13.2 | Selection Methods for a Part | 304 |
| | 13.2.1 Decision Theory | 304 |
| | 13.2.2 Approaches to Determining Feasibility | 305 |
| | 13.2.3 Approaches to Selection | 307 |
| | 13.2.4 Selection Example | 310 |

| | | |
|-----------|---|------------|
| 13.3 | Challenges of Selection | 312 |
| 13.4 | Example System for Preliminary Selection | 316 |
| 13.5 | Production Planning and Control | 321 |
| | 13.5.1 Production Planning | 322 |
| | 13.5.2 Pre-processing | 323 |
| | 13.5.3 Part Build | 323 |
| | 13.5.4 Post-processing | 324 |
| | 13.5.5 Summary | 324 |
| 13.6 | Open Problems | 325 |
| 13.7 | Exercises | 326 |
| | References | 326 |
| 14 | Post-processing | 329 |
| 14.1 | Introduction | 329 |
| 14.2 | Support Material Removal | 329 |
| | 14.2.1 Natural Support Post-processing | 330 |
| | 14.2.2 Synthetic Support Removal | 331 |
| 14.3 | Surface Texture Improvements | 334 |
| 14.4 | Accuracy Improvements | 334 |
| | 14.4.1 Sources of Inaccuracy | 335 |
| | 14.4.2 Model Pre-processing to Compensate for Inaccuracy | 335 |
| | 14.4.3 Machining Strategy | 337 |
| 14.5 | Aesthetic Improvements | 341 |
| 14.6 | Preparation for Use as a Pattern | 342 |
| | 14.6.1 Investment Casting Patterns | 342 |
| | 14.6.2 Sand Casting Patterns | 343 |
| | 14.6.3 Other Pattern Replication Methods | 344 |
| 14.7 | Property Enhancements Using Non-thermal Techniques | 345 |
| 14.8 | Property Enhancements Using Thermal Techniques | 346 |
| 14.9 | Conclusions | 349 |
| 14.10 | Exercises | 349 |
| | References | 350 |
| 15 | Software Issues for Additive Manufacturing | 351 |
| 15.1 | Introduction | 351 |
| 15.2 | Preparation of CAD Models: The STL File | 352 |
| | 15.2.1 STL File Format, Binary/ASCII | 352 |
| | 15.2.2 Creating STL Files from a CAD System | 354 |
| | 15.2.3 Calculation of Each Slice Profile | 355 |
| | 15.2.4 Technology-Specific Elements | 359 |
| 15.3 | Problems with STL Files | 361 |
| 15.4 | STL File Manipulation | 364 |
| | 15.4.1 Viewers | 365 |
| | 15.4.2 STL Manipulation on the AM Machine | 365 |

| | | |
|-----------|---|------------|
| 15.5 | Beyond the STL File | 367 |
| 15.5.1 | Direct Slicing of the CAD Model | 367 |
| 15.5.2 | Color Models | 368 |
| 15.5.3 | Multiple Materials | 368 |
| 15.5.4 | Use of STL for Machining | 368 |
| 15.6 | Additional Software to Assist AM | 369 |
| 15.6.1 | Survey of Software Functions | 370 |
| 15.6.2 | AM Process Simulations Using Finite Element Analysis | 371 |
| 15.7 | The Additive Manufacturing File Format | 372 |
| 15.8 | Exercises | 373 |
| | References | 374 |
| 16 | Direct Digital Manufacturing | 375 |
| 16.1 | Align Technology | 375 |
| 16.2 | Siemens and Phonak | 377 |
| 16.3 | Custom Footwear and Other DDM Examples | 380 |
| 16.4 | DDM Drivers | 383 |
| 16.5 | Manufacturing Versus Prototyping | 385 |
| 16.6 | Cost Estimation | 387 |
| 16.6.1 | Cost Model | 387 |
| 16.6.2 | Build Time Model | 389 |
| 16.6.3 | Laser Scanning Vat Photopolymerization Example | 392 |
| 16.7 | Life-Cycle Costing | 393 |
| 16.8 | Future of DDM | 395 |
| 16.9 | Exercises | 396 |
| | References | 397 |
| 17 | Design for Additive Manufacturing | 399 |
| 17.1 | Motivation | 400 |
| 17.2 | Design for Manufacturing and Assembly | 401 |
| 17.3 | AM Unique Capabilities | 404 |
| 17.3.1 | Shape Complexity | 404 |
| 17.3.2 | Hierarchical Complexity | 405 |
| 17.3.3 | Functional Complexity | 407 |
| 17.3.4 | Material Complexity | 409 |
| 17.4 | Core DFAM Concepts and Objectives | 411 |
| 17.4.1 | Complex Geometry | 411 |
| 17.4.2 | Integrated Assemblies | 412 |
| 17.4.3 | Customized Geometry | 412 |
| 17.4.4 | Multifunctional Designs | 412 |
| 17.4.5 | Elimination of Conventional DFM Constraints | 413 |

| | | |
|-----------|---|------------|
| 17.5 | Exploring Design Freedoms | 413 |
| 17.5.1 | Part Consolidation and Redesign | 414 |
| 17.5.2 | Hierarchical Structures | 415 |
| 17.5.3 | Industrial Design Applications | 417 |
| 17.6 | CAD Tools for AM | 418 |
| 17.6.1 | Challenges for CAD | 418 |
| 17.6.2 | Solid-Modeling CAD Systems | 420 |
| 17.6.3 | Promising CAD Technologies | 422 |
| 17.7 | Synthesis Methods | 426 |
| 17.7.1 | Theoretically Optimal Lightweight Structures | 426 |
| 17.7.2 | Optimization Methods | 427 |
| 17.7.3 | Topology Optimization | 428 |
| 17.8 | Summary | 433 |
| 17.9 | Exercises | 434 |
| | References | 434 |
| 18 | Rapid Tooling | 437 |
| 18.1 | Introduction | 437 |
| 18.2 | Direct AM Production of Injection Molding Inserts | 439 |
| 18.3 | EDM Electrodes | 443 |
| 18.4 | Investment Casting | 444 |
| 18.5 | Other Systems | 445 |
| 18.5.1 | Vacuum Forming Tools | 445 |
| 18.5.2 | Paper Pulp Molding Tools | 446 |
| 18.5.3 | Formwork for Composite Manufacture | 446 |
| 18.5.4 | Assembly Tools and Metrology Registration Rigs | 446 |
| 18.6 | Exercises | 448 |
| | References | 448 |
| 19 | Applications for Additive Manufacture | 451 |
| 19.1 | Introduction | 451 |
| 19.2 | Historical Developments | 452 |
| 19.2.1 | Value of Physical Models | 453 |
| 19.2.2 | Functional Testing | 453 |
| 19.2.3 | Rapid Tooling | 454 |
| 19.3 | The Use of AM to Support Medical Applications | 455 |
| 19.3.1 | Surgical and Diagnostic Aids | 457 |
| 19.3.2 | Prosthetics Development | 458 |
| 19.3.3 | Manufacturing | 460 |
| 19.3.4 | Tissue Engineering and Organ Printing | 460 |
| 19.4 | Software Support for Medical Applications | 461 |

| | | |
|-----------|---|------------|
| 19.5 | Limitations of AM for Medical Applications | 463 |
| 19.5.1 | Speed | 464 |
| 19.5.2 | Cost | 464 |
| 19.5.3 | Accuracy | 465 |
| 19.5.4 | Materials | 465 |
| 19.5.5 | Ease of Use | 466 |
| 19.6 | Further Development of Medical AM Applications | 466 |
| 19.6.1 | Approvals | 466 |
| 19.6.2 | Insurance | 467 |
| 19.6.3 | Engineering Training | 467 |
| 19.6.4 | Location of the Technology | 468 |
| 19.6.5 | Service Bureaus | 468 |
| 19.7 | Aerospace Applications | 468 |
| 19.7.1 | Characteristics Favoring AM | 469 |
| 19.7.2 | Production Manufacture | 469 |
| 19.8 | Automotive Applications | 472 |
| 19.9 | Exercises | 473 |
| | References | 474 |
| 20 | Business Opportunities and Future Directions | 475 |
| 20.1 | Introduction | 475 |
| 20.2 | What Could Be New? | 477 |
| 20.2.1 | New Types of Products | 477 |
| 20.2.2 | New Types of Organizations | 479 |
| 20.2.3 | New Types of Employment | 480 |
| 20.3 | Digiproneurship | 481 |
| 20.4 | Exercises | 485 |
| | References | 486 |
| | Index | 487 |



<http://www.springer.com/978-1-4939-2112-6>

Additive Manufacturing Technologies
3D Printing, Rapid Prototyping, and Direct Digital
Manufacturing

Gibson, I.; Rosen, D.; Stucker, B.

2015, XXI, 498 p. 224 illus., 108 illus. in color.,

Hardcover

ISBN: 978-1-4939-2112-6