Additive Manufacturing Technologies

Ian Gibson • David Rosen • Brent Stucker

Additive Manufacturing Technologies

3D Printing, Rapid Prototyping, and Direct Digital Manufacturing

Second Edition

Springer

Ian Gibson
School of Engineering
Deakin University
Victoria, Australia

David Rosen
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA USA

Brent Stucker
Department of Industrial Engineering, J B Speed
University of Louisville
Louisville, KY USA

ISBN 978-1-4939-2112-6 ISBN 978-1-4939-2113-3 (eBook)
DOI 10.1007/978-1-4939-2113-3
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2014953293

© Springer Science+Business Media New York 2010, 2015
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Thank you for taking the time to read this book on Additive Manufacturing (AM). We hope you benefit from the time and effort it has taken putting it together and that you think it was a worthwhile undertaking. It all started as a discussion at a conference in Portugal when we realized that we were putting together books with similar aims and objectives. Since we are friends as well as colleagues, it seemed sensible that we join forces rather than compete; sharing the load and playing to each other's strengths undoubtedly means a better all-round effort and result.

We wrote this book because we have all been working in the field of AM for many years. Although none of us like to be called "old," we do seem to have 60 years of experience, collectively, and have each established reputations as educators and researchers in this field. We have each seen the technologies described in this book take shape and develop into serious commercial tools, with tens of thousands of users and many millions of parts being made by AM machines each year. AM is now being incorporated into curricula in many schools, polytechnics, and universities around the world. More and more students are becoming aware of these technologies and yet, as we saw it, there was no single text adequate for such curricula. We believe that the first edition of this book provided such a text, and based upon the updated information in this 2nd edition, we hope we've improved upon that start.

Additive Manufacturing is defined by a range of technologies that are capable of translating virtual solid model data into physical models in a quick and easy process. The data are broken down into a series of 2D cross-sections of a finite thickness. These cross-sections are fed into AM machines so that they can be combined, adding them together in a layer-by-layer sequence to form the physical part. The geometry of the part is therefore clearly reproduced in the AM machine without having to adjust for manufacturing processes, like attention to tooling, undercuts, draft angles, or other features. We can say therefore that the AM machine is a What You See Is What You Build (WYSIWYB) process that is particularly valuable the more complex the geometry is. This basic principle drives nearly all AM machines, with variations in each technology in terms of the techniques used for creating layers and in bonding them together. Further variations

include speed, layer thickness, range of materials, accuracy, and of course cost. With so many variables, it is clear to see why this book must be so long and detailed. Having said that, we still feel there is much more we could have written about.

The first three chapters of this book provide a basic overview of AM processes. Without fully describing each technology, we provide an appreciation for why AM is so important to many branches of industry. We outline the rapid development of this technology from humble beginnings that showed promise but still requiring much development, to one that is now maturing and showing real benefit to product development organizations. In reading these chapters, we hope you can learn the basics of how AM works.

The next nine chapters (Chaps. 4–12) take each group of technologies in turn and describe them in detail. The fundamentals of each technology are dealt with in terms of the basic process, whether it involves photopolymer curing, sintering, melting, etc., so that the reader can appreciate what is needed in order to understand, develop, and optimize each technology. Most technologies discussed in this book have been commercialized by at least one company; and these machines are described along with discussion on how to get the best out of them. The last chapter in this group focused on inexpensive processes and machines, which overlaps some of the material in earlier chapters, but we felt that the exponentially increasing interest in these low-cost machines justified the special treatment.

The final chapters deal with how to apply AM technology in different settings. Firstly, we look at selection methods for sorting through the many options concerning the type of machine you should buy in relation to your application and provide guidelines on how to select the right technology for your purpose. Since all AM machines depend on input from 3D CAD software, we go on to discuss how this process takes place. We follow this with a discussion of post-processing methods and technologies so that if your selected machine and material cannot produce exactly what you want, you have the means for improving the part's properties and appearance. A chapter on software issues in AM completes this group of chapters.

AM technologies have improved to the extent that many manufacturers are using AM machine output for end-product use. Called Direct Digital Manufacturing, this opens the door to many exciting and novel applications considered impossible, infeasible, or uneconomic in the past. We can now consider the possibility of mass customization, where a product can be produced according to the tastes of an individual consumer but at a cost-effective price. Then, we look at how the use of this technology has affected the design process considering how we might improve our designs because of the WYSIWYB approach. This moves us on nicely to the subjects of applications of AM, including tooling and products in the medical, aerospace, and automotive industries. We complete the book with a chapter on the business, or enterprise-level, aspects of AM, investigating how these systems

enable creative businesses and entrepreneurs to invent new products, and where AM will likely develop in the future.

This book is primarily aimed at students and educators studying Additive Manufacturing, either as a self-contained course or as a module within a larger course on manufacturing technology. There is sufficient depth for an undergraduate or graduate-level course, with many references to point the student further along the path. Each chapter also has a number of exercise questions designed to test the reader's knowledge and to expand their thinking. A companion instructor's guide is being developed as part of the 2nd edition to include additional exercises and their solutions, to aid educators. Researchers into AM may also find this text useful in helping them understand the state of the art and the opportunities for further research.

We have made a wide range of changes in moving from the first edition, completed in 2009, to this new edition. As well as bringing everything as up to date as is possible in this rapidly changing field, we have added in a number of new sections and chapters. The chapter on medical applications has been extended to include discussion on automotive and aerospace. There is a new chapter on rapid tooling as well as one that discusses the recent movements in the low-cost AM sector. We have inserted a range of recent technological innovations, including discussion on the new Additive Manufacturing File Format as well as other inclusions surrounding the standardization of AM with ASTM and ISO. We have also updated the terminology in the text to conform to terminology developed by the ASTM F42 committee, which has also been adopted as an ISO international standard. In this 2nd edition we have edited the text to, as much as possible, remove references to company-specific technologies and instead focus more on technological principles and general understanding. We split the original chapter on printing processes into two chapters on material jetting and on binder jetting to reflect the standard terminology and the evolution of these processes in different directions. As a result of these many additions and changes, we feel that this edition is now significantly more comprehensive than the first one.

Although we have worked hard to make this book as comprehensive as possible, we recognize that a book about such rapidly changing technology will not be up-to-date for very long. With this in mind, and to help educators and students better utilize this book, we will update our course website at http://www.springer.com/978-1-4419-1119-3, with additional homework exercises and other aids for educators. If you have comments, questions, or suggestions for improvement, they are welcome. We anticipate updating this book in the future, and we look forward to hearing how you have used these materials and how we might improve this book.

As mentioned earlier, each author is an established expert in Additive Manufacturing with many years of research experience. In addition, in many ways, this book is only possible due to the many students and colleagues with whom we have collaborated over the years. To introduce you to the authors and some of the others who have made this book possible, we will end this preface with brief author biographies and acknowledgements.

Singapore, Singapore — Ian Gibson
Atlanta, GA, USA — David Rosen
Louisville, KY, USA — Brent Stucker

Acknowledgements

Dr. Brent Stucker thanks Utah State and VTT Technical Research Center of Finland, which provided time to work on the first edition of this book while on sabbatical in Helsinki; and more recently the University of Louisville for providing the academic freedom and environment needed to complete the 2nd edition. Additionally, much of this book would not have been possible without the many graduate students and postdoctoral researchers who have worked with Dr. Stucker over the years. In particular, he would like to thank Dr. G.D. Janaki Ram of the Indian Institute of Technology Madras, whose coauthoring of the "Layer-Based Additive Manufacturing Technologies" chapter in the *CRC Materials Processing Handbook* helped lead to the organization of this book. Additionally, the following students' work led to one or more things mentioned in this book and in the accompanying solution manual: Muni Malhotra, Xiuzhi Qu, Carson Esplin, Adam Smith, Joshua George, Christopher Robinson, Yanzhe Yang, Matthew Swank, John Obielodan, Kai Zeng, Haijun Gong, Xiaodong Xing, Hengfeng Gu, Md. Anam, Nachiket Patil, and Deepankar Pal. Special thanks are due to Dr. Stucker's wife Gail, and their children: Tristie, Andrew, Megan, and Emma, who patiently supported many days and evenings on this book.

Prof. David W. Rosen acknowledges support from Georgia Tech and the many graduate students and postdocs who contributed technically to the content in this book. In particular, he thanks Drs. Fei Ding, Amit Jariwala, Scott Johnston, Ameya Limaye, J. Mark Meacham, Benay Sager, L. Angela Tse, Hongqing Wang, Chris Williams, Yong Yang, and Wenchao Zhou, as well as Lauren Margolin and Xiayun Zhao. A special thanks goes out to his wife Joan and children Erik and Krista for their patience while he worked on this book.

Prof. Ian Gibson would like to acknowledge the support of Deakin University in providing sufficient time for him to work on this book. L.K. Anand also helped in preparing many of the drawings and images for his chapters. Finally, he wishes to thank his lovely wife, Lina, for her patience, love, and understanding during the long hours preparing the material and writing the chapters. He also dedicates this book to his late father, Robert Ervin Gibson, and hopes he would be proud of this wonderful achievement.

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

Erratum . . . E1

Index . . . 487