Additive Manufacturing Technologies

I. Gibson • D. W. Rosen • B. Stucker

Additive Manufacturing Technologies

Rapid Prototyping to Direct Digital Manufacturing

Springer

Dr. Ian Gibson
Department of Mechanical & Production Engineering
National University of Singapore
9 Engineering Drive 1
Singapore 117576
Singapore
mpegi@nus.edu.sg

Dr. David W. Rosen
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
813 Ferst Drive, N.W.
Atlanta, GA 30332-0405
USA
david.rosen@me.gatech.edu

Dr. Brent Stucker
Department of Mechanical & Aerospace Engineering
Utah State University
4130 Old Main Hall
Logan, UT 84322
USA
brent.stucker@usu.edu

ISBN: 978-1-4419-1119-3 e-ISBN: 978-1-4419-1120-9
DOI 10.1007/978-1-4419-1120-9
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2009934499

Cover design: The Cover Artwork is Courtesy of Bathsheba Grossman and Bathsheba Sculpture LLC

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 others' 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 decades 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 see it, there is no single text adequate for such curricula. We hope that now, with this book, there is.

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 is 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 seven chapters (Chaps. 4–10) 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 is 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 final chapters deal with how to apply AM technology in different settings. Firstly, 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. Having said that, there are many options concerning the type of machine you should buy in relation to your application, so we 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.

These 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. This moves us on nicely to the subject of medical products made using AM where each part can be created according to an individual patient's data. Then we go on to discuss how to finish parts once they come off the AM machine so that they can best suit the final application. We complete the book with chapters on emerging areas of AM, with discussions on multiple material and embedded systems, 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. Researchers into AM may also find this text useful in helping them understand the state of the art and the opportunities for further research.

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.

Author Biographies

Dr. Brent Stucker is an Associate Professor of Mechanical & Aerospace Engineering at Utah State University. After receiving his Ph.D. from Texas A&M University in 1997, he joined the Industrial & Manufacturing Engineering faculty of the University of Rhode Island, where he established the Rapid Manufacturing Center. In 2002, he moved to Utah State, where he established and continues to lead the Additive Manufacturing Laboratory. Dr. Stucker has taught courses on AM technologies for more than 10 years, sits on the Rapid Technologies & Additive Manufacturing Steering Committee for the Society of Manufacturing Engineers, was a Selective Laser Sintering Users Group 2005 "Dinosaur Award" recipient, and is the current Chairman of ASTM International's Committee F42 on Additive Manufacturing Technologies. His research focuses on metal AM, including Ultrasonic Consolidation, Direct Write, Laser Engineered Net Shaping, Selective Laser Sintering, and their applications.

Prof. David W. Rosen is a Professor in the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology. After receiving his Ph.D. from the University of Massachusetts in 1992, he joined the faculty at Georgia Tech. In 1995, the Rapid Prototyping & Manufacturing Institute was started at Georgia Tech through an ARPA manufacturing education grant and Dr. Rosen was asked to become its head. Since then, he has led the additive manufacturing research and education program at Georgia Tech. He is active in the Society of Manufacturing Engineers Direct Digital Manufacturing Tech Group and the 3D Systems User Group conference. His research focuses on photopolymer processing, ink-jet printing, and design for additive manufacturing.

Dr. Ian Gibson is an Associate Professor at the National University of Singapore (NUS). Originally from Scotland, he moved to England where he gained a Ph.D. in robotics at Hull University. His teaching career started at Nottingham University, where he specialized in advanced manufacturing technology and first came to learn about the AM technology that was then called Rapid Prototyping.

In 1994, he moved to Hong Kong, where he helped establish the technology in Asia, started the Rapid Prototyping Journal and the Global Alliance of Rapid Prototyping Associations. In 2005, he joined NUS, where he concentrates mostly on medical applications and direct digital manufacturing.

Acknowledgement

Dr. Brent Stucker thanks Utah State and VTT Technical Research Center of Finland, which provided time to work on this book while on sabbatical in Helsinki. Additionally, much of this book would not have been possible without the many graduate students and post-doctoral 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 co-authoring 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: Muni Malhotra, Xiuzhi Qu, Carson Esplin, Adam Smith, Joshua George, Christopher Robinson, Yanzhe Yang, Matthew Swank and John Obielodan. 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. Lastly, as the right atmosphere helps stir the creative juices, Dr. Stucker appreciates the many hours he could spend at Café Carusel in Helsinki, Finland (which he highly recommends to anyone passing through).

Prof. David W. Rosen acknowledges support from Georgia Tech and the many graduate students and post-docs who contributed technically to the content in this book. In particular, he thanks Drs. Fei Ding, Scott Johnston, Ameya Limaye, J. Mark Meacham, Benay Sager, L. Angela Tse, Sanjay Vohra, Hongqing Wang, Chris Williams, and Yong Yang, as well as Patrick Chang, Jane (Chen) Chu, Sarah Engelbrecht, Greg Graf, Amit Jariwala, 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.

Dr. Ian Gibson would like to acknowledge the support of NUS 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 father, Robert Ervin Gibson, and hopes he is proud of this wonderful achievement.

Contents