# Additive Manufacturing Technologies

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Third Edition

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# Abstract

Thank you for taking the time to read this textbook 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 we were putting together books with similar aims and objectives. Since we are friends as well as colleagues, it seemed sensible 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 textbook 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 around 85 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 textbook take shape and develop into serious commercial tools, with hundreds of thousands of regular 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. 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 provided such a text, and based upon updated information, the 2nd and 3rd editions were developed.

Additive Manufacturing includes a range of technologies that are capable of translating virtual solid model data into physical models in an automated process. The data are broken down into a series of 2D cross-sections of finite thickness. These cross-sections are fed into AM machines so that they can be created, combined, and added together in a layer-by-layer sequence to form the physical part. The geometry of the digital part is therefore reproduced physically in the AM machine without having to adjust for manufacturing processes, like attention to tooling, undercuts, draft angles, or other features. We can therefore say that the AM machine is a What You See Is What You Build (WYSIWYB) process that is particularly valuable the more complex the geometry. This basic principle drives nearly all AM machines, with variations in each technology in terms of the techniques used for creating layers and 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 textbook must be so long and detailed. Having said that, we still feel there is much more we could have written.

The first three chapters of this textbook 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, which showed promise but still required much development, to one that is now maturing and showing a real benefit to product development organizations. By reading these chapters, we hope you can learn the basics of how AM works.

The next eight chapters (Chaps. 4, 5, 6, 7, 8, 9, 10 and 11) 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, inkjet printing, sintering, melting, etc., so that the reader can appreciate what is needed in order to understand, develop, optimize, and use each technology. Most technologies discussed in this textbook have been commercialized by at least one company, and many of these commercial variants are described along with discussion on how to get the best out of them.

The next two chapters are about hybrid AM (the mix of AM and other manufacturing processes in a single machine) and low-cost AM techniques. The low-cost AM chapter focuses on inexpensive machines, which overlaps some of the material in earlier chapters. However, we felt that the increasing interest in these low-cost machines justified the special treatment.

The final nine chapters deal with how to apply AM technology in different settings. We look at the materials available for AM and the post-processing you need to perform after removing a part from the machine, before it can be used. We provide selection methods for sorting through the many machine options. Since all AM machines depend on input from 3D CAD software, we go on to discuss how software is used. We follow this with a discussion of novel applications which utilize AM machine output for end-product use, called Direct Digital Manufacturing. Many of these products were impossible, infeasible, or uneconomic in the past, including mass customization, where a product can be produced according to the tastes of an individual consumer but at a cost-effective price. Next we look at how AM affects the design process, considering how we might improve designs to take advantage of unique benefits of AM. This moves us on nicely to the subjects of applications of AM, including tooling and products in the medical, aerospace, and automotive sectors. We complete the textbook with a chapter on the business and societal implications of AM, investigating how AM enables creative businesses and entrepreneurs to invent new products.

This textbook is primarily aimed at students and educators studying AM, 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 3rd edition. Researchers into AM may also find this text useful in helping them

understand the state of the art and the opportunities for further research. AM industry practitioners will also find this textbook useful as they guide their companies in adopting AM.

We made a wide range of changes in moving from the first edition, completed in 2009, to the 2nd edition published in 2015. We added a number of new sections and chapters, including expanding the chapter on medical applications to include discussion on automotive and aerospace applications. A new chapter on rapid tooling was also added in the 2nd edition.

Between the 1st and 2nd editions, the authors helped establish the ASTM F42 and ISO TC261 committees on Additive Manufacturing. These committees developed standard terminology for AM, and the 2nd edition used this updated terminology. In the 2nd edition, we also edited the text to reduce references to company-specific technologies and instead focused 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. We inserted a range of recent technological innovations, including discussion on the Additive Manufacturing File format. As a result of these many additions and changes, we believe the 2nd edition was significantly more comprehensive than the first. The response to this 2nd edition was positive, as sales increased by almost 40% 2 years after publishing, and by 2019 this book was firmly established as the leading AM textbook worldwide.

To keep up with the extensive growth of AM since 2015, we decided to publish a 3rd edition. This took nearly 2 years of effort with a new co-author added to the list. Older examples of vat photopolymerization, material jetting, and binder jetting machines were replaced by newer technologies and applications. New variants of existing AM techniques, such as high-speed sintering, multi-material jetting, cold spray, friction stir AM, and more, were added to relevant chapters. We continue to update our materials to conform to international standards, including ASTM 52900 terminology. To help our readers understand how new terminology relates to older company-specific and technology-specific names, we have added information to Chaps. 5 and 10 cross-referencing nomenclature for AM processes to help address any confusion.

Approximately 200 figures have been redrawn to improve understanding of the contents. We have significantly expanded our discussion of post-processing methods to improve surface quality, dimensional accuracy, and mechanical properties. We provide a better classification for different AM-related software. New topics like the influence of AM within Industry 4.0, design for 4D printing, and a discussion of design of experiments have also been added.

Hybrid AM techniques and materials for AM have expanded dramatically since the 2nd edition, so we significantly expanded our treatment of these topics, resulting in two new chapters. Hybrid AM is a combination of additive and conventional manufacturing into a single process, resulting in significantly improved capabilities. In the new chapter on materials, we classify the feedstock based on the physical state of the material when added to the machine, including liquid, powder, and solid

states. This new chapter should help students, researchers, and professionals select a suitable machine/material combination for their research and businesses.

We are currently working on online supplementary information for this textbook. In particular, we hope to publish a solutions manual soon. Please check online for its availability.

Although we have worked hard to make this textbook as comprehensive as possible, we recognize that a textbook about such rapidly changing technology will not remain up-to-date for very long. If you have comments, questions, or suggestions for improvement, they are welcome. We anticipate updating this textbook in the future, and we look forward to hearing how you have used these materials and how we might improve this textbook.

As mentioned earlier, each author is an established expert in AM with many years of research experience. In addition, in many ways, this textbook 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 textbook possible, we will end this preface with brief author acknowledgments.

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