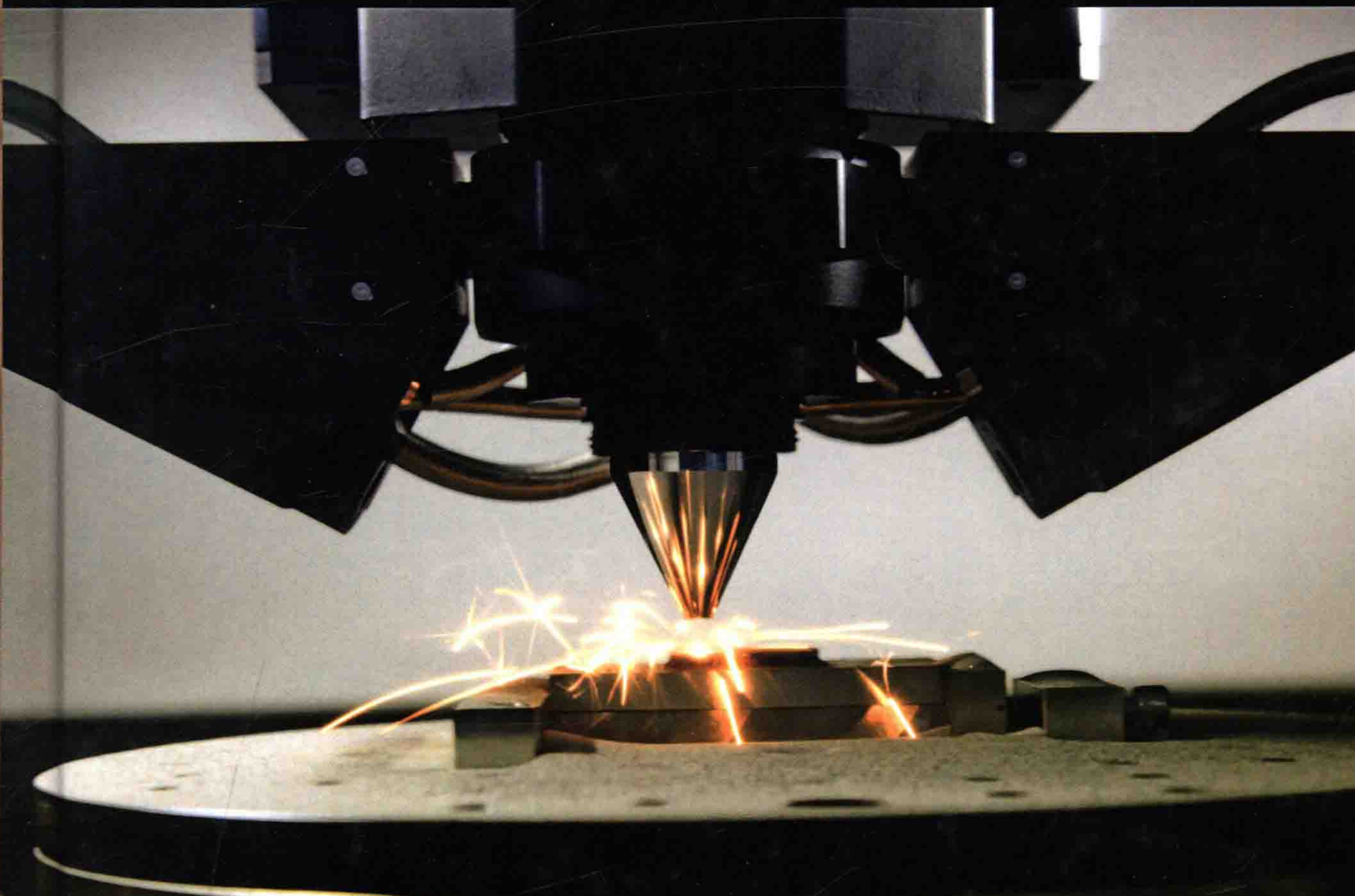
ADVANCED AND ADDITIVE MANUFACTURING SERIES

Laser-Based Additive Manufacturing of Metal Parts

Modeling, Optimization, and Control of Mechanical Properties



Edited by
Linkan Bian • Nima Shamsaei • John M. Usher

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Since the advent of laser-based additive manufacturing (LBAM) technologies for producing metallic parts in the late 1990s, their usage continues to be extended towards many applications. Metallic LBAM parts are now used as functional parts within many industrial sectors such as tooling, dental, medical, and aerospace. This popularity is driven by LBAM's unique feature of generating complex-shaped, functionally-graded or custom-tailored parts that can be utilized for a variety of engineering and industrial applications. The recent flurry of LBAM research and development can be attributed to the manufacturing industry at-large seeking new "in-house" methods to fabricate custom structures and to the consumer/societal appeal of "3D printing". LBAM technologies, hailed by some as the "third industrial revolution," can increase product performance, while reducing time-to-market and manufacturing costs.

Laser-Based Additive Manufacturing of Metal Parts: Modeling, Optimization, and Control of Mechanical Properties is a comprehensive look at new technologies in LBAM of metal parts, covering topics such as mechanical properties, microstructural features, thermal behavior and solidification, process parameters, optimization and control, uncertainty quantification, and more. The book is aimed at addressing the needs of a diverse cross-section of engineers and professionals. It also:

- Shows how LBAM technologies can reduce cost, increase product performance, and reduce manufacturing time
- Details how LBAM will revolutionize mass customization
- Gives specific focus on metal parts
- Provides case studies, detailed examples and equations
- Presents comprehensive information on technologies and metals that apply across industry types

The authors have designed this book to educate the reader on the history/development of LBAM, help them grasp the fundamental process physics and post-fabrication mechanical properties, understand the issues of process optimization and control, and recognize the various applications of LBAM.

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Laser-Based Additive Manufacturing of Metal Parts

Advanced and Additive Manufacturing Series

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Laser-Based Additive Manufacturing of Metal Parts: Modeling, Optimization, and Control of Mechanical Properties

Linkan Bian, Nima Shamsaei, and John M. Usher

Computer-Aided Inspection Planning: Theory and Practice

Abdulrahman Al-Ahmari, Emad Abouel Nasr, and Osama Abdulhameed

Preface

Overview

Since the advent of laser-based additive manufacturing (LBAM) technologies for producing metallic parts in the late 1990s, their usage continues to be extended toward many applications. Metallic LBAM parts are now used as functional parts within many industrial sectors such as tooling, dental, medical, and aerospace. This popularity is driven by virtue of LBAM unique feature of generating complex-shaped, functionally graded, or custom-tailored parts that can be utilized for a variety of engineering and industrial applications. The recent flurry of LBAM research and development can be attributed to the manufacturing industry at large, seeking new "in-house" methods to fabricate custom structures and to the consumer/societal appeal of "three-dimensional (3D) printing." The idea of "printing" a 3D prototype or part, as opposed to purchasing or sending the computer-aided design (CAD) out-of-house for machining, has become alluring to technical and lay persons across the globe. A large number of companies have begun to use LBAM technologies to reduce time-to-market, increase product performance, and reduce manufacturing costs. Hailed by some as the "third industrial revolution," LBAM has the potential to revolutionize cost-effective mass customization and time-efficient mass production.

While LBAM processes have advanced greatly in recent years, many challenges remain to be addressed, such as relatively poor part accuracy (net shape), insufficient repeatability and consistency of parts, and lack of in-process control methodologies. To realize additive manufacturing (AM) potential for ushering in the "third industrial revolution," products must be fabricated rapidly, efficiently, and inexpensively while meeting all stringent functional requirements. The key to large-scale customization and mass production, two important LBAM business frontiers, is the capability of LBAM of a vast array of components with desired features. To compete with conventional mass production processes, AM technology needs to advance further in order to drastically reduce the cost of production, improve the performance of fabricated parts, and achieve consistency between parts. This book is designed to educate readers on the history/development of LBAM, help them grasp the fundamental process of physics and postfabrication mechanical properties, understand the issues of process optimization and control, and recognize the various applications of LBAM.

Target Readership

Advanced manufacturing education and training is critical to our economy, considering that 83% of US manufacturers recently reported an overall shortage of qualified employees. University–industry collaborative AM research in the United States has been initiated primarily through a variety of federally funded programs. To ensure and facilitate the transition of AM moving from the laboratory to a production environment, AM education and training has begun to play an important role in establishing a healthy engineering education ecosystem among US universities and colleges. Taking full advantage of AM will require educating the current workforce and recruiting a new generation of students. Identified focus areas for education and workforce development include AM foundational understanding, representative processes, design for AM, quality assurance for AM, and advanced AM research and education. *The purpose of this book is to fill an existing need in education materials for AM by providing background knowledge, reviewing recent research advances in mechanical/microstructural properties of LBAM built parts, and addressing topics on how to design, optimize, and control the thermal history to achieve desired part features.*

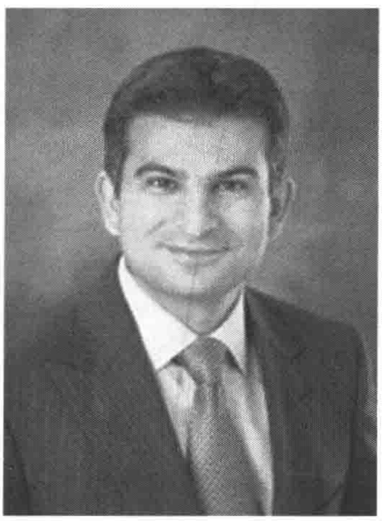
This book is not only designed to educate researchers, practicing engineers, and manufacturing industry professionals, who are interested in entering the arena of AM, but also to provide a *textbook* for senior undergraduate or graduate students. The book will include in-depth, detailed discussions of mechanical properties, materials science, and mathematical/numerical methods. Each chapter will begin by providing theoretical background information, terminology, definitions, etc., on the subject matter to aid nonsubject expert readers as they delve further into the chapter. To help readers understand the topics, examples, case studies, and problems/solutions will be presented at the end of each chapter. Problems will allow students/readers to test their comprehension of the topics requiring them to utilize mathematical models, engineering software, and external resources to solve/answer the problems effectively.

Contents

This book consists of a total of nine chapters, each contributed by invited authors. Chapter 1 introduces the history and development of LBAM as a process and how it has evolved from rapid prototyping to an automated technique for direct conversion of 3D CAD data into physical objects. The concepts and technology related to LBAM will be described and differentiated from other AM methods. A large number of LBAM processes, in conjunction with their corresponding support technologies such as software systems and postmanufacturing processing, will be reviewed. Chapter 2 focuses on methods and technologies related to the CAD of parts with the objective of achieving better part quality (e.g., mechanical properties, geometric accuracy, life cycles, etc.). Research issues related to designing parts with complex geometry (e.g., overhang structures, staircase effects, etc.) as well as the related research efforts will be reviewed. Chapter 3 compares the mechanical/microstructural properties of LBAM parts with those produced using traditional manufacturing processes. Advantages and limitations of LBAM will be discussed. Since the loading condition for many metallic parts in automobiles, airplanes, heavy machinery, bio-implants, and other industrial applications is cyclic, fatigue is the most prominent failure mode. Since fatigue failures account for up to 90% of all mechanical failures, Chapter 4 focuses on recent studies in the fatigue properties of LBAM parts. Studies related to the optimization of these parameters to achieve application-specific physical/mechanical properties are reviewed in Chapter 5. Chapter 6 reviews mainstream control methods that focus on maintaining constant melt pool morphology/temperature and deposited layer height. Due to the complex, coupled thermo physical dynamics associated with the LBAM process, process parameters need to be adjusted in real time to ensure that desired mechanical/microstructural properties can be obtained, which is in direct contrast to the traditional "set-it-and-forget-it" open-loop process that consists of time-invariant process parameters. Chapter 7 reviews the recent research efforts in the thrust areas of functionally, compositionally graded materials and the mechanical properties of the fabricated parts. Among all powder-based AM methods, LBAM is capable of feeding different feedstock (preform) materials simultaneously to produce various alloys and functionally graded parts. Each feed rate can be adjusted to produce materials with different chemical compositions and microstructural properties as well. Accordingly, a large number of alloys have been developed using LBAM techniques over the past decade. At the same time, this also raises new challenges in process modeling, optimization, and control. Chapter 8 overviews the applications of LBAM in various industrial sectors, such as healthcare, aerospace, automotive, and others. Examples are presented, those expressing key advantages of LBAM over traditional manufacturing methods. Applications that improve biocompatibility, efficiency, safety, ergonomics, and performance are discussed. Chapter 9 discusses the economic impacts of AM in terms of three different aspects: The first involves measuring the size of AM. This includes measuring the value of the goods produced using this technology in the context of the total economy. The second aspect involves measuring the costs and benefits of using this technology. It includes understanding when AM is more cost effective than traditional manufacturing, and why it is more cost effective. It also involves understanding other advantages such as new products that might not be possible with traditional manufacturing. The last aspect of AM economics is the adoption and diffusion of this technology.

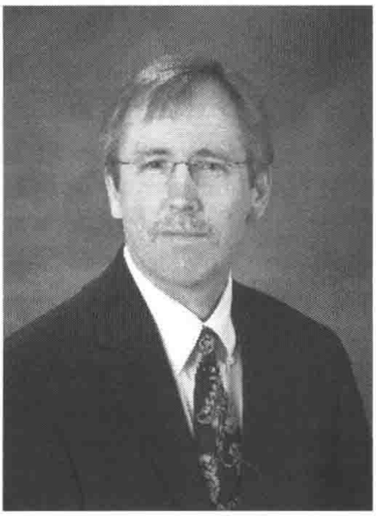
About the Editors

Dr. Linkan Bian is an assistant professor in the Industrial and Systems Engineering Department at Mississippi State University. He received his PhD degree in industrial and systems engineering from Georgia Institute of Technology in 2013, a dual master degree in statistics from Michigan State University, and a BS degree in applied mathematics from Beijing University in 2005. Dr. Bian's research interests focus on the combination of data mining and optimization methods for modeling and control of additive manufacturing processes. Other applications of his research include cybersecurity and supply chains. He has received external funding from Department of Defense, Department of Energy, National Science Foundation, and industrial companies. Dr. Bian's publications have appeared in journals such as *IIE Transactions* (*Institute of Industrial Engineering*), *Additive Manufacturing*, *Rapid Prototyping*, *IEEE Transactions* (*Institute of Electrical and Electronics Engineers*), and others. His work has received multiple awards/nominations from the Quality Control & Reliability Engineering (QCRE) division of the Institute of Industrial and Systems Engineers (IISE). He is serving as a council member of Data Mining Quality, Statistics, Reliability (DM-QSR) section within the Institute of Operations Research and Management Science (INFORMS) professional society.



Dr. Nima Shamsaei is currently an associate professor in the Mechanical Engineering Department at Auburn University. He has several years of industry experience, most notably at Chrysler Group LLC as a senior engineer and a technical leader specializing in durability test development for all Chrysler products. He received his PhD degree in mechanical engineering from the University of Toledo in 2010. His BS and MS degrees in mechanical engineering were obtained from Isfahan University of Technology and Sharif University of Technology, respectively. Dr. Shamsaei has extensive research experience in additive manufacturing, mechanical behavior of materials, design, and fatigue and failure analysis. He has published over 100 scientific papers in refereed journals and conference proceedings in the areas of fatigue and additive manufacturing. He is the founder and codirector of the

Laboratory for Fatigue and Additive Manufacturing Excellence (FAME) at Auburn University and is currently leading multiple sponsored research projects from the National Science Foundation (NSF), Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and several private companies. He is a member of American Society of Mechanical Engineers (ASME), the Minerals, Metals, and Materials Society (TMS), American Institute of Aeronautics and Astronautics (AIAA), and Society of Automotive Engineers (SAE), and is actively engaged in the ASTM E08 committee on Fatigue and Fracture and the F42 committee on Additive Manufacturing. Dr. Shamsaei is the recipient of multiple awards and recognitions, including the SAE International Henry O. Fuchs Fatigue Award in 2010, the Schillig Special Teaching Award in 2015, and the American Society for Testing and Materials (ASTM) International Emerging Professional Award in 2016. He is also a consultant for multiple private companies, including Fiat Chrysler Automobiles.



Dr. John M. Usher currently serves as professor and head of the Industrial & Systems Engineering Department at Mississippi State University. He received his PhD degree in engineering sciences at Louisiana State University, where he also earned master's degrees in both chemical and industrial engineering. As well, he has a bachelor's degree in chemical engineering from the University of Florida. Prior to his academic career, John worked for Texas Instruments in the area of process development for the manufacture of multilayer printed circuit boards. John's research interests focus on production systems and systems simulation, modeling, and analysis, with applications in both manufacturing and transportation. He has published numerous papers in technical journals and conference proceedings, edited several books, and continues to serve on the editorial staff of several journals. John is a registered professional engineer in Mississippi and a senior member of IISE and SME.

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