Friction Based Additive Manufacturing Technologies

Principles for Building in Solid State, Benefits, Limitations, and Applications

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List of Abbreviations

3D	Three-dimensional
3DP	Three-dimensional printing
AFS	Additive friction stir
AFW	Angular friction welding
AM	Additive manufacturing
AS	Advancing side
AWS	American Welding Society
BLISK	Blade + disk
BM	Base metal
BPM	Ballistic particle manufacture
CAD	Computer aided design
CAM	Computer-aided manufacturing
CDFW	Continuous drive friction welding
CDRX	Continuous dynamic recrystallization
CNC	Computer numerical controlled
DDRX	Discontinuous dynamic recrystallization
DMD	Direct metal deposition
DMLS	Direct metal laser sintering
DRX	Dynamic recrystallization
EBM	Electron beam melting
FASW	Friction-assisted (lap) seam welding
FATs	Friction based additive manufacturing technologies
FD	Friction deposition
FDM	Fused deposition modeling
FS	Friction surfacing
FSAM	Friction stir additive manufacturing
FSATs	Friction stir additive techniques
FSBW	Friction stir butt welding
FSLW	Friction stir lap welding
FSP	Friction stir processing
FSSW	Friction stir spot welding
FSW	Friction stir welding
FW	Friction welding
FWTs	Friction-welding techniques
HAZ	Heat-affected zone
IFW	Inertia friction welding
IJP	Inkjet printing
LAM	Laser additive manufacturing
LENS	Laser-engineered net shaping
LOM	Laminated object manufacturing

LFW	Linear friction welding
MAM	Metal additive manufacturing
NZ	Nugget zone
OM	Optical microscopic
PMZ	Partially melted zone
RFW	Rotary friction welding
RPM	Rotations per minute
RPS	Rotations per second
RS	Retreating side
SGC	Solid ground curing
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
TL4	Technology level 4
TMAZ	Thermomechanical affected zone
TWI	The Welding Institute
UAM	Ultrasonic additive manufacturing

Preface

The exchange of ideas and effectiveness of communication are prerequisites of any learning process. In today's era of the need for high technical competence, it is the moral responsibility of every professional to share knowledge gained for societal development. This work is an attempt by the authors toward dissemination of the information and experience gathered by the authors in the domains of additive manufacturing, friction welding, and their confluence, that is, friction based additive manufacturing techniques.

The authors started their work in the field of friction based additive manufacturing techniques as part of their experimentation, but the encouraging results that were obtained inspired the authors to venture into their depths. Much lies unexplored in this domain, and the results will definitely be worth the efforts invested. Meagre literature and absence of a book in this field has inspired the authors to undertake the responsibility of coming up with the idea of the present book. This book is written in simple language so that it will be useful even for people who are venturing in the field of friction based additive manufacturing techniques for the first time.

Friction based additive manufacturing is a term coined for utilizing friction based solid-state welding/processing techniques in conjugation with advancements of layered/additive manufacturing to produce components with superior structural and mechanical properties. This is a novel manufacturing technology area for developing high structural performance components. It utilizes the principle of layer-by-layer additive manufacturing and is a major breakthrough in the domain of the solid-state metal additive manufacturing sector.

Since these techniques are basically confluence of additive manufacturing (AM) and friction welding/processing, therefore, a primary understanding of both these fields is mandatory to fully understand the concept of friction based additive techniques. To facilitate learning, this book introduces all aspects of AM necessary to outline the need for and concept of friction based AM processes. It further introduces the friction welding techniques. A timeline of friction based AM processes is then presented. Details of various friction based additive techniques, that is, linear friction welding, rotary friction welding, friction deposition, friction surfacing, friction stir additive manufacturing, friction-assisted seam welding, and additive friction stir processes are described. Applications, trends, and the future scope of these techniques are then discussed. This book is an attempt to provide an exhaustive and extensive compilation to enrich the reader's knowledge about friction based AM processes.

Rapid ongoing technical and technological advancements in the field of fabrication processes make it difficult to present an exhaustive account of various topics. The authors have, however, put their best efforts into making this book as informative and useful as possible by including each aspect, major advancement, and trend in the field of both the parent technologies and various aspects of friction based AM techniques. Enough literature has been reviewed and the practical knowledge of the authors based upon their several years of work/research experience has been utilized to write this book.

The authors sincerely hope that this book holds value for researchers, academicians, and university students who plan to pursue a research career in the field of advancements in solid-state friction based additive manufacturing. We genuinely hope that the readers can apply knowledge of the information presented to promote research and development in this field.

The authors will genuinely welcome and appreciate any queries, advice, and observations by the readers.

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The author Dr. Manu Srivastava wishes to thank her director, Dr. Sraban Mukherjee (IMS Engineering College, Ghaziabad), for his inspiration and support. She also thanks her colleagues for their support. The author wishes to convey her heartfelt thanks to her supervisors, Dr. T. K. Kundra and Dr. Sachin Maheshwari. The author feels indebted and takes this platform to acknowledge that she is blessed to be under the professional guardianship of supervisors who are like parents to her. No magnitude of words can ever quantify the love and gratitude the author feels in thanking her family members, especially her late parents, Mr. Indrapal Singh Chauhan and Mrs. Saroj Chauhan; her parents-in-law, especially her father-in-law, Dr. T. K. Singh; her sisters, Mrs. Shilpi Chauhan and Mrs. Rachna Chauhan; her husband, Mr. Ramkrishna Yashaswi, who is her pillar of strength; and her child, little Yashkrishna Srivastava, who is the world's best child. Pursuing active research always sets up a pressing need for time and hard work that required her to spend much of her time, which is otherwise meant exclusively for the family and especially her child, in academic work. The author also deeply thanks her co-author and fellow researcher, Mr. Sandeep Rathee, for the constant feedback on her strengths, for his ability to teach by example, and for his valuable feedback.

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The author Dr. Arshad Noor Siddiquee wishes to thank his family and his friends for their unconditional support.

Finally, the authors devote and dedicate this work to the divine creator. They thank the Almighty for giving them the strength to bring these thoughts and understanding of concepts into physical form. The authors pray that this work may be of enough technical competence to enlighten the readers about each aspect of friction based additive manufacturing techniques.

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1

General Introduction and Need of Friction Based Additive Manufacturing Techniques

Foreword

People tend to doubt the effectiveness and working of friction based additive manufacturing technologies (FATs) when they hear about them for the first time. The usual reactions that are encountered include "Do these processes work?" "How do they work?" "What are the prerequisites of FATs?" "Do these processes involve complex procedures?" The present book is a sincere endeavor by the authors to answer these research queries. Actually, these processes are very simple in operation and produce impressive results in terms of improved microstructures as well as enhanced mechanical and structural properties. Observing the working of these processes is quite intriguing, where there is a rotational component in the form of a consumable/nonconsumable rod/part and a consumable/nonconsumable metallic tool. The joining of two metallic rods/surfaces, the deposition of consumable rod over substrate, the joining of parts via a nonconsumable rotating tool without fusion, and the deposition of material through a hollow tool have the ability to capture technical inquisitiveness and attract anyone. The realization of additive manufacturing of three-dimensional (3D) parts via these techniques is also quite interesting. During these processes, there are no fumes, melting, or emanation of affluent lines, hazardous gases, or radiation. Noise during these processes is also low. This leads people to normally disbelieve or underestimate the capabilities of these innovative techniques and makes it hard to assimilate the fact that these processes can fabricate 3D components easily in shorter cycle times and with enhanced properties as compared to base metals. In general, these techniques utilize principles of friction based processes to build a 3D part through layer by layer additive manufacturing. Some of these processes are old, however, their AM versions are quite recently developed.

The primary objective of this book is to articulate the process principles of different FATs. This includes description of process parameters involved and their effect upon process efficiency, fabricated part characteristics, general features, and process-specific limitations, done in a simple, logical, and concise way. As these processes are new and evolving, based on current knowledge of these techniques and available literature, applications of these techniques in different sectors are described. Toward the end, a brief conclusion of these techniques is presented, followed by discussion on their future prospects.

1.1 Introduction

The consistent need to reduce weight in the aerospace, marine, and automobile sectors has always been an area of key interest among researchers. In recent times, utilizing lightweight materials has been found to enhance the performance of components in such applications. For example, there is an approximate annual reduction of hundreds of gallons of fuel usage in air carriers and carbon dioxide emission using lightweight materials [1,2]. In today's technical scenarios, optimal fabrication of such lightweight components with improved properties using a suitable process is a key focus of research. Moreover, the ease with which complex shaped components can be fabricated is useful in improving the effectiveness and efficiency of any process used to produce high-end components for specific applications. One of the most suitable techniques for fulfilling such a need is additive manufacturing.

AM is an advanced and highly established three-decade-old technology for fabrication of various complex shaped parts with little effort as compared to conventional manufacturing techniques. Apart from being used for the 3Fs, that is, form, fit, and functional applications, AM techniques are applied to process chains for minimizing cost and time requirements. AM refers to a class of manufacturing where three-dimensional parts are fabricated via 2.5 dimensional layer additions directly from CAD designs by utilizing different strategies. These techniques require minimal human intervention and are appreciably economical. In addition to these benefits, several comprehensive studies have also established that wastage in using AM techniques is appreciably less and they are more environmentally friendly as compared to conventional processes.

Despite the manifold advantages of AM techniques, they suffer from some inherent technical limitations and challenges, as illustrated in Figure 1.1. Lots of research is in progress to address these challenges.

AM is currently used for both metallic and nonmetallic raw materials. A huge quantum of research has been accomplished on nonmetallic materials as compared to metals. Metal-based additive manufacturing (MAM) is still in its development stage. MAM has been developed for only a few metals, and poor lateral strength is a serious issue even in them [4,5]. Parts manufactured using MAM possess the inherent disadvantage of anisotropy

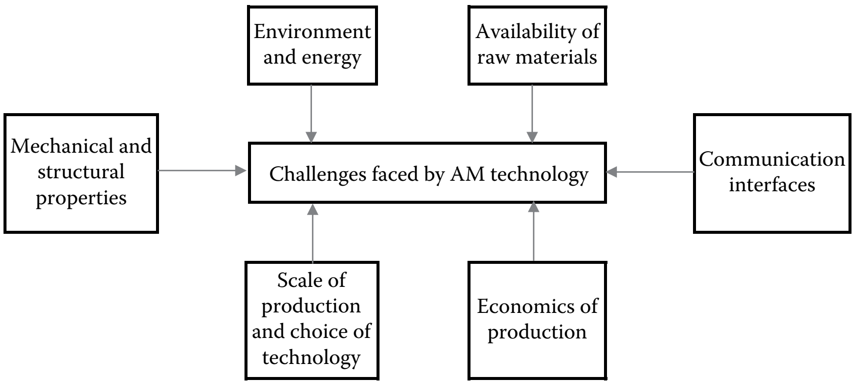

FIGURE 1.1
Challenges faced by AM technology. (Adapted from Srivastava, M. et al. Design and processing of functionally graded material: Review and current status of research, in *7th International Conference on 3D Printing & Additive Manufacturing Technologies- AM 2017, Global Summit* 2017, Bengaluru, India.) [3]

and low transverse strength, chiefly owing to accompanying liquidus-solidus phase transformations. This renders the parts unsuitable for structural applications, thereby putting restrictions on utilization of structural parts manufactured using MAM [6,7]. Popular MAM techniques like electron beam melting, selective laser melting, and so on are highly cost intensive, too. In order to fulfill demands from various sectors like aerospace, automotive, and tooling, the focus of AM research has shifted toward the development of processes/methods for AM of metallic components. Any improvements in MAM technology to troubleshoot the inherent fabrication problems mentioned in the foregoing text will have a huge significance in improving the usage of such a game-changing process. Thus, there is a strong need for a process that can utilize the fast development time and ease of fabrication of AM and also simultaneously address the anisotropy-related issues of the metallic components. In line with concerns raised above, numerous studies have been carried out to alleviate these limitations. One feasible solution is the incorporation of solid-state friction based approaches into AM. These processes are hybrid in nature and work on the layer-by-layer principle along with friction based joining. There are different innovative approaches to friction based additive techniques (FATs) and can basically be categorized into seven types: rotary friction welding (RFW), linear friction welding (LFW), friction deposition (FD), friction surfacing (FS), friction stir additive manufacturing (FSAM), friction assisted (lap) seam welding (FASW), and additive friction stir (AFS) [8–15]. All of these techniques are basically variants of friction welding. The friction joining of materials in these processes may take place directly or indirectly. In RFW and LFW, direct friction welding takes place wherein the addition of material occurs in the form of joining of two surfaces (rod forms in RFW and rectangular or other shapes in LFW).

For the realization of 3D parts, joined parts are machined into sliced contours using CNC machining, and these steps are repeated until a desired build height is achieved. In FD and FS, deposition of material takes place from a consumable rod rotating against the substrate. In FSAM, FASW, and AFS, addition of material is accomplished following the principles of the friction stir welding (FSW) process, which is also a variant of friction welding.

1.2 Need for Friction Based Additive Manufacturing Techniques

The ability of MAM techniques to be used for the fabrication of intricate parts has led to AM being considered an option for replacing parts fabricated via conventional manufacturing, especially in the aviation, prosthesis, biomedical, automotive, and marine sectors. Several MAM techniques are in practice that generally utilize powder and a metal wire or sheet as feedstock material for their consolidation into dense metallic components by application of suitable energy sources like electron beam, laser, electric arc, ultrasonic vibration, and so on [16]. These techniques can be categorized into four main heads (as per ASTM standard terminology for AM techniques [17]): processes based on powder bed fusion like electron beam melting, selective laser sintering, and so on; processes based on directed energy deposition like laser consolidation, arc additive manufacturing, and so on; processes based on binder jetting such as inkjet 3D printing; and processes based on sheet lamination such as ultrasonic consolidation, laminated object manufacturing, and so on [18]. Processes based on the first three categories utilize either metal powder or metal wire as feedstock material, and most of these processes generally rely on liquid phase processing. Owing to this, there are several issues related to fusion-based processing that limit its utility in certain applications. These include the fact that during fusion-based processes, the powder particle-based substrate and particles are in an activated state due to high surface energy content, making them vulnerable to contamination. This can be further explained as follows: during AM, the substrate is in a molten state, and it is more prone to form discontinuities such as internal porosity, inclusions, and other solidification defects. Also, metal wire–based processes are prone to fabricating inhomogeneous microstructures. These processes can be considered equivalent to microcasting or microwelding. The processes based on fourth category, that is, sheet lamination processes, utilize metallic foil/sheet/laminate as feedstock material and are still in the nascent stage [16]. However, ultrasonic additive manufacturing (UAM) reduces the defects occurring owing to solid liquid phase transformations owing to its solid-state nature [19,20]. It has the ability to fabricate multimaterial components in the solid state and is largely utilized for AM of metallic materials. However, it suffers from its own limitations of inhomogeneous microstructures at interfacial and noninterfacial regions, resulting in inferior properties as compared to base material [21].

Thus, the issues in the fabrication of metallic components using fusion-based AM techniques can be summarized as: poor structural strength, porosity, shrinkage defects, inclusions, and other solidification defects due to liquid-solid phase transformations, powder contamination, inhomogeneity in microstructures and directionally variant mechanical properties, poor properties along the build direction owing to processing misalignments, the stair-stepping effect, restricted production volume, requirement of closely controlled chambers, limitations on the number of possible alloys, and so on. For successful utilization of MAM in biomedical, transportation, aviation, and other critical sectors, it is mandatory to overcome the aforementioned challenges, which will then open altogether new avenues for MAM. This is in turn related to devising some methods to obtain superior microstructures and discontinuity-free parts fabricated via MAM. These challenges necessitate the requirement to focus ongoing research upon issues beyond intricate shapes and try to develop components that can meet the strict strength restrictions of user industry requirements.

This demands incorporation of solid-state friction based approaches into AM, which brings FATs into the main role. These processes utilize the layer-by-layer building principle of AM with the strength enhancement ability of friction joining, thereby resulting in a rare excellent choice and flexibility to get complicated robust components in a limited time. Thus, FATs can be considered as a special innovative class of novel, fast, and size-independent enabling MAM techniques. They have been successfully employed for fabrication of simple shaped objects by various researchers. They can be utilized to produce fully dense and near net shape wrought graded components economically from a broad range of alloys with graded structures.

1.3 Benefits of Friction Based Additive Manufacturing Techniques

The specific advantages of FATs as compared to fusion-based MAM are their considerably low-energy consumption, optimal part consolidation, and structural efficacy. It has been established by various research studies that friction based AM processes consume only around 2.5% of the energy consumed by fusion-based processes [22]. A perspective representation of fusion-based MAM and FATs was proposed by Palanivel et al. [8], and states that FATs consume less energy (power requirement) and produce less distorted parts with high structural performance as compared to fusion-based AM processes. In addition, the appreciably high heat flux required in fusion-based AM processes adds to woes such as porous structures, shrinkage cavities, and so on. All of the aforementioned FATs are free from/less prone solidification defects. Fewer distortional defects, lower porosities, the ability to fabricate larger components, multimaterial bonding abilities, greater reproducibility rates, excellent metallic properties, tailor-made microstructures, and so on are major benefits of friction based AM techniques as compared to fusion-based MAM processes.

Thus, depending on their solid-state nature, these techniques have several advantages, which can be summarized as follows:

- Green manufacturing technologies
- Eliminate the majority of fusion-based defects
- Utilize less energy as compared to fusion-based MAM techniques
- Can be used for a broad material range of ferrous and nonferrous metals
- Produce fine-grained equiaxed microstructures
- Produce high-strength components as compared to base materials
- Engineered microstructures possible
- Dissimilar material builds can be easily manufactured using these techniques
- Limitations on the size of components that can be fabricated via conventional AM processes can be easily overcome because of the absence of build volume restrictions.

1.4 Content Outline

This book provides comprehensive details on newly developed hybrid solid-state FATs. The main aim of the book is to enhance the spectrum of reader interest toward understanding the concept of these intriguing hybrid processes apart from AM and core friction based techniques fields. Also, necessary information about parent processes (AM and FW) is provided in a single platform to fully understand the basics of FATs. The authors have attempted to provide comprehensive details of these processes in terms of process principles, present research status, advancements, industrial applications, and future scope of these techniques. However, these details are not exhaustive owing to the restriction on scope of the present work, and readers with a keen interest are advised to refer to the references for a particular process for more details.

The book consists of eight chapters and is organized as follows:

Chapter 1, *Introduction*, presents the various aspects of AM, friction welding, and their confluence, that is, FATs. This chapter presents an overview of various aspects/chapters addressed in this book.

Chapter 2, *Additive Manufacturing (AM) Technologies*, briefly describes the major commercial AM processes, their timelines, and recent developments. The issues and challenges in fusion-based MAM techniques are systematically described.

Chapter 3, *Friction Based Joining Techniques*, introduces various friction based processes and describes the potential techniques that can be effectively utilized for AM of metallic materials. A timeline of these techniques is presented for clarity of evolution of these processes.

Chapter 4, *Friction Joining-Based Additive Manufacturing Techniques*, defines two friction welding-based AM processes (i.e., rotary friction welding and linear friction welding), which can be successfully used for AM of metallic parts. The current status of research, their working principles, benefits, and limitations of these techniques are discussed. A few interesting applications of these techniques are also discussed.

Chapter 5, *Friction Deposition-Based Additive Manufacturing Techniques*, addresses deposition-based friction AM techniques. These are mainly termed FD- and FS-based AM techniques. The working principles, effect of process parameters, benefits, limitations, and current status of research of both processes are discussed. Various intriguing applications of these techniques are also illustrated.

Chapter 6, *Friction Stir Welding-Based Additive Manufacturing Techniques*, addresses friction stir welding-based AM techniques, that is, FSAM, FASW, and AFS. An introduction to friction stir welding; terminology used in this process; and evolution of microstructure during FSAM, FASW, and AFS are described. Defect formation during these processes and their causes are explained, with suitable illustrations. Machines utilized for these techniques and the effect of process parameters are discussed in detail.

Chapter 7, *Applications and Challenges of Friction Based Additive Manufacturing Technologies*, presents a detailed discussion of the present as well as the proposed applications of FATs. The challenges to accomplish full-scale application of these innovative techniques are discussed in a concise way.

Chapter 8, *Conclusion*, concludes the book based upon analysis accomplished in the previous chapters. Future scope/trends are also highlighted toward the end of this chapter.

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