FRICTION STIR WELDING AND PROCESSING

FUNDAMENTALS TO ADVANCEMENTS

EDITED BY
SANDEEP RATHEE • MANU SRIVASTAVA
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Friction Stir Welding and Processing

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Fundamentals to Advancements

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Contents

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He has a total teaching and research experience of more than ten years. He has delivered invited lectures, chaired scientific sessions in several national and international conferences, STTPs, and QIP programs. He is a life member of the Additive Manufacturing Society of India (AMSI), and Vignana Bharti (VIBHA).

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Dr. Manu Srivastava is presently serving PDPM Indian Institute of Information Technology, Design and Manufacturing Jabalpur, India, in the Department of Mechanical Engineering. Her previous assignment was as a Prof. & Head, Department of Mechanical Engineering and Director Research, Faculty of Engineering and Technology, MRIIRS, Faridabad, India. She has completed her PhD in the field of additive manufacturing from Faculty of Technology, University of Delhi. Her field of research is additive manufacturing, friction-based AM, friction stir processing, advanced materials, manufacturing practices, and optimization techniques. She has authored/coauthored around 100 publications in various technical platforms of repute. She has been awarded 18 industrial design patents and 1 copyright.

She has authored/edited seven books in the field of advanced manufacturing. Out of these, three have already been published with CRC press, Taylor & Francis group, and others are either in press or in an accepted stage. Two of them are with Wiley, one with Elsevier, and one with Springer publishing house.

She is working as an editor-in-chief of a book series titled "Advanced Manufacturing of Materials" with CRC Press, Taylor & Francis Group. She has also worked as guest editor for a special issue of a Scopus Indexed Elsevier journal. She is on the editorial board of several reputed journals in the capacity of editorial member. She is also serving as the regional editor of International Journal of Experimental Design & Process Optimization, Inderscience Publishers. Additionally, she is serving as a reviewer in more than 30 Journals. She is working on various projects of around 5 million INR and has completed several consultancy works funded by Govt. of India in the field of Hybrid Additive Manufacturing and rehabilitation robotics. She has a total teaching and research experience of around 15 years. She has won several proficiency awards during the course of her career including merit awards, best teacher awards, etc. One special award that needs mention is the young leader award. She has delivered invited lectures, chaired scientific sessions in several national and international conferences, STTPs, and QIP programs. She is a life member of Additive Manufacturing Society of India (AMSI), Vignana Bharti (VIBHA), The Institution of Engineers (IEI India), Indian Society for Technical Education (ISTE), Indian society of Theoretical and Applied Mechanics (ISTAM), and Indian Institute of Forging (IIF).

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Preface

"This book is dedicated to the relationships of trust and respect that stay strong like an anchor to ward off all obstacles and are a divine intervention to create an oasis of hope in the desert of aimless souls"

Manu

Morally, every researcher and academician is bound to effectively share, exchange, and communicate ideas, knowledge, and experience with the global technical society. The unpredictable nature of life encourages us as an investigator of scientific truths to make every effort to not only share our learnings but also bring together a group of eminent researchers of this technical society to come up with this edited book. This book has contributions from researchers in the field of friction stir welding, processing (FSW/P), and their variants from across the world. The intent is also to facilitate our future generation of researchers with the knowledge gained so far to provide them a consolidation of the accomplished research. This will most definitely empower them with a vision to make a technologically and socially strong community based on deep-rooted foundations. With this thought process in place, the editors have come together to disseminate information gathered from years of experience in the field of FSW/P and their variants with the technical society. Today, a wide variety of high-quality literature in the form of a few monographs and a multitude of journal articles are available in the field of FSW/P, but most of these are confined only to some focused areas. A resource that presents the overall picture in FSW/P and their variants is very much required. This book is a novel venture toward the said direction. It is ensured to present details in simple yet precise language with clarity to cater to a wide variety of readers globally.

FSW is the art and science of joining materials in solid state using a nonconsumable tool with the application of frictional heat. It is frequently utilized for obtaining high-strength welds and join a wide range of materials including but not limited to aluminum and its alloys, copper and its alloys, titanium and its alloys, stainless steel variants, magnesium and its alloys, and so on. When FSW is applied for processing applications or for fabricating composites, the FSW technology is called FSP. With slight modifications, today this technology has more than 25 different variants, each dedicated to some specific applications. At present, FSW/P technology is been increasingly utilized in shipbuilding, aircraft and space applications, welding and processing a variety of exotic and specially engineered structures like shape memory alloys, honey comb, metal matrix, polymer matrix composites, and so on.

This book has 20 chapters each of which is dedicated to a different aspect of FSW/P. The chapters included in this book have been briefly introduced here to make the reader well versed with the overall content.

Chapter 1 presents an overview of friction stir welding technique as a sustainable alternative to conventional metal joining and welding techniques. This chapter also explains the principle and working of FSW, its different variants, and the kind of tool variations incorporated in these variants. Some common defects encountered during FSW are also mentioned. Some of FSW's advantages and limitations are also added in the end.

Chapter 2 presents an introduction to friction stir welding and the single-point incremental forming procedure on friction stir welded blanks, recent developments in tool design, tool materials, parameter optimization, mechanical properties, etc. The chapter offers quick idea about selection of FSW and SPIF processes to prepare customized components in real-time applications. Two similar or dissimilar materials can be joined and formed with this hybrid manufacturing process. The combined process has versatile applications in automotive and defense sector. SPIF has special advantages over conventional forming processes which includes heterogeneity, quicker lead time, versatility, etc. The chapter concludes with several recommendations for future research.

Chapter 3 presents an overview of friction stir brazing and its variants. Two case studies are presented viz. joining of low carbon steels by application of friction stir brazing and Sn–Pb alloy as filler and intermetallic compound formation and mechanical characteristics of brazed samples made by friction stir vibration brazing with Sn–Pb filler material and SiC reinforcing particles. Applications of friction stir brazing in different sectors are discussed followed by summary and future directions of the chapter.

Chapter 4 introduces and discusses details of friction stir processing (FSP) as a comprehensive microstructure tailoring tool. This chapter starts with the history behind the evolution of the FSP from the conventional friction stir welding processes. The second section of the chapter gives an overview of the working principle of FSP followed by its comparison with other SPD techniques in third section. The fourth section of the chapter elaborates on the factors affecting the process such as tool rotational speed, traverse speed, and in-process cooling. It is followed by discussion related to mechanisms of microstructural evolution. The last section of the chapter describes the challenges and opportunities associated with FSP to resonate with recent trends and become industry ready.

Chapter 5 gives a fundamental overview of friction stir processing along with the process parameters that affect surface integrity. Discussion on the basic mechanism of thermal spray technique along with their classification and applications is provided. Further, discussed the role of surface engineering as a modification technique and how it affects surface morphologies. In the end, the inappropriate parameters that affect the surface modification technique have been assessed.

Chapter 6 deals with surface composites manufacturing by solid-state friction stir processing method. A detailed discussion on the factors affecting the microstructure and mechanical properties of FSPed processed surface composites is provided. This chapter also explains the factors promoting the dominance of various strengthening mechanisms in the surface composites processed through FSP.

Chapter 7 presents the issues in friction stir welding (FSW) of dissimilar material joining such as dissimilar aluminum (Al) alloys, aluminum to copper alloys (Al–Cu), aluminum to titanium (Al–Ti), and aluminum to steel (Al–Fe), recent developments in tool design, tool materials, parameter optimization, microstructure, mechanical properties, common defects occurred, etc. The chapter concludes with several recommendations for future research.

Chapter 8 covers the friction stir welding process, particularly the joining of aluminum and its alloys, which includes the introduction, advancements, applications, and conclusion. Emphasis is given to critical factors that will affect the FSW method in the joining of aluminum alloys.

The current state of the art for FSW of aluminum and its alloy, as well as the basics of the process and its influences, are examined. Additionally, additive mixed FSW of Al alloy, testing and characterization like tensile, hardness, and microstructure analysis, as well as industrial applications, are covered in the FSW mechanical characteristics section.

Chapter 9 presents an experimental study on the mechanical characterization of FSWed joints of dissimilar aluminum alloys of AA7050 and AA6082. This work analyzed the effect of processing parameters on the mechanical characterization of the friction stir welded joint (FSWed) of AA7050 and AA6082. Well-material mixing of FSWed joints on high rotational tool speed (RTS) was observed. The fracture of the welded joint at HAZ reveals the excellent weld quality and bonding between the dissimilar metals.

Chapter 10, In this chapter, standard microstructural characterization techniques are presented. Various aspects such as the microstructure sample preparation procedure with brief introduction of equipment used in microstructural characterization are covered. A few illustrative examples are added toward the end of each section of this chapter with an aim to facilitate understanding of concepts.

Chapter 11 focuses on the microstructural characterization and mechanical testing of samples subjected to friction stir welding (FSW) and friction stir processing (FSP) techniques. The aim is to investigate the resulting microstructure and evaluate the mechanical properties of the welded/processed samples. The chapter begins by describing the methodology used for microstructural analysis, which includes techniques such as optical microscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD). The microstructural features, such as grain structure, grain boundaries, and phase composition, are examined and documented. The findings provide valuable insights into the relationship between process parameters, microstructure, and mechanical behavior, aiding in the optimization of FSW and FSP techniques for desired material properties. In conclusion, this chapter provides a comprehensive analysis of the microstructural characterization and mechanical testing of FSWed/FSPed samples, shedding light on the effects of the welding/processing techniques on the resulting material properties.

Chapter 12 provides state-of-the-art information on the joining of metal matrix-reinforced (MMR) welds by employing the FSW technique. The results are critically evaluated with more emphasis on the reinforcement particles and plasticized material flow behavior that affects the metallurgical properties of MMR welds. In addition, the mechanical performance of reinforced FSW welds is evaluated directly related to welding specifications. Fractography and wear behavior characteristics of reinforced FSW welds are also evaluated based on the materials' combination of reinforcement particles and base material.

Chapter 13 attempts to summarize the applications, and manufacturing methods of sandwich sheet structures, specifically the solid-state joining methods such as friction stir welding, friction stir spot welding, accumulative roll bonding, and adhesive bonding. Applications in trains, marine sector, turbines, aerospace, and ship construction are presented. From the scarce literature, the problems associated with the manufacturing and joining methods is also highlighted at last.

Chapter 14 provides a bird's eye view of different types of defects noticed in friction stir welding (FSW). It elaborates on major defects and discusses the possible causes of the emergence of certain types of flaws and the ways to mitigate them. It further exposes the readers to discrete friction stir variants and typical defects observed in these processes. The chapter concludes with a few solutions to avoid defects in friction stir processes.

Chapter 15 explains ultrasound wave propagation behaviors associated with the macrostructure, microstructure, and residual stresses. Then, the explanations of the methodologies are discussed that involved such principles into ultrasonic inspections, evaluations, and monitoring.

Furthermore, the cases studies regarding the recent ultrasonic NDT/Es in friction stir-based manufacturing processes are introduced and discussed.

Chapter 16 covers the significance of friction stir welding comparing with other solid-state metal joining processes. The application of FSW on different materials such as aluminum alloys, magnesium alloys, copper alloys, titanium alloys, steels, composite materials, polymers, and plastics is discussed. The recent developments and applications of FSW metal joining process in various industries were also discussed. The industrial applications such as aerospace, automobile, ship building, railways, and other industries were reviewed.

Chapter 17 discusses on the development of an indigenous method of friction stir process (FSP) fabrication technique. A discussion is made on the impetus development of FSP setup to fabricate surface composites with fortified properties for specific applications. Various shoulder and pin profiles have been designed and their effects on the microstructural evolution and mechanical properties were also discussed. The fundamental understanding and critical thinking of the tool modifications and the manufacturing process paves way for the development of new surface composites.

Chapter 18 presents a case study that provides a comprehensive analysis of the effects of various pin profiles on the performance of the FSW tool.

Chapter 19 presents a case study that provides static analysis of honey comb structure (HCS) fabricated by FSP. Several researchers have carried out fabrication of HCS by using FSP method with different materials, but there is meager reported research on its analysis.

Chapter 20 provides a comprehensive review of the friction stir additive manufacturing (FSAM) technique, highlighting its advantages over other gas-/liquid-based technologies. FSAM offers clean and green technology, defect-free parts, cost-effectiveness, and the ability to process intricate designs with excellent mechanical properties. The chapter explores the application of FSAM in the field of additive manufacturing (AM), particularly in complex structural design. The chapter concludes by discussing the microstructural development, recent advancements, and future prospects of FSAM.

The quantum of information related to different friction stir welding/processing techniques, fast degree of obsolescence, and extremely high levels of ongoing technical as well as technological advances puts a restraint on presenting details of every aspect of each related topic. Editor group has, however, put in their best efforts in making this book informative and interesting. This book is a result of dedicated research in the field of FSW/P as well as collaboration with different peer groups and an in-depth literature review. Editors most sincerely hope that the book is a valued knowledge source for upcoming research groups, academia, and industry. It is advised to apply the information in this book for promoting research and development in the field of FSW/P and related processes.

All queries, advice, and observations regarding the book are most welcome.

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