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A Review on Recent Advancements in Friction Stir Additive Manufacturing

Siripuram Vivek, Korra Nagu, D Swarnalatha, K Madhukar and Y Pavan
Department of Mechanical Engineering
B V Raju Institute of Technology
Narsapur, Medak, Telangana, 508212, India

Abstract

Friction Stir Additive Manufacturing (FSAM) has emerged as a novel and promising technique for producing components with enhanced mechanical properties. This review explores recent advancements in FSAM, focusing on its potential to address limitations of traditional additive manufacturing methods, such as porosity, residual stress, and anisotropic properties. Key developments in process optimization, tool design, and microstructural refinement are discussed, emphasizing their impact on mechanical performance and microstructure of manufactured components. Additionally, the integration of advanced control systems, machine learning algorithms, and the use of novel interlayer materials for improved bonding are examined. By highlighting these innovations, this review provides insights into the current challenges and future opportunities in the field of FSAM, contributing to the broader understanding of this emerging technology.

Keywords
Friction Stir Additive Manufacturing, Tool Design, Solid-State Welding, Tool Design, Aerospace Manufacturing, Additive Manufacturing.

1. Introduction
Friction Stir Additive Manufacturing (FSAM) represents a cutting-edge technology that integrates the concepts of Friction Stir Welding (FSW) combined with additive manufacturing (AM) processes (Majid et al. 2023). As a solid-state technique, FSAM operates below the melting point of the materials involved, offering distinct advantages over conventional fusion-based additive manufacturing methods like Selective Laser Melting (SLM) and Electron Beam Melting (EBM). FSAM addresses many of the challenges faced by traditional additive manufacturing processes, including issues related to porosity, residual stresses, and microstructural inhomogeneity, which often result in inferior mechanical properties.

FSW, developed by The Welding Institute (TWI) in 1991, was originally used as a method to join materials in the solid state, particularly for materials challenging to weld with conventional techniques, such as aluminium alloys. In FSW, a rotating tool is utilized to produce frictional heat, plasticizing the material without causing it to reach its melting point, resulting in high-quality, defect-free joints (Joey et al. 2019). Leveraging the success of FSW, FSAM emerged as an innovative approach to depositing material layer by layer, combining the benefits of solid-state welding with the flexibility of additive manufacturing (Figure 1).

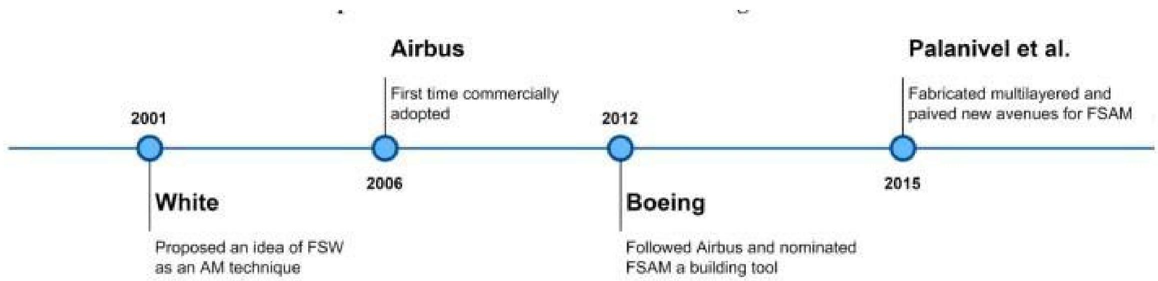

Figure 1. Timeline and development of FSAM (White, 2022).

The motivation behind the development of FSAM lies in the need to improve the material properties of parts produced by additive manufacturing, especially for high-performance applications in aerospace, automotive, and marine industries. These industries require components that exhibit superior strength, durability, and resistance to fatigue, properties that are often compromised by fusion-based additive techniques. In contrast, FSAM produces parts with enhanced grain refinement, reduced porosity, and improved mechanical performance, making it an attractive alternative for producing critical components (Rajib 2023).

Another significant advantage of FSAM is its ability to process a wide range of materials, including dissimilar metals and alloys that are difficult to weld or join using conventional techniques. This capability opens new opportunities for manufacturing multi-material components with tailored properties, which is crucial for industries where material optimization is key to achieving performance goals (Hassan, 2023).

Figure 2. The experimental setup and intricate component created using FSAM by the Edison Welding Institute (EWI) (Cruz, 2022)

In recent years, FSAM has gained considerable attention due to its potential to revolutionize the additive manufacturing landscape (Figure 2). Researchers have explored various aspects of FSAM, from optimizing tool designs to improving process control and automation. These advancements have positioned FSAM as a viable solution for producing large-scale, high-performance parts with improved efficiency and lower defect rates compared to traditional methods.

Despite its promise, FSAM is still in its developmental stages, with challenges remaining in areas such as process scalability, cost reduction, and the expansion of its material capabilities. Moreover, while FSAM has demonstrated superior mechanical properties, its adoption in industrial-scale applications is still limited due to the complexity of the process and the need for precise control over heat generation, tool movement, and material deposition.

The goal of this paper is to provide a comprehensive overview of the FSAM process, its advantages and challenges, and its current and potential applications in industry. We will also examine the future directions of FSAM, including innovations in tool design, material research, and the integration of advanced control systems for enhanced process automation (Musabanganji, 2024).

1.1 Objectives:

The primary objectives of this paper are:
- To provide a detailed understanding of the FSAM process and its unique advantages.
- To explore recent advancements in the field, including tool design and material integration.
- To identify challenges that limit the scalability of FSAM.
- To propose potential improvements and future research directions for FSAM technology.

2. Literature Review:

FSAM is built on the foundation of FSW, which was developed in the 1990s by The Welding Institute. FSW's solid-state process eliminates the need to melt materials, reducing defects such as porosity and cracking. Various studies have explored its extension into additive manufacturing, with research focusing on optimizing tool design, enhancing material compatibility, and improving heat generation control. Recent advances in FSAM demonstrate significant improvements in material properties and manufacturing precision.

FSAM is gaining traction in aerospace applications where the ability to manufacture large, complex parts with superior mechanical properties is critical. Research also highlights FSAM's ability to process dissimilar materials, which is a key advantage over traditional additive methods like laser-based systems.

Mishra et al. (2022conducted an in-depth analysis of friction stir-based additive manufacturing (FSAM), highlighting the ability of FSAM and Additive Friction Stir Deposition (AFSD) to produce high-quality parts with refined microstructures. Their study emphasized that FSAM is a solid-state process, meaning it operates below the material's melting point, thereby eliminating issues such as porosity and residual stress typically seen in fusion based methods. By utilizing plastic deformation, FSAM can fabricate complex parts from materials like aluminium, magnesium, and titanium alloys. Mishra's research also underscores the importance of alloy selection in achieving optimized mechanical properties and overcoming the strength-ductility trade-off.

Hassan et al. (2023) provided a comprehensive review focusing on FSAM of non-ferrous alloys. They found that FSAM results in equiaxed grain structures that improve mechanical properties, such as increased tensile strength and microhardness (Kumar, 2021). The review noted that FSAM components show reduced thermal stresses and fewer
solidification defects compared to fusion-based techniques. The researchers also explored the influence of process parameters, such as tool rotation speed and material thickness (Reddy, 2019), on the final product's quality.

Both studies emphasize that FSAM and AFSD offer superior mechanical properties over conventional methods, particularly when dealing with high-strength alloys. The challenges noted by both groups include tool wear and difficulties in processing high-temperature materials, though ongoing advancements in tool materials and automation show promise for overcoming these limitations.

3. Methods:

FSAM operates by feeding material into a tool that heats and stirs the material using frictional force, allowing the material to be deposited layer by layer (Figure 3). The process occurs below the material's melting point, which significantly reduces common additive manufacturing defects. Key factors in the FSAM process include:
-Tool Design: Proper tool geometry and material are crucial to ensure efficient stirring and bonding.
- Heat Management: Controlling frictional heat ensures proper bonding without overheating the material.

- Layer Deposition: Material is deposited in a controlled manner to achieve the desired geometry with minimal defects (Prototyping, 2019)
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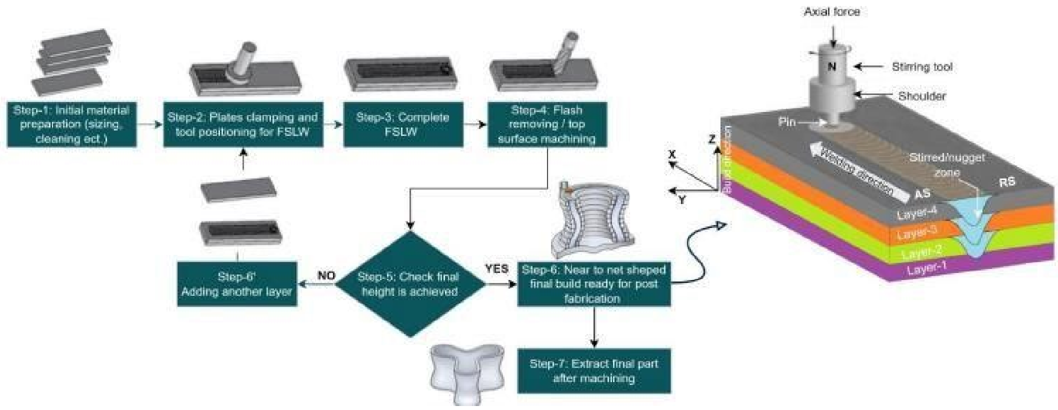

Figure 3. Schematic illustration of FSAM and the resulting four-layered structure produced (Padhi, 2018)

4. Data Collection

Data for this review is collected from recent studies on FSAM applications in various industries. Research papers from journals and conferences, particularly from aerospace and automotive manufacturing, provide insights into the process's effectiveness. Comparative analysis of FSAM versus traditional additive methods (e.g., selective laser melting, electron beam melting) is used to evaluate its performance regarding mechanical properties and manufacturing precision.

5. Results and Discussion

5.1 Numerical Results

Studies indicate that components manufactured using FSAM exhibit higher tensile strength, Figure 4 illustrates the tensile properties, highlighting an increase in hardness, with the yield strength rising from 190 MPa to 267 MPa and the ULTIMATE TENSILE STRENGTH is improved from 336 MPA to 362 MPA [8].The percentage of porosity will also reduce from 60% to 90% compared to those produced using fusion based additive manufacturing. In aerospace applications, FSAM parts show up to 30% higher strength-to-weight ratios. The grain size of a FSAM component is less or similar to 2 micrometres (Figure 5). (Mishra 2022). The Detailed measurements of grain refinement and microstructural properties demonstrate the superior mechanical performance of FSAM components (Hassan, 2023).

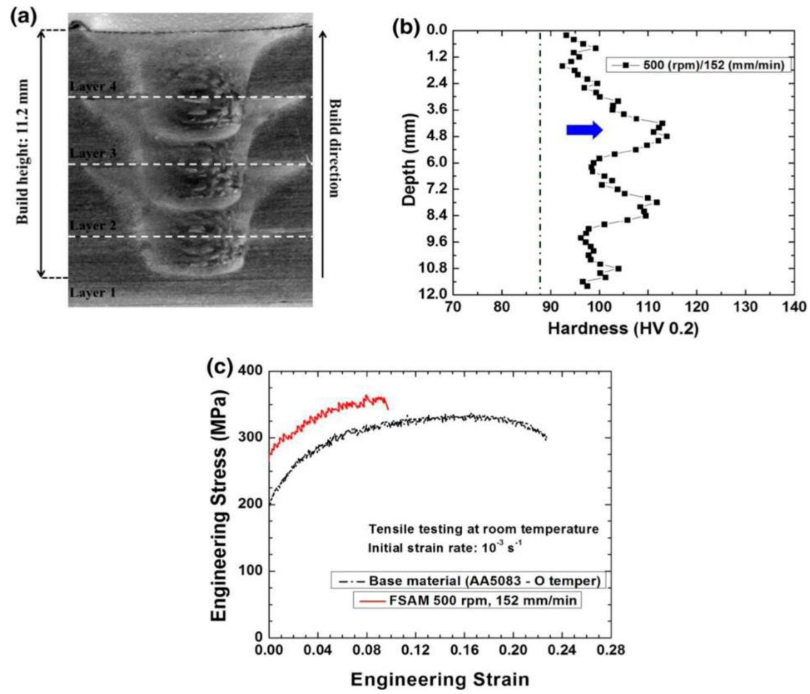

Figure 4. (a) A macrograph displays an AA5083 alloy created through Friction Stir Additive Manufacturing (FSAM) at a speed of 500 rev/min and a feed rate of 152 mm/min, with dashed horizontal lines marking the interfaces of the plates. (b) A microhardness profile along the centreline of the build is shown, with the dash-dot line indicating the hardness of the base material. (c) An engineering stress-strain curve is presented, comparing the base material to the fabricated structure (Palanivel, 2015)

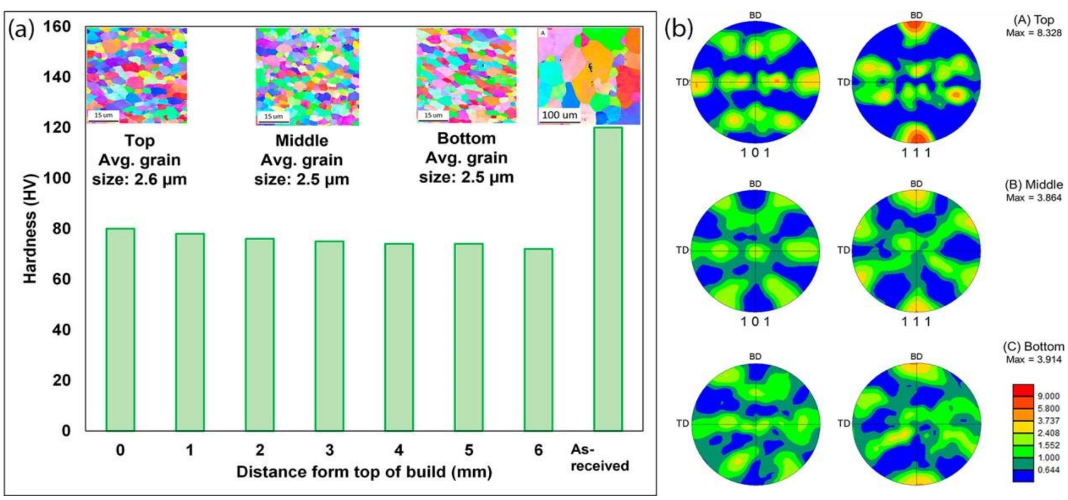

Figure 5. EBSD micrographs display the grain size of the AA 2219 AFSD rod, the deposited AA 2219 material, and the variation in microhardness across the thickness of the deposit. (b) The microstructural texture is presented for the top, middle, and bottom sections of the deposited material (Mishra , 2022).

5.2 Proposed Improvements

Future improvements in FSAM could focus on optimizing the tool geometry to handle a wider range of materials, including high-temperature alloys and composites [18]. Integrating real-time monitoring systems and artificial intelligence (AI) for process control could significantly enhance the precision and scalability of FSAM for largescale industrial applications.

5.3 Validation

Validation of FSAM's performance comes from mechanical testing of components produced using this method. Fatigue testing, hardness measurements, and corrosion resistance tests all confirm the reliability of FSAM in producing high-performance components. Additionally, statistical analysis shows that FSAM consistently outperforms traditional methods in critical applications.

6. Conclusion

FSAM is a transformative technology that combines the best of friction stir welding and additive manufacturing. It offers superior mechanical properties, reduced defects, and improved material efficiency, making it ideal for industries requiring high-strength, lightweight components [10]. While challenges remain in terms of process control and scalability, ongoing research into tool design and automation will continue to expand FSAM's capabilities. This paper concludes that FSAM has the potential to revolutionize modern manufacturing, especially in high performance sectors like aerospace and automotive (Additive Manufacturing for Aerospace Applications, 2018)

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