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Recent Advances in Friction Stir Additive Manufacturing: A Review of Mechanical and Microstructural Performance in Similar and Dissimilar Composites

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1. Introduction

Additive Manufacturing (AM) has revolutionized modern engineering by enabling the layer-by-layer fabrication of complex geometries directly from digital models. This paradigm shift has significantly impacted high-precision industries such as aerospace, automotive, and marine sectors, where lightweight, high-performance materials such as aluminium, magnesium, and titanium are essential [1]. Compared to conventional manufacturing methods, AM offers significant advantages, including enhanced design flexibility, reduced material waste, and the capability to fabricate intricate geometries. However, fusion-based metal AM techniques, such as Directed Energy Deposition (DED) and Direct Metal Laser Sintering (DMLS), present challenges like residual stresses, internal porosity, anisotropic mechanical properties, and the necessity for extensive post-processing. Recent studies have highlighted these issues and explored reduction strategies [2]. To overcome these limitations, solid-state AM techniques have emerged, operating below the melting temperature of metals and relying on frictional heat and plastic deformation for material consolidation. Among these, Friction Stir Welding (FSW), Additive Friction Stir Deposition (AFSD), and Friction Stir Additive Manufacturing (FSAM) represent significant advancements [3]. Friction Stir Welding (FSW) is a solid-state joining method that produces defect-free welds in materials traditionally difficult to fuse. AFSD extends this approach by depositing consumable rods in a layer-wise fashion, achieving fine-grained microstructures without melting [4]. FSAM combines these concepts, employing a layer-by-layer deposition strategy with in-situ reheating and mechanical stirring, which promotes strong interlayer bonding and microstructural homogeneity. The process is particularly suited for high-strength aluminium and titanium alloys, which are challenging to process through conventional AM techniques [5]. Compared to fusion-based techniques, FSAM offers reduced porosity, improved ductility, and minimal thermal distortion. The commercial relevance of FSAM has been recognized since its patenting in 2002 [6], with industrial applications initiated by Airbus in 2006 for efficient aircraft component fabrication [7]. The FSAM process involves the sequential stacking of metallic sheets or plates, joined layer by layer using a rotating tool that generates frictional heat to consolidate the materials. This layer-wise deposition enables precise control over mechanical properties and grain structure. The process begins with the preparation of flat sheets or plates machined to the required dimensions. These are positioned above the base plate of a milling machine, securely clamped at the edges, and processed using a rotating tool equipped with a pin. Upon tool engagement, frictional heat softens the interface, facilitating solid-state bonding between layers. Additional layers are subsequently added in a similar manner until the desired build height is achieved [8]. Fig. 1, a presents the fully fabricated FSAM component, while Fig. 1, b illustrates the tool in operation during the process.

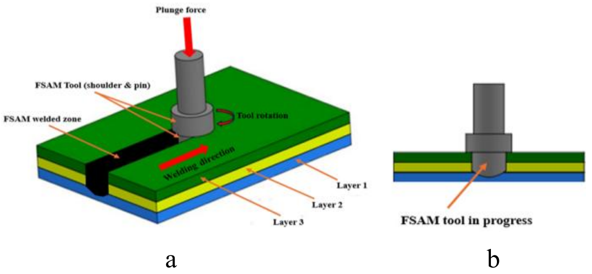

Fig. 1 FSAM process. a – FSAM completed process, b – FSAM tool in progress

This study examines the evolution, underlying mechanisms, and performance characteristics of FSAM, with a particular focus on its advantages over conventional AM techniques. By analyzing the influence of process parameters on both similar and dissimilar material systems, along with corresponding material responses and microstructural developments, the study underscores FSAM's potential as a next-generation manufacturing approach for fabricating high-performance metallic components tailored for advanced engineering applications.

2. Material and Parameter Overview

2.1. Employment of FSAM on similar materials

This section provides an overview of key materials and parameters that impact FSAM effectiveness on similar materials refer to Fig 2.

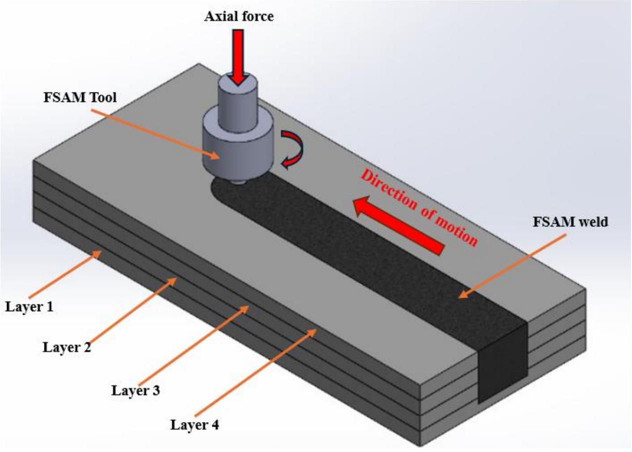

Fig. 2 FSAM technique on similar alloy

Zhao et al. [8] fabricated a multilayered component using the friction stir additive manufacturing (FSAM) technique. The process parameters included a rotational speed of 300 rpm, a traverse speed of 100 mm/min, and an axial pressure of 2 MPa. Microstructural analysis revealed variations in grain structure and size between layers throughout the build. These differences were attributed to localized regions experiencing intense plastic deformation and prolonged thermal exposure during processing. Despite these variations, an average grain size of approximately 6 µm was found to predominate across the entire structure. The build also exhibited a high fraction of recrystallized grains, as evidenced by the dominance of high-angle grain boundaries in different regions. Tensile testing indicated noticeable variations in ultimate tensile strength and elongation along the thickness of the component. These differences in mechanical performance were linked to the previously observed microstructural heterogeneity. Overall, the study demonstrates that the FSAM technique has strong potential to enhance the mechanical properties of aluminium-based components, particularly when microstructural evolution is carefully controlled to optimise performance.

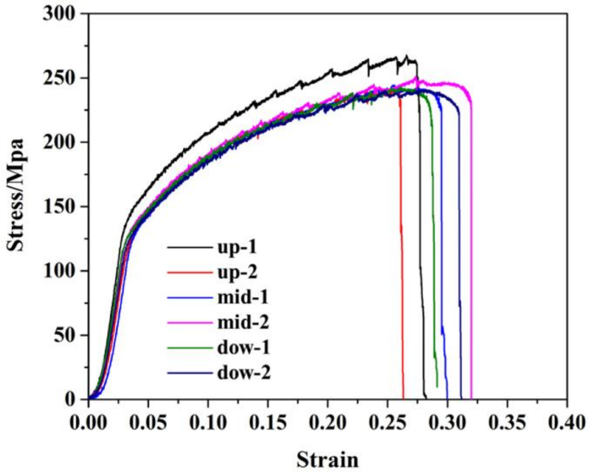

Fig. 3 FSAM component performance: stress vs strain graph [8]

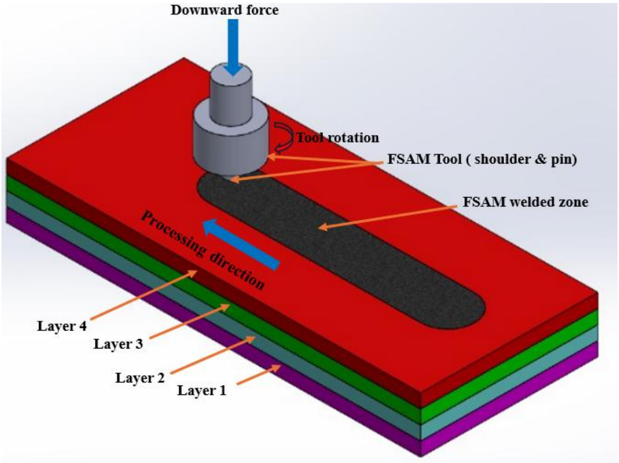

Fig. 4 FSAM technique on dissimilar alloys

2.2. Employment of FSAM on dissimilar materials

For dissimilar materials, FSAM offers a novel way to combine metals and alloys that have various chemical and physical properties, enabling the fabrication of components with enhanced strength that may be challenging to produce using conventional techniques. Refer to Fig. 4 and the following description of dissimilar alloys.

2.3. Effect of process parameters and tool design in FSAM

The optimal parameter selection in FSAM, which includes tool rotation speed, traverse speed, and tool shape,

Table 1

Summary of FSAM studies on similar materials

Ref.	Material(s)	FSAM Parameters	Key Findings	Outcomes
[8]	AA5A06 (multi-layered)	–	Refined grains; high-angle boundaries; proportion of low-angle boundary	Strength increased; elongation increased.
[9]	AA2050, AA2050-T3, AA2050-T6	Rotational speed: not specified; Force: 30 kN	Inhomogeneous hardness: strain concentrated in overlapping HAZs; reduced properties after ageing	UTS decreases from 365 MPa to 354 MPa; Elongation decreases from 10.9% to 9.1%
[10]	7N01-T4 Aluminium (12-layer build)	1200 rpm, 60 mm/min	Strength increased over 6 months; kissing bonds at overlap weakened interface	UTS increased from 353 MPa to 483 MPa (73% of base strength)
[11]	Laminated steel composite (2-layer)	–	Post-annealing showed hot-worked microstructure; excess flow caused surface roughness	Average grain size: 80 µm; surface texture affected
[12]	Al 5A03-H	Traverse speed: 60 mm/min; 0° tilt angle	Wider interfaces with ↑ traverse speed; unjoined zones at large FSAM spacing	Optimal bonding with controlled spacing

Table 2

Comparative summary of FSAM studies on dissimilar composite materials

Ref.	**Material(s) Joined**	**Key FSAM Parameters**	**Main Observations**	**Outcomes**
[13]	AA5053-O / 6061-T6 / 7075-T6	750 rpm, 55 mm/min, plunge: 4.7 mm	Stir zone (SZ) showed grain refinement and highest hardness; TMAZ/HAZ had elongated grains	SZ hardness > other zones; $Al_{0.4}Zn_{0.6}$ peak in XRD
[14]	Cu / Al / Mg / Zn alloys (layered)	700 rpm, 160 mm/min	Microhardness decreased top to bottom; soft zones after ageing	Tensile strength and hardness lowest at top to bottom
[15]	Al-Li 2195-T8 (multi-layered)	800–1000 rpm, 100 mm/min	Weak interfacial bonding; asymmetric hardness at RS/AS	Max UTS - 56.6% of base metal
[16]	Mg-4Y-3Nd / AA5083	800 rpm, 102 mm/min	Post-ageing showed interfacial hardening; refined microstructure	UTS - 336 MPa, Yield - 267 MPa, Max hardness - 135 HV
[17]	AA5086 / C12200 copper	–	Intermetallics ($CuAl_2$, Cu_9Al_4) formed in SZ; thermal strain studied	Peak hardness - 301.4 HV, UTS - 319.5 MPa, ε 19.47%
[18]	Al 5059 / SiC composite (6-layer)	450 rpm, 63 mm/min, 2° tilt	Smaller grains in NZ; high microhardness due to plastic deformation	Microhardness increased by 62% vs base metal
[19]	AA6061-T6 / AA6082	Thermal model-controlled	Grain coarsening in second layer due to reheating variation	Yield - 155.6 MPa; Hardness - 67.3 HV
[20]	Al 6061-T651 / Steel 1018 (bimetallic)	Shoulder: 18 mm, Probe: 8 mm	Effective metallurgical bonding confirmed via SEM	Qualitative microstructural validation
[21]	ST52 / IF Steel (laminate)	600 rpm, 40-100 mm/min, 6 mm pin	Improved bonding at 70 mm/min; oxide layer removal at optimal speed	Yield strength - 472 MPa
[22]	ABS / Silica augmentation	1400 rpm, 80 mm/min	Optimized bending via silica content and pass control	Tensile - 43 MPa; Hardness - 11 HV

Table 3

Summary of FSAM process parameters and tool design

Ref.	**Focus Area**	**Key FSAM Parameters**	**Main Observations**	**Outcomes**
[23, 24, 25, 25, 26, 27]	Process optimization	Rotational & traverse speed	Imbalanced heat (too high/low) causes pores, cracks, voids; material flow strongly parameter-dependent	Optimal heat input critical for quality and structural integrity
[15]	Tool geometry effects	Various pin shapes: threads, tapers, polygons	Pin shape influences plastic flow and grain refinement	Stirring action varies with geometry
[15, 28, 29, 30]	Tool pin design impact	Five pin types (T1–T5); 800 rpm, 100 mm/min	T2, T5 caused poor bonding; T1, T3, T4 (esp. T4) enhanced mixing and bonding	Pin design and dimensions are key to bonding and material mixing
[15]	Tool geometry -Al 2195-T8	5-layer build, five pin geometries	Cylindrical/conical pins with flat sides caused poor bonding; concave/flaring pins enhanced mixing	Maximum tensile strength increased by 56.6%; hardness: 95.7 to 116.8 HV
[15]	Rotational effect on microstructure	800, 900, 1000 rpm; 100 mm/min	Best quality at 800 rpm; higher speeds caused more defects at the top than and lower.	800 rpm yielded superior microstructure and fewer defects compared to others.
[31]	Multi-layer FSAM builds	800-1000 rpm; 100 mm/min	Cavities appeared at higher speeds; top layer most defect-prone	800 rpm achieved uniformity; shoulder effect grows with lower heat
[32, 33, 34, 35]	AA6061 / AA7075	Traverse speed (<40 mm/min, <50 mm/min)	Insufficient plastic flow at high speeds caused tunnelling and wormholes near tool pin AS	Formation defects limited joint quality
[36]	AZ31B-H24 Mg alloy (2-layer)	Tool speed: 500-2000 rpm	Moderate speeds improved bonding: high speeds led to grain coarsening and lower hardness	Strength increased initially; hardness decreased with high rotational speed
[11]	ST52 / IF steel laminate	Traverse speed: 40-70 mm/min	Best uniform bonding achieved at 40 mm/min, poor vertical flow at higher speeds	Improved interface integrity at lower speed
[37]	AZ31B Mg alloy	Traverse speed: 40-160 mm/min	Moderate speeds optimized tensile stress; hardness varied due to dissimilar base materials	Enhanced tensile strength with moderate speed
[38]	Aluminium alloys	Shoulder diameter: 10, 12, 16 mm	Larger shoulders increased heat, 10 mm showed material-dependent effects, grain size impacted	Weld zone hardness increased with refined grain structure

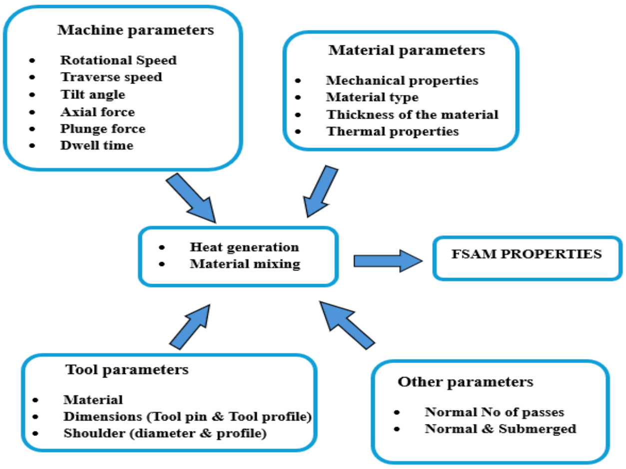

Fig. 5 FSAM parameters

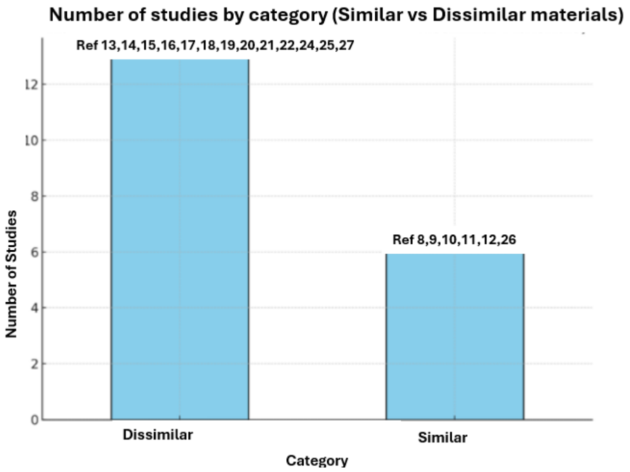

Fig. 6 The use of FSAM on similar and dissimilar materials

is critical for attaining strong material bonding and appropriate mechanical properties. The optimal parameters can be achieved by utilizing various optimization techniques. The incorrect combination of parameters can lead to various macro and microstructural defects [8, 13, 15]. The existence of these defects can results in prematurely failure of the produced material when in service.

Additionally, Fig. 6 illustrates the application of FSAM to both similar and dissimilar materials, highlighting the research focus on combining dissimilar materials to achieve tailored material properties.

3. Microstructural Characteristics in FSAM Fabricated Components

The evolution of microstructure during FSAM plays a pivotal role in determining the mechanical and metallurgical integrity of the final build. Several studies have investigated the grain refinement mechanisms, precipitate behavior, and interface quality within multi-layered FSAM structures fabricated using varying parameters and material systems [39, 40, 41]. Li et al. [37] introduced a novel FSAM approach to fabricate an Al5059-SiC composite using 4 mm thick Al5059 sheets pre-drilled with 1 mm spaced holes filled with SiC powder. This six-layered structure exhibited uniform dispersion of SiC particles in the stir zone (SZ), which significantly refined grain size compared to the thermo-mechanically affected zone (TMAZ) and heat-affected zone (HAZ). The grain refinement was attributed to Al5059's non-heat-treatable nature and the pinning effect of SiC particles that inhibited grain growth during thermal cycling. In a related study, Palanivel et al. [16] employed FSAM at rotational speeds of 1200 rpm and 1400 rpm, using a constant traverse speed of 102 mm/min. SEM analysis indicated that lower rotational speeds, corresponding to reduced heat input, produced very fine equiaxed grains, particularly near the interface. Energy-dispersive spectroscopy (EDS) identified β-phase precipitates with a composition resembling $Mg_{14}NdY_{0.5}$. Notably, intermetallic compounds (IMCs) were absent in the lower rpm builds, suggesting that thermal input was sufficient for dissolution without inducing excessive coarsening [42, 43]. This observation highlights the critical influence of process temperature, strain rate, and peak thermal exposure on microstructural evolution during FSAM. Yuqing et al. [8] conducted an in-depth analysis of a nine-layer FSAM build, revealing the formation of fine, equiaxed grains in the SZ via dynamic recrystallization. However, static annealing effects from successive thermal cycles led to grain size variation along the build direction, with coarser grains at the base and finer grains near the top [44, 45]. Overlapping transition zones featured banded and coarser grains, particularly in the ninth layer where interfacial grain coarsening was evident. Precipitate morphology also followed this pattern, with SEM imaging showing irregular distribution and EDX analysis confirming the presence of T-phase (AlZnMgCu) and η-phase ($MgZn_2$) particles [46]. Hassan et al. [10] employed the friction stir additive man-ufacturing (FSAM) technique to fabricate multilayered Al-7075 composites reinforced with silicon carbide (SiC) and titanium carbide (TiC). The aim of the study was to address the challenge of producing defect-free composites with homogeneous reinforcement while enhancing the microstructural and mechanical properties, as well as evaluating tool wear during processing. The results showed that TiC reinforcement promoted finer grain structures and resulted in higher hardness and tensile strength compared with SiC reinforcement. Furthermore,

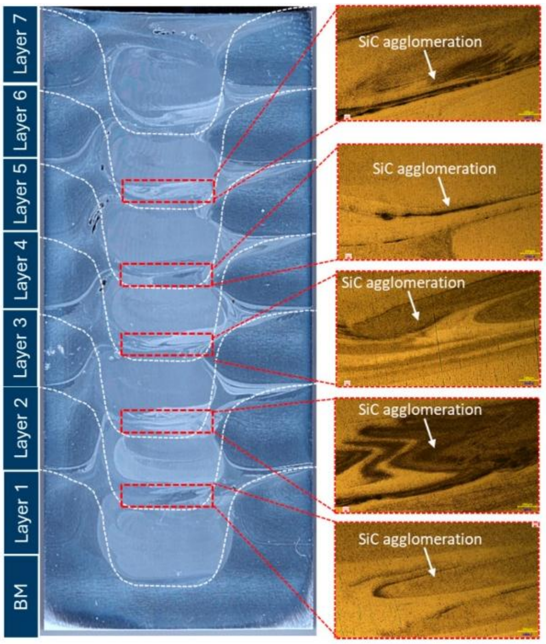

Fig. 7 Macro and micro-structure of FSAM build [10]

post-weld heat treatment (PWHT) led to additional improvements in the mechanical properties of the fabricated composites. The study also revealed that the use of SiC caused more severe tool degradation due to its high abrasiveness, whereas TiC resulted in comparatively lower tool wear. Overall, the findings suggest that TiC is a more suitable reinforcement for the FSAM processing of Al-7075 composites, as it enhances mechanical performance while improving process stability and reducing tool wear.

Despite substantial grain refinement induced by high shear and thermal gradients, defects such as kissing bonds were observed at interfacial regions [47, 48]. These findings underscore the challenges in achieving consistent metallurgical bonding across layers and highlight the sensitivity of FSAM to process-induced heat and mechanical input. Collectively, these studies demonstrate that grain size refinement, precipitate distribution, and interfacial integrity are highly dependent on FSAM parameters, particularly rotational speed, material reinforcement, and thermal history. Optimizing these factors is essential for producing defect-free, high-performance multi-layered structures.

4. Potential Contributions of FSAM to Diverse Manufacturing Industries

Fig. 8 illustrates the estimated contribution of FSAM at various stages of production across multiple sectors within the manufacturing industry. The data highlights FSAM's applicability across several disciplines, including the fabrication of industrial equipment, measuring devices, functional machine components, Pattern moulds and operational equipment, and many more [49]. This underscores the versatility of FSAM as a manufacturing process capable of addressing a broad spectrum of industrial needs. The promising outcomes of FSAM in enhancing microstructural and mechanical properties expand its potential for advanced applications. Its ability to produce components with improved mechanical characteristics suggests FSAM is a promising technique for industries where structural integrity and durability are important. Examples include the production of aviation components and automotive engine parts, where the mechanical performance of materials is prioritized over surface aesthetics [50]. Additionally, the evolving understanding of FSAM's capabilities invites further exploration into its range and optimization. Continued research into this innovative process could unlock new opportunities for its implementation, particularly in high-performance and safety-critical applications, solidifying FSAM's role as a key enabler in modern manufacturing.

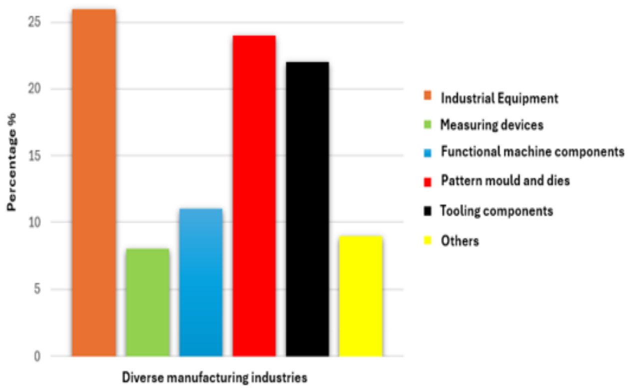

Fig. 8 Potential contributions of FSAM to diverse manufacturing industries

5. Conclusions

1. FSAM is a robust solid-state method that overcomes key limitations of fusion-based techniques for both similar and dissimilar materials.

2. The process improves mechanical properties such as strength, hardness, and wear resistance through microstructural refinement.

3. Grain refinement and interlayer bonding are enhanced via dynamic recrystallization from frictional heat and stirring.

4. Critical process parameters such as rotational, traverse speed, tool geometry strongly influences part quality and structural integrity.

5. FSAM supports uniform particle distribution and defect reduction, especially in reinforced composites.

6. The method enables the joining of dissimilar materials, expanding its versatility for multifunctional applications.

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RECENT ADVANCES IN FRICTION STIR ADDITIVE MANUFACTURING: A REVIEW OF MECHANICAL AND MICROSTRUCTURAL PERFORMANCE IN SIMILAR AND DISSIMILAR COMPOSITES

Summary

This review has examined recent advancements, underlying mechanisms, and performance characteristics of FSAM, with particular emphasis on its application to both similar and dissimilar aluminium composites. FSAM demonstrates significant potential in addressing the limitations of conventional fusion-based additive manufacturing, offering enhanced mechanical properties, refined microstructures, and superior interfacial bonding. A systematic evaluation of key process parameters such as tool geometry, rotational speed, and traverse speed reveals their critical role in defect mitigation and structural optimization. Furthermore, the incorporation of reinforcement particles illustrates FSAM's ability to fabricate composite materials with tailored properties for high-performance applications. Owing to its versatility and capability to fabricate complex, multi-material structures, FSAM stands out as a promising solution for sectors including aerospace, automotive, and biomedical industries. Overall, this study not only consolidates current knowledge but also lays a foundation for continued innovation and optimization in solid-state additive manufacturing technologies.

Keywords: additive manufacturing, aluminium composite, friction stir additive manufacturing, mechanical properties, parameters, microstructure.

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