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Tool Path Strategies and Reinforcement Approaches in Friction Stir Processed Non-Ferrous Alloys: A Comprehensive Review

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***Abstract*— Friction Stir Processing (FSP) has emerged over the past decade as a powerful solid-state technique for tailoring surface and subsurface properties of metallic materials. It enables the development of functionally graded materials (FGMs) exhibiting gradual transitions in micro structure and mechanical behaviour. The intense plastic deformation and thermal cycles inherent to FSP promote ultra-fine-grained micro structures, surface hardening, and homogeneous particle distribution, thereby enhancing strength, wear resistance, and fatigue life. Recent advancements have focused on incorporating reinforcing particulates, forming in-situ and hybrid composite layers, and optimising tool path strategies to achieve controlled property gradients. Path variability—including multi-pass, overlapping, spiral, and contour processing routes—has been recognised as a key parameter influencing material flow, heat input distribution, and defect minimisation. This review summarises the current progress in FSP of non-ferrous metallic alloys such as aluminium, copper, titanium, and magnesium, with emphasis on the mechanisms governing subsurface gradient formation, micro structural refinement, and the resulting mechanical and tribological properties. The paper also highlights the impact of process parameters, tool design, and tool path variability on micro structure–property relationships, providing a comprehensive overview of FSP as a versatile platform for surface engineering and advanced material design.**

***Keywords*—Friction Stir Processing, micro structure and Path variability.**

I. Introduction

Al–Li 2195 is widely used in aerospace structures because of its low weight and high specific strength, but its performance can be limited by non-uniform precipitate distribution, surface defects, and micro structural inconsistencies. Friction Stir Processing (FSP), a solid-state refinement technique, has emerged as an effective method to improve micro structural homogeneity and mechanical behavior in this alloy as shown in fig.I.

Studies have shown that carefully selected tool rotational and traverse speeds encourage dynamic re-crystallization, producing fine, equiaxed grains and enhancing tensile strength, hardness, fatigue life, and corrosion resistance [1][3]. FSP has also been applied in additive manufacturing routes such as friction stir additive manufacturing, where micro structural stability depends heavily on thermal cycling and heat input control across deposited layers [10]. Parameter optimization approaches, including DOE and hybrid Taguchi–ANN frameworks, have further enabled prediction and fine-tuning of surface integrity and mechanical response [6][11].

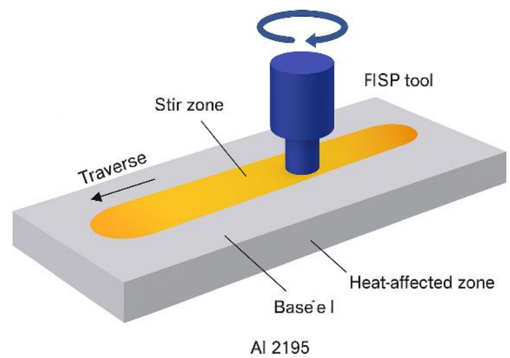

Fig. I. Schematic setup diagram of the friction stir processing process

Recent research has expanded FSP to create reinforced surface and bulk composites by incorporating ceramic nano particles such as TiB_2, Al_2O_3, TiC, B_4C, and SiC to improve wear resistance, hardness, and thermal stability [2][4][5]. Multi-pass FSP techniques have demonstrated their effectiveness in enhancing dispersion uniformity and reducing reinforcement agglomeration. However, excessive heat accumulation or too many passes can cause precipitate coarsening and slight ductility loss, highlighting the need for optimised interpass cooling and a suitable pass count [7][8][9][13][15].

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Comprehensive reviews emphasize the competing effects of grain refinement and thermal softening in multi-pass processing and call for improved quantitative characterization to define robust processing windows [12][14]. Collectively, the literature confirms that controlled FSP and reinforcement strategies provide a powerful route to tailor the micro structure and mechanical performance of Al–Li 2195 for demanding aerospace applications.

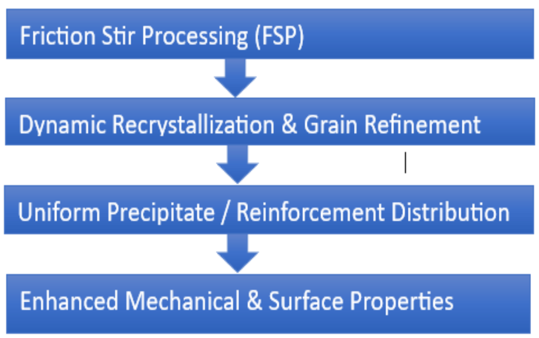

Fig.II. Schematic setup diagram of the Friction Stir Processing Process

II. Review

Rajakumar and Balasubramanian (2022) investigated the micro structural evolution and mechanical behaviour of friction stir-processed Al–Li 2195 alloy. The study revealed significant grain refinement in the stir zone due to dynamic recrystallisation. Optimal tool rotational and traverse speeds produced enhanced tensile strength and hardness with minimal defects. Micro structural analysis showed uniform redistribution of strengthening precipitates. The research concluded that controlled FSP parameters can effectively improve the performance of Al–Li 2195 for aerospace applications.

Singh, Mehta, and Chattopadhyay (2023) developed Al2195/TiB_2 surface composites using friction stir processing, demonstrating effective in-situ incorporation of TiB_2 into the alloy matrix. The study reported marked increases in surface hardness and wear resistance compared to the base Al2195, attributed to hard-particle reinforcement and grain refinement. Micro structural characterisation showed relatively uniform TiB_2 dispersion in the stir zone with reduced particle agglomeration under optimised tool parameters. Process variables (rotation and traverse speeds) were identified as critical for balancing material flow, heat input, and reinforcement distribution in 3rd phase of FSP as shown in fig. II.

The authors conclude that FSP-mediated TiB_2 reinforcement significantly enhances surface properties of Al2195 for potential high-performance applications.

Chen and Zhang (2021) explored the effects of friction stir processing on the fatigue and corrosion behavior of Al–Li 2195 alloy. Their study revealed that FSP significantly reduced surface defects and porosity, leading to enhanced fatigue life. The refined grain structure and homogenized micro structure improved corrosion resistance through the formation of a stable passive layer. Optimal process parameters were found to balance mechanical strength and corrosion performance. The authors concluded that FSP is an effective post-processing technique to improve the durability of Al–Li 2195 alloys for aerospace applications.

Ramesh and Senthil Kumar (2023) examined the impact of multiple friction stir processing passes on Al2195–Al_2O_3 nanocomposites, showing that successive passes greatly improved particle distribution and reduced agglomeration. Multi-pass FSP promoted further grain refinement and increased micro hardness in the stir zone compared with single-pass processing. TEM and SEM analyses revealed a more homogeneous dispersion of Al_2O_3 nanoparticles and a reduction in voids and interfacial defects after repeated passes. Mechanical testing indicated notable gains in yield strength and wear resistance, with a modest trade-off in ductility. The study concludes that controlled multi-pass FSP is an effective route to produce high-performance Al2195–Al_2O_3 nanocomposites for structural applications.

Patel and Kumar (2022) conducted a comparative investigation of Al2195 and AA7075 composites reinforced with TiC nanoparticles through friction stir processing. The study demonstrated that Al2195 exhibited superior mechanical strength and lower porosity compared to AA7075 under identical processing conditions. Uniform TiC nanoparticle distribution led to enhanced hardness, wear resistance, and thermal stability in both alloys. Micro structural analysis confirmed refined grains and strong interfacial bonding between the matrix and reinforcement. The authors concluded that FSP with TiC reinforcement effectively improves the performance of Al2195 alloys for advanced structural and aerospace applications.

Ghosh and Rao (2024) optimized friction stir processing parameters for Al2195/B_4C surface composites using combined Taguchi and artificial neural network (ANN) techniques. Their study identified the most influential factors affecting hardness, tensile strength, and surface integrity. The hybrid Taguchi–ANN model accurately predicted optimal process conditions, minimizing experimental effort while maximizing material performance.

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Results showed that optimized parameters produced uniform B_4C dispersion, refined grains, and significantly enhanced mechanical properties. The authors concluded that integrating statistical and AI-based approaches provides an efficient framework for parameter optimization in FSP of Al2195 composites.

Muribwathoho, Mabuwa & Msomi (2020) review multi-pass friction stir processing (FSP) across aluminium alloys, synthesizing experimental observations on how repeated passes affect micro structure and properties. They report that successive passes generally improve particle dispersion and homogenization, reduce agglomeration, and produce finer, more equiaxed grains in the stir zone. The review highlights consistent gains in hardness, wear resistance, and tensile strength with up to an optimum number of passes, beyond which accumulated heat can cause precipitate coarsening or grain growth. Key process factors—tool geometry, rotation/traverse speeds, and inter pass cooling—are shown to control the balance between refinement and thermal softening. The authors call for standardized reporting of thermal cycles, quantitative EBSD/TEM metrics, and alloy-specific studies (e.g., Al–Li 2195) to better correlate multipass histories with precipitate evolution and long-term performance.

Raja et al. (2024) investigated the effects of multi-pass friction stir processing as shown in schematic diagram in fig.III, micro hardness and micro structure, showing that successive passes generally increase micro hardness in the stir zone due to progressive grain refinement and breakup of reinforcement clusters. EBSD and SEM analyses revealed a transition to finer, more equiaxed grains and more homogeneous particle distribution with 2–3 passes, while additional passes produced diminishing returns. The authors documented an optimal pass window where strengthening from strain-induced recrystallization outweighs softening from accumulated heat. Wear tests correlated hardness gains with improved tribological performance, but tensile ductility showed modest reduction at higher pass numbers. The study emphasizes careful control of interpass cooling and tool parameters to maximize the benefits of multi-pass FSP without causing precipitate coarsening or grain growth.

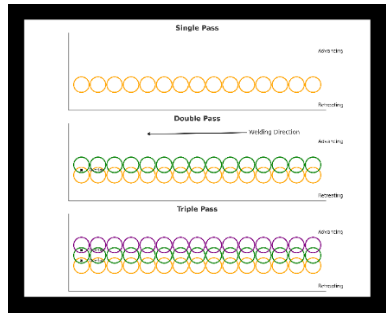

Fig. III. Schematic diagram of the multi-pass friction stir processing process

El-Sayed (2023) examines the effects of multi-pass friction stir alloying on Al-based composites, reporting that successive passes refine the grain structure and promote more uniform reinforcement dispersion in the stir zone. The study finds progressive increases in micro hardness and wear resistance with 1–3 passes, while additional passes show diminishing returns or slight softening due to accumulated thermal exposure. TEM/SEM evidence highlights reduced particle agglomeration and stronger matrix–reinforcement interfaces after controlled multi-pass processing. Mechanical testing indicates improved yield and tensile strength but a possible modest loss in ductility at high pass counts. The paper emphasises optimisation of interpass cooling, tool geometry, and parameter control to maximise strengthening while avoiding precipitate coarsening and grain growth.

Shen et al. (2022) investigated friction stir additive manufacturing (FSAM) of 2195 Al–Li, mapping local micro structure evolution across deposited layers and correlating it with mechanical performance. EBSD and TEM analyses revealed layer-dependent grain refinement, recrystallised nugget zones, and variation in precipitate distribution due to cyclic thermal-mechanical exposure. Mechanical testing showed improved hardness and tensile strength in optimally processed regions, but marked anisotropy and property gradients persisted between layers. The study highlights the importance of controlling tool path, heat input, and interpass conditions to minimise heterogeneity and preserve Al–Li strengthening precipitates for aerospace-grade performance.

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Alzahrani et al. (2023) optimized the friction stir processing (FSP) parameters for AlSi7Mg0.2 alloy to maximize mechanical property improvements using a design of experiments approach. They found that appropriate combinations of rotational speed, traverse speed, and tool tilt angle significantly refined grain structure and redistributed Si particles more uniformly in the stir zone. Micro hardness and tensile strength increased notably, attributed to grain boundary strengthening and refined second-phase dispersion. The study's regression models allowed prediction of optimal FSP settings, making it useful for process control. Although this work focuses on AlSi7Mg0.2 rather than Al2195, the methodology and insights into parameter-property relationships are highly applicable to friction stir processing of Al–Li alloys.

Khan, Butola & Gupta (2023) present a comprehensive review of nanoparticle-reinforced surface composites manufactured by friction stir processing (FSP), covering a broad range of matrices, reinforcements, process conditions, and properties. They compile and analyze how nanoparticle type, volume fraction, tool geometry, and FSP parameters influence grain refinement, particle dispersion, hardness, wear resistance, and tensile behavior. The review highlights the challenges of reinforcement clustering, porosity, and interfacial bonding, and discusses strategies (such as multi-pass FSP, pre-placement, and stirring aids) to mitigate them. It provides a detailed table of parameter-property relationships, making it a valuable reference for parameter optimization in systems like Al2195-based composites. The authors emphasize future directions including real-time thermal monitoring, machine learning for parameter selection, and life-cycle evaluation of FSP composites for critical structural applications.

Srivastava et al. (2019) examined multi-pass FSP of Al–Mg/SiC surface composites and systematically assessed how SiC reinforcement and different cooling media affect micro structure and properties. They found that appropriate cooling (e.g., water/air-assisted) reduces peak temperatures, limits particle agglomeration, and promotes finer, more uniform SiC distribution in the stir zone.

Multi-pass processing improved particle break-up and homogeneity, leading to increased micro hardness and wear resistance compared with single-pass FSP. However, excessive passes or inadequate cooling caused thermal accumulation, precipitate coarsening, and slight reductions in ductility. The study highlights the critical role of cooling strategy and controlled pass count to balance grain refinement and thermal stability in Al-Mg/SiC FSP composites. Heidarzadeh et al. (2023) present a comprehensive review of multipass friction stir processing across a range of alloys, systematically comparing micro structural evolution, mechanical and tribological outcomes. The authors synthesize evidence that successive FSP passes generally enhance particle break-up, homogenize reinforcement distribution, and refine grains—up to an alloy-dependent optimum pass number. They emphasize the competing effects of strain-induced recrystallization (strengthening) versus thermal accumulation (possible precipitate coarsening or grain growth) when passes are increased. The review consolidates best practices for tool geometry, interpass cooling, and parameter windows to maximize benefits while minimizing thermal softening. Finally, it calls for standardized reporting of thermal cycles and quantitative EBSD/TEM metrics to enable clearer cross-study comparisons and alloy-specific optimization.

Fashami (2020) investigated multi-pass friction stir processing of AZ91 magnesium alloy, focusing on how repeated passes alter thermal cycles and resultant mechanical behavior. The study showed that initial passes promote severe plastic deformation and dynamic recrystallization, producing finer, equiaxed grains and increased hardness. Accumulated heat from successive passes was found to reduce the marginal gains—leading to partial recovery or coarsening of grains when interpass cooling was insufficient. Mechanical tests demonstrated improved yield and wear resistance after an optimal number of passes, but further passes caused slight ductility loss. The paper highlights the importance of controlling interpass cooling, tool parameters, and pass count to maximize strengthening while avoiding thermal softening.

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TABLE I
SEVERAL REINFORCEMENT PROPERTIES, APPLICATIONS, AND THE NUMBER OF PASSES ARE USED IN THE DEVELOPMENT OF FSPS.

S.No	Base Material	Reinforced Material	Reinforced Material Properties	Applications	No Of Passes
1	AA6082-T651 and AA8011-H14	--	--	Structural,Automotive,Aerospac e and Marian Applications(7).	1,2,3,4
2	AZ91 Magnesium Alloy	--	--	Automotive Components (Gear box housings,brackets) Laptop and mobile Frames (15).	1,2
3	AA6061	SiC	Improve Hardness,Better wear resistance	Light weight load bearing parts(16).	1,2
4	ZE41 Megnisium alloy	B_4C	wear resistance, Hardness, Load bearing capacity.	Automotive light weight Structural parts(17).	1,2
5	Al-8.5Fe-1.3 V-1.7Si (Fvs0812) alloy.	--	--	High Temperature resistance,Toughness and fatigue strength(18).	1,2,4

Hardik Vyas et al. reported that Friction stir processing (FSP) has been widely employed to modify the surface and enhance the mechanical performance of aluminum alloys such as AA6061. In the reported investigation, multi-pass FSP with 100% overlap was performed using constant processing parameters while varying the number of passes, tool rotation directions (clockwise and anti-clockwise), and processing paths (forward, reverse, and revert). Surface inspection, macro structural features, and micro structural evolution revealed significant changes in the processed zone compared to the base material. Multi-pass FSP induced intense dynamic recrystallization, resulting in a refined and homogeneous grain structure with reduced grain size relative to single-pass and base alloy conditions. Two-pass FSP exhibited superior hardness due to enhanced grain refinement and strain accumulation. However, double-sided FSP led to a reduction in tensile strength, indicating over-processing effects. Notably, single-pass and two-pass FSP showed comparable tensile strength values, highlighting the effectiveness of controlled multi-pass processing. Overall, the study demonstrates that multi-pass FSP with optimized overlap and processing directions significantly influences micro structural refinement and mechanical behavior of AA6061.

Paidar et al. (2019) investigated the influence of multi-pass friction stir processing (FSP) on the micro structure, mechanical behavior, and tribological performance of an Al/B_4C composite fabricated via accumulative roll bonding.

The study demonstrated that successive FSP passes significantly improved the dispersion uniformity of B_4C reinforcement particles within the aluminum matrix. Multi-pass processing promoted intense plastic deformation and dynamic recrystallization, leading to substantial grain refinement and enhanced interfacial bonding between the matrix and reinforcement. As the number of FSP passes increased, micro-structural homogeneity was markedly improved while particle agglomeration was minimized. Mechanical testing revealed notable improvements in hardness and strength due to refined grain structure and effective load transfer mechanisms. Additionally, wear resistance and tribological performance were enhanced with increasing FSP passes. The results confirmed that multi-pass FSP is an effective post-processing technique for optimizing micro structural integrity and functional properties of Al/B_4C composites.

III. CONCLUSION

Friction Stir Processing has proven to be a highly effective solid-state technique for tailoring surface and subsurface characteristics of non-ferrous metallic alloys, particularly Al–Li 2195. The reviewed studies demonstrate that severe plastic deformation and controlled thermal exposure inherent to FSP contribute to refined micro structures, homogeneous distribution of reinforcement phases, and improved mechanical and tribological performance.

Incorporation of particulates such as TiB_2, B_4C, SiC, TiC, and Al_2O_3 has been shown to significantly enhance micro hardness, tensile strength, fatigue resistance, and wear behaviour as shown in table I. Furthermore, multi-pass and overlapping tool path strategies enable greater surface modification depth and structural uniformity, although excessive heat accumulation may lead to grain coarsening if not optimized.

The literature also emphasizes the critical role of process parameters, tool geometry, and path sequencing in governing defect-free surface composite formation and gradient property development. Data-driven optimization approaches such as Taguchi design and ANN-based modeling have contributed to more reliable parameter selection for targeted performance outcomes. Despite notable advancements, achieving precise control over gradient transition zones, mitigating residual stresses, and maintaining stability of nano-reinforcements remain ongoing challenges.

Overall, FSP continues to evolve as a versatile platform for surface engineering and functionally graded material design. Future research directions include multi-scale modeling of material flow, real-time thermal control, integration with additive manufacturing routes, and long-term performance evaluation under complex service environments. Such developments are expected to broaden the applicability of FSP in aerospace, marine, and structural components requiring lightweight, high-strength, and wear-resistant surfaces.

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