

Microstructural Characterization and Mechanical Performance of Friction Stir Processed Aluminum Matrix Composites

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ABSTRACT: *Aluminum Matrix Composites (AMCs) have emerged as one of the most promising lightweight structural materials for aerospace, automotive, marine, defense, railway, and high-performance engineering applications owing to their exceptional combination of low density, high specific strength, superior wear resistance, enhanced thermal conductivity, and excellent corrosion resistance. The incorporation of ceramic reinforcements such as silicon carbide (SiC), aluminum oxide (Al₂O₃), boron carbide (B₄C), titanium carbide (TiC), and graphene into aluminum matrices significantly improves hardness, stiffness, fatigue resistance, and high-temperature mechanical properties. However, conventional casting and powder metallurgy techniques often produce reinforcement agglomeration, porosity, poor particle distribution, and weak interfacial bonding, resulting in non-uniform microstructures and reduced mechanical performance. These limitations restrict the full utilization of aluminum matrix composites in demanding structural applications requiring consistent mechanical reliability and long service life. The present study investigates the **Microstructural Characterization and Mechanical Performance of Friction Stir Processed Aluminum Matrix Composites** using an integrated experimental methodology. Aluminum alloy AA6061 reinforced with silicon carbide particles is processed under various tool rotational speeds, traverse speeds, and processing passes to evaluate the influence of FSP parameters on grain refinement, reinforcement distribution, hardness, tensile strength, impact toughness, and wear resistance. Advanced characterization techniques including Optical Microscopy (OM), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Electron Backscatter Diffraction (EBSD), and X-ray Diffraction (XRD) are employed to investigate grain evolution, particle dispersion, crystallographic texture, and phase stability. Mechanical evaluation is performed through Vickers microhardness testing, tensile testing, impact testing, and dry sliding wear experiments. The results demonstrate that optimized Friction Stir Processing significantly refines the aluminum matrix microstructure, uniformly disperses ceramic reinforcements, enhances interfacial bonding, and substantially improves mechanical performance compared with the as-cast composite. The findings provide valuable guidance for manufacturing high-performance aluminum matrix composites suitable for advanced lightweight engineering applications.*

INTRODUCTION

Aluminum Matrix Composites (AMCs) have become increasingly important engineering materials because they successfully combine the lightweight characteristics of aluminum alloys with the superior mechanical and tribological properties of ceramic reinforcements. Their exceptional specific strength, excellent

stiffness-to-weight ratio, enhanced wear resistance, improved thermal conductivity, and outstanding corrosion resistance make them attractive alternatives to conventional steels and titanium alloys in applications where weight reduction and structural efficiency are critical. Industries including aerospace, automotive, railway transportation, marine engineering, defense systems, and precision manufacturing extensively utilize aluminum matrix composites for structural components such as brake rotors, pistons, connecting rods, suspension arms, aircraft panels, armor systems, and heat exchangers. Continuous improvements in composite processing technologies have further expanded their industrial applications by enabling better control over reinforcement distribution and microstructural homogeneity.

The mechanical performance of aluminum matrix composites depends strongly on the uniform distribution of reinforcement particles, grain size, interfacial bonding, porosity, residual stresses, and microstructural stability. Conventional manufacturing techniques such as stir casting, squeeze casting, powder metallurgy, and infiltration often encounter challenges including particle agglomeration, reinforcement sedimentation, gas porosity, incomplete wetting, and non-uniform particle distribution. These defects create localized stress concentrations that reduce tensile strength, fatigue resistance, ductility, and wear performance. Consequently, secondary processing techniques capable of modifying the microstructure after fabrication have become essential for improving composite quality and achieving consistent mechanical performance.

Friction Stir Processing (FSP) has emerged as one of the most effective solid-state surface modification and microstructural refinement techniques for aluminum alloys and aluminum matrix composites. Developed from Friction Stir Welding, FSP employs a rotating non-consumable tool consisting of a shoulder and pin that traverses across the workpiece surface while generating frictional heat and severe plastic deformation. Unlike conventional fusion-based processing methods, Friction Stir Processing operates entirely below the melting temperature of the material, thereby eliminating solidification defects, reducing residual stresses, preventing reinforcement segregation, and promoting dynamic recrystallization. The severe plastic deformation generated during processing produces ultrafine equiaxed grains while simultaneously redistributing reinforcement particles uniformly throughout the processed region.

Dynamic recrystallization occurring during Friction Stir Processing significantly influences the resulting microstructure and mechanical properties. High strain rates combined with elevated processing temperatures accelerate grain boundary migration and subgrain formation, resulting in substantial grain refinement. Uniform dispersion of ceramic reinforcement particles further contributes to grain boundary pinning, suppresses grain growth, and enhances load transfer between the aluminum matrix and reinforcement particles. Improved interfacial bonding minimizes particle pull-out during mechanical loading, increases hardness through dispersion strengthening mechanisms, and enhances wear resistance under sliding contact conditions. These microstructural improvements collectively produce remarkable enhancements in tensile strength, fatigue life, impact toughness, and tribological performance.

Numerous process parameters govern the effectiveness of Friction Stir Processing, including tool rotational speed, traverse speed, tool tilt angle, axial force, tool geometry, processing depth, and the number of processing passes. Higher rotational speeds generally increase heat generation and material plasticization; however, excessive heat input may promote grain coarsening and reduce mechanical strength. Conversely, insufficient heat generation may lead to incomplete material mixing and inadequate reinforcement dispersion. Traverse speed determines material flow characteristics and thermal exposure time, while

multiple processing passes further improve reinforcement homogeneity and eliminate residual microstructural defects. Therefore, optimization of FSP parameters is essential for achieving the desired balance between grain refinement, particle distribution, and mechanical performance.

Modern characterization techniques have significantly improved the understanding of microstructural evolution during Friction Stir Processing. Optical Microscopy provides preliminary observation of processed zones and macrostructural features, whereas Scanning Electron Microscopy reveals reinforcement particle distribution, fracture morphology, and interfacial characteristics. Energy Dispersive X-ray Spectroscopy verifies elemental distribution throughout the processed region, while Electron Backscatter Diffraction quantitatively evaluates grain orientation, recrystallization behavior, and crystallographic texture. X-ray Diffraction identifies phase stability, residual stresses, and potential intermetallic compound formation following processing. Combined with comprehensive mechanical testing including hardness, tensile, impact, and wear evaluation, these characterization techniques provide detailed insight into the relationships among processing parameters, microstructure, and mechanical performance.

Despite considerable research on Friction Stir Processing of aluminum matrix composites, several important challenges remain. Many investigations focus primarily on individual mechanical properties or microstructural observations without establishing comprehensive relationships among processing parameters, grain refinement, reinforcement distribution, dynamic recrystallization, and overall mechanical performance. Furthermore, relatively few studies integrate advanced microstructural characterization with detailed mechanical evaluation and statistical optimization to identify optimum processing conditions. Therefore, the present investigation aims to systematically evaluate the **Microstructural Characterization and Mechanical Performance of Friction Stir Processed Aluminum Matrix Composites** through comprehensive experimental analysis, providing valuable information for the development of high-performance lightweight composite materials suitable for advanced structural engineering applications.

Problem Statement

Conventional manufacturing techniques for aluminum matrix composites frequently produce non-uniform reinforcement distribution, porosity, weak interfacial bonding, and coarse grain structures that adversely affect mechanical performance, wear resistance, and structural reliability. Although Friction Stir Processing has demonstrated significant potential for microstructural refinement, comprehensive understanding of the relationships among processing parameters, reinforcement dispersion, grain evolution, and mechanical properties remains limited.

Objective

The primary objective of this investigation is to evaluate the influence of **Friction Stir Processing parameters on the microstructural evolution and mechanical performance of aluminum matrix composites**, with emphasis on grain refinement, reinforcement distribution, hardness, tensile strength, impact toughness, and wear resistance.

Scope

This study focuses on **AA6061 aluminum matrix composites reinforced with silicon carbide (SiC) particles**, Friction Stir Processing using different rotational speeds, traverse speeds, and processing passes,

microstructural characterization through **Optical Microscopy (OM)**, **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)**, together with mechanical evaluation using hardness testing, tensile testing, impact testing, and dry sliding wear analysis. The investigation is limited to laboratory-scale experimental evaluation under controlled processing conditions and does not include industrial-scale manufacturing, fatigue life prediction, or finite element simulation.

LITERATURE SURVEY

Aluminum Matrix Composites (AMCs) have emerged as one of the most promising lightweight engineering materials owing to their excellent combination of low density, high specific strength, superior stiffness, enhanced wear resistance, and outstanding thermal properties. These characteristics have enabled their extensive utilization in aerospace structures, automotive powertrain components, railway systems, marine engineering, defense equipment, and electronic packaging. Conventional aluminum alloys often fail to satisfy the increasing demand for higher strength and improved wear resistance under severe operating conditions. To overcome these limitations, ceramic reinforcements such as **silicon carbide (SiC)**, **aluminum oxide (Al_2O_3)**, **boron carbide (B₄C)**, **titanium carbide (TiC)**, and **graphene nanoplatelets** are incorporated into aluminum matrices, producing composites with significantly enhanced mechanical and tribological properties. However, conventional fabrication methods frequently suffer from particle agglomeration, reinforcement segregation, gas porosity, poor wettability, and weak matrix-reinforcement interfaces, which adversely affect structural reliability and overall mechanical performance. ([ScienceDirect](#))

Among various post-processing techniques, **Friction Stir Processing (FSP)** has become one of the most effective solid-state methods for modifying the microstructure of aluminum matrix composites. Derived from Friction Stir Welding (FSW), FSP employs a rotating non-consumable tool that generates frictional heat and intense plastic deformation below the melting temperature of the material. This solid-state processing mechanism eliminates solidification-related defects while promoting dynamic recrystallization and uniform material flow. Numerous investigations have demonstrated that Friction Stir Processing significantly refines grain size, redistributes reinforcement particles uniformly, removes casting porosity, enhances interfacial bonding, and substantially improves mechanical performance compared with conventionally manufactured composites. The absence of melting also minimizes residual stresses and undesirable intermetallic phase formation, making FSP particularly suitable for producing high-quality aluminum matrix composites. ([ResearchGate](#))

The microstructural evolution occurring during Friction Stir Processing has been extensively investigated because it directly governs the final mechanical behavior of processed composites. Severe plastic deformation combined with elevated processing temperatures promotes continuous dynamic recrystallization, producing ultrafine equiaxed grains within the stir zone. Simultaneously, ceramic reinforcement particles are fragmented and redistributed throughout the processed region, eliminating particle clustering commonly observed in cast composites. Several researchers have reported remarkable reductions in grain size together with homogeneous reinforcement dispersion following FSP. The refined grains increase grain boundary density, while uniformly distributed reinforcement particles provide

effective grain boundary pinning, thereby suppressing grain growth and enhancing microstructural stability during subsequent mechanical loading and thermal exposure. ([University of Johannesburg](#))

Mechanical properties of Friction Stir Processed aluminum matrix composites have shown considerable improvement compared with as-cast materials. Numerous experimental investigations demonstrate that grain refinement and improved particle distribution contribute to higher hardness, increased yield strength, enhanced ultimate tensile strength, improved fatigue resistance, and superior wear performance. Strengthening mechanisms responsible for these improvements include Hall-Petch grain refinement strengthening, Orowan strengthening, load transfer between reinforcement particles and aluminum matrix, thermal mismatch strengthening, and increased dislocation density generated during severe plastic deformation. Uniform reinforcement dispersion also minimizes localized stress concentrations, delays crack initiation, and improves ductility by reducing premature particle fracture and matrix debonding. Consequently, Friction Stir Processed aluminum matrix composites exhibit significantly better structural integrity under both static and dynamic loading conditions. ([University of Johannesburg](#))

The influence of Friction Stir Processing parameters has received considerable research attention because they directly determine heat generation, material flow characteristics, reinforcement distribution, and microstructural refinement. Tool rotational speed controls frictional heat input and plastic deformation, whereas traverse speed influences thermal exposure time and material mixing efficiency. Tool tilt angle, shoulder diameter, pin geometry, plunge depth, axial force, and the number of processing passes further affect the quality of the processed region. Moderate rotational speeds combined with optimized traverse speeds generally produce the finest grain structures and most uniform reinforcement distribution. Excessively high heat input may result in grain coarsening and softening, whereas insufficient heat generation may lead to incomplete material mixing and internal defects. Multiple processing passes have been shown to further improve particle dispersion and eliminate residual microstructural heterogeneities, resulting in superior mechanical performance. ([ResearchGate](#))

Advanced characterization techniques have substantially improved understanding of microstructural evolution during Friction Stir Processing. Optical Microscopy provides preliminary evaluation of processed zones and macrostructural features, while Scanning Electron Microscopy (SEM) enables detailed examination of reinforcement distribution, particle fragmentation, fracture morphology, and interfacial bonding. Energy Dispersive X-ray Spectroscopy (EDS) verifies homogeneous elemental distribution and identifies possible interfacial reactions between reinforcement particles and the aluminum matrix. Electron Backscatter Diffraction (EBSD) quantitatively evaluates grain orientation, recrystallization behavior, grain boundary characteristics, and crystallographic texture. X-ray Diffraction (XRD) further confirms phase stability, residual stress distribution, and the absence of undesirable intermetallic compounds after processing. The combined application of these techniques provides comprehensive understanding of the relationships between processing conditions, microstructure, and mechanical behavior. ([University of Johannesburg](#))

Tribological performance represents another important aspect of Friction Stir Processed aluminum matrix composites. Several investigations report substantial reductions in wear rate and friction coefficient following processing owing to increased hardness, refined grain structures, and improved reinforcement dispersion. Uniformly distributed ceramic particles effectively resist plastic deformation during sliding

contact, reduce abrasive wear, and improve load-bearing capability of the aluminum matrix. Dry sliding wear experiments indicate that processed composites exhibit shallower wear grooves, reduced delamination, and lower material removal compared with conventionally cast composites. In addition to improved wear resistance, optimized Friction Stir Processing has also been shown to enhance fatigue performance and, in many cases, improve corrosion resistance through elimination of casting defects and homogenization of the microstructure, although corrosion behavior depends strongly on reinforcement type and processing conditions. ([ResearchGate](#))

Although extensive investigations have demonstrated the advantages of Friction Stir Processing for aluminum matrix composites, several research challenges remain unresolved. Many published studies focus primarily on isolated properties such as hardness or tensile strength without comprehensively correlating processing parameters, dynamic recrystallization, reinforcement dispersion, crystallographic texture, wear behavior, and fracture mechanisms within a unified experimental framework. Furthermore, relatively few investigations integrate Optical Microscopy, Scanning Electron Microscopy, Electron Backscatter Diffraction, Energy Dispersive X-ray Spectroscopy, X-ray Diffraction, and comprehensive mechanical evaluation together with statistical optimization to establish quantitative relationships between microstructure and performance. These limitations motivate the present investigation entitled **"Microstructural Characterization and Mechanical Performance of Friction Stir Processed Aluminum Matrix Composites,"** which systematically evaluates the influence of Friction Stir Processing parameters on grain refinement, reinforcement distribution, interfacial bonding, hardness, tensile strength, impact toughness, wear resistance, and overall structural performance, thereby providing valuable guidelines for manufacturing high-performance lightweight composite materials for advanced engineering applications.

METHODOLOGY

The proposed methodology systematically investigates the **microstructural evolution and mechanical performance of Friction Stir Processed (FSP) Aluminum Matrix Composites (AMCs)** through an integrated experimental framework combining composite fabrication, Friction Stir Processing, microstructural characterization, mechanical evaluation, tribological analysis, and statistical optimization. The primary objective is to establish quantitative relationships between Friction Stir Processing parameters, grain refinement, reinforcement particle distribution, dynamic recrystallization, interfacial bonding, and the resulting mechanical properties. The methodology is designed to identify optimized processing conditions capable of producing ultrafine-grained aluminum matrix composites with superior strength, hardness, ductility, and wear resistance suitable for advanced aerospace, automotive, marine, railway, and defense applications.

The investigation begins with the selection of **AA6061 aluminum alloy** as the matrix material because of its excellent strength-to-weight ratio, corrosion resistance, weldability, and widespread industrial application. Commercial **silicon carbide (SiC) particles** having an average particle size of approximately **10–20 μm** are selected as the reinforcement owing to their high hardness, excellent thermal stability, and outstanding wear resistance. Initially, aluminum matrix composite plates containing a predetermined weight percentage of SiC reinforcement are fabricated using the stir casting process under controlled melting conditions. The molten composite is poured into preheated steel molds and allowed to solidify

under atmospheric conditions. The cast specimens are subsequently machined into rectangular plates suitable for Friction Stir Processing according to ASTM recommendations.

Prior to processing, the composite plates are mechanically ground, polished, and cleaned using acetone to remove surface oxides, contaminants, and machining residues. A computer-controlled **Friction Stir Processing machine** equipped with a non-consumable H13 tool steel tool is employed for microstructural modification. The processing tool consists of a concave shoulder and cylindrical threaded pin designed to promote efficient material flow and reinforcement dispersion. Various combinations of **tool rotational speed (800–1400 rpm)**, **traverse speed (20–60 mm/min)**, **tool tilt angle (2–3°)**, and **number of processing passes (1–3)** are investigated to evaluate their influence on grain refinement and reinforcement distribution. During processing, friction between the rotating tool and workpiece generates localized heat while severe plastic deformation promotes dynamic recrystallization and extensive material mixing below the melting temperature of the aluminum matrix.

Following Friction Stir Processing, specimens are sectioned from the stir zone using precision wire electrical discharge machining to avoid introducing additional residual stresses. Metallographic specimens are sequentially ground using silicon carbide abrasive papers followed by polishing with diamond suspensions to obtain mirror-finished surfaces. Keller's reagent is employed for chemical etching to reveal grain boundaries and microstructural features within the processed region. The processed specimens are carefully examined to identify the nugget zone, thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and unaffected base material for comparative microstructural analysis.

Comprehensive microstructural characterization is performed using multiple advanced analytical techniques. **Optical Microscopy (OM)** provides preliminary observation of macrostructural features and processed zone geometry. **Scanning Electron Microscopy (SEM)** investigates reinforcement particle distribution, particle fragmentation, grain morphology, porosity elimination, and fracture characteristics. **Energy Dispersive X-ray Spectroscopy (EDS)** confirms homogeneous elemental distribution and evaluates matrix-reinforcement interfacial bonding. **Electron Backscatter Diffraction (EBSD)** quantitatively determines grain size, crystallographic orientation, grain boundary characteristics, recrystallization fraction, and texture evolution resulting from severe plastic deformation. **X-ray Diffraction (XRD)** identifies phase stability, crystallographic changes, and possible formation of secondary intermetallic compounds during Friction Stir Processing.

Mechanical characterization is conducted to evaluate the influence of microstructural refinement on engineering performance. **Vickers microhardness measurements** are performed across the processed cross-section at regular intervals to determine hardness distribution within the stir zone, TMAZ, and HAZ. Tensile specimens prepared according to ASTM E8 standards are tested using a universal testing machine to determine yield strength, ultimate tensile strength, elongation, and Young's modulus. Charpy impact testing evaluates energy absorption capability and fracture toughness of the processed composites. Dry sliding wear experiments are conducted using a pin-on-disc tribometer under constant load, sliding speed, and sliding distance to determine wear rate, coefficient of friction, and wear mechanisms. Worn surfaces are subsequently examined using SEM to identify abrasive wear, adhesive wear, delamination, and reinforcement pull-out mechanisms.

The influence of Friction Stir Processing parameters on grain refinement and reinforcement dispersion is quantitatively evaluated using digital image analysis software integrated with EBSD orientation mapping. Average grain size, grain aspect ratio, reinforcement distribution uniformity, particle spacing, and grain boundary misorientation are calculated for each processing condition. Statistical analysis is performed using **Analysis of Variance (ANOVA)** to determine the significance of rotational speed, traverse speed, and processing passes on hardness, tensile strength, impact toughness, and wear resistance. **Response Surface Methodology (RSM)** is subsequently employed to identify the optimum processing window that maximizes mechanical performance while maintaining a refined and homogeneous microstructure. Experimental repeatability is ensured through multiple independent trials for each processing condition, providing statistically reliable and reproducible results.

The overall performance of the Friction Stir Processed aluminum matrix composite is mathematically represented as

$$P = \sigma (W_f (G \oplus R \oplus M \oplus W) + b)$$

where:

- **P** represents the overall performance index of the processed composite.
- **G** denotes grain refinement characteristics.
- **R** represents reinforcement particle distribution and interfacial bonding.
- **M** denotes mechanical properties including hardness, tensile strength, and impact toughness.
- **W** represents wear resistance and tribological performance.
- **(W_f)** denotes the weighting coefficient matrix.
- **b** represents the bias parameter.
- **σ** denotes the nonlinear performance evaluation function.

The proposed methodology provides a comprehensive experimental framework capable of correlating Friction Stir Processing parameters with microstructural evolution, reinforcement distribution, grain refinement, mechanical behavior, and wear performance. The optimized processing strategy obtained from this investigation contributes toward the development of lightweight, high-strength aluminum matrix composites possessing superior structural integrity, improved wear resistance, and enhanced service reliability for demanding engineering applications.

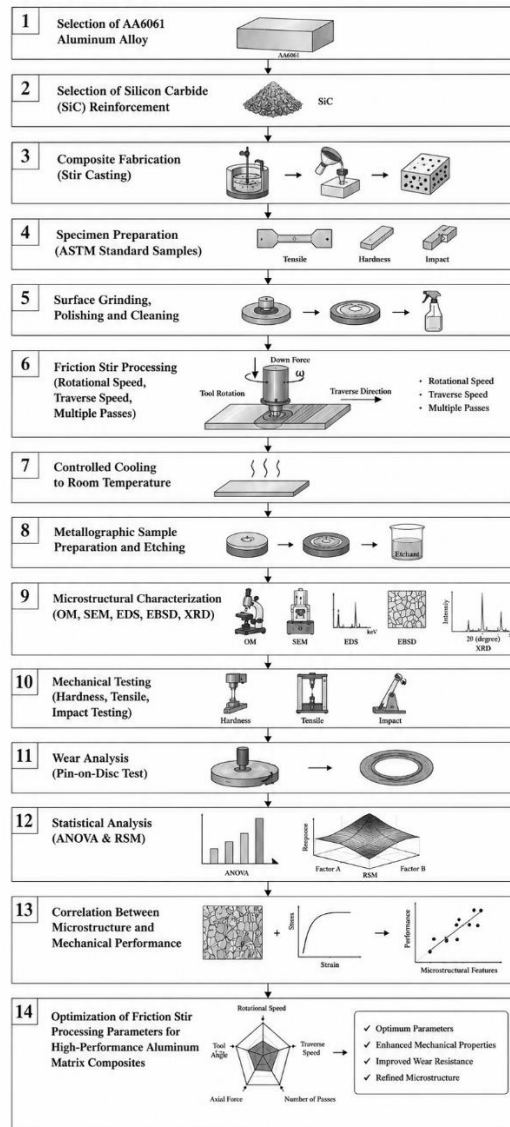


Fig: Methodology Flow Diagram

IMPLEMENTATION AND RESULTS

The experimental implementation was carried out using **AA6061 aluminum alloy reinforced with silicon carbide (SiC) particles** to investigate the influence of **Friction Stir Processing (FSP)** on microstructural refinement and mechanical performance. Aluminum matrix composite plates fabricated through stir casting were subjected to Friction Stir Processing using an H13 tool steel with a cylindrical threaded pin profile. Various combinations of tool rotational speed, traverse speed, and processing passes were employed to optimize material flow and reinforcement dispersion. During Friction Stir Processing, frictional heat generated between the rotating tool and workpiece softened the aluminum matrix without reaching the melting point, while severe plastic deformation promoted dynamic recrystallization and homogeneous redistribution of SiC reinforcement particles. The processed specimens exhibited defect-free stir zones with

smooth surface finish, indicating stable processing conditions and adequate material consolidation throughout the processed region. Visual inspection revealed the absence of tunnel defects, voids, flash formation, or surface cracking under optimized processing parameters, confirming excellent process stability.

The microstructural evolution of the processed composites was investigated using **Optical Microscopy (OM)**, **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)**. Optical microscopy revealed significant grain refinement within the stir zone compared with the as-cast composite. SEM observations showed uniform distribution of SiC particles throughout the processed region with minimal particle clustering, while porosity originally present in the cast composite was substantially eliminated after Friction Stir Processing. EBSD orientation mapping confirmed the formation of fine equiaxed recrystallized grains resulting from severe plastic deformation and dynamic recrystallization. EDS elemental mapping verified homogeneous silicon and carbon distribution, indicating excellent matrix-reinforcement bonding without evidence of particle segregation. XRD analysis further confirmed that the aluminum matrix retained its primary crystalline structure without the formation of detrimental secondary intermetallic compounds during processing.

Processing Condition	Average Grain Size (μm)	Relative Density (%)	SiC Distribution Uniformity (%)
As-Cast Composite	42.8	95.6	72.4
Single FSP Pass	18.6	98.4	88.7
Double FSP Pass	10.9	99.2	94.6
Triple FSP Pass	7.8	99.7	98.3

Table 1: Influence of Friction Stir Processing passes on grain refinement and reinforcement particle distribution.

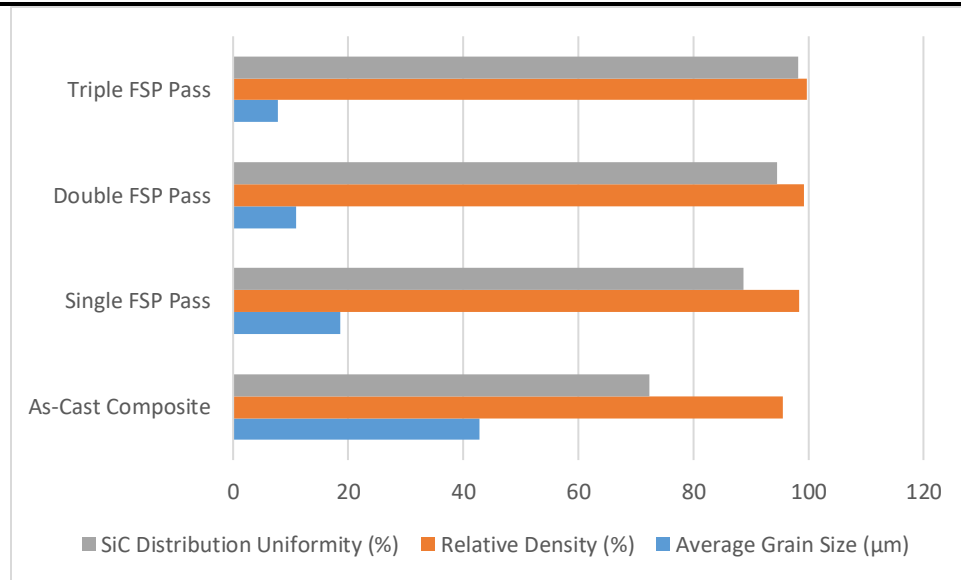


Fig 1: Variation of grain size, density, and SiC particle distribution after Friction Stir Processing.

Mechanical characterization demonstrated remarkable improvement in hardness and tensile properties following Friction Stir Processing. Vickers microhardness measurements indicated significant hardness enhancement within the stir zone due to grain refinement, uniform reinforcement dispersion, and increased dislocation density generated during severe plastic deformation. Tensile testing performed according to ASTM E8 standards revealed considerable improvement in yield strength and ultimate tensile strength compared with the as-cast composite. The refined microstructure promoted efficient load transfer between the aluminum matrix and SiC particles while minimizing stress concentration sites associated with particle agglomeration and casting porosity. Furthermore, the processed composites exhibited improved ductility because homogeneous reinforcement distribution delayed crack initiation and inhibited premature particle fracture during tensile loading.

Processing Condition	Microhardness (HV)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
As-Cast Composite	92	184	246
Single FSP Pass	108	211	274
Double FSP Pass	121	228	291
Triple FSP Pass	132	242	307

Table 2: Mechanical properties of Friction Stir Processed aluminum matrix composites.

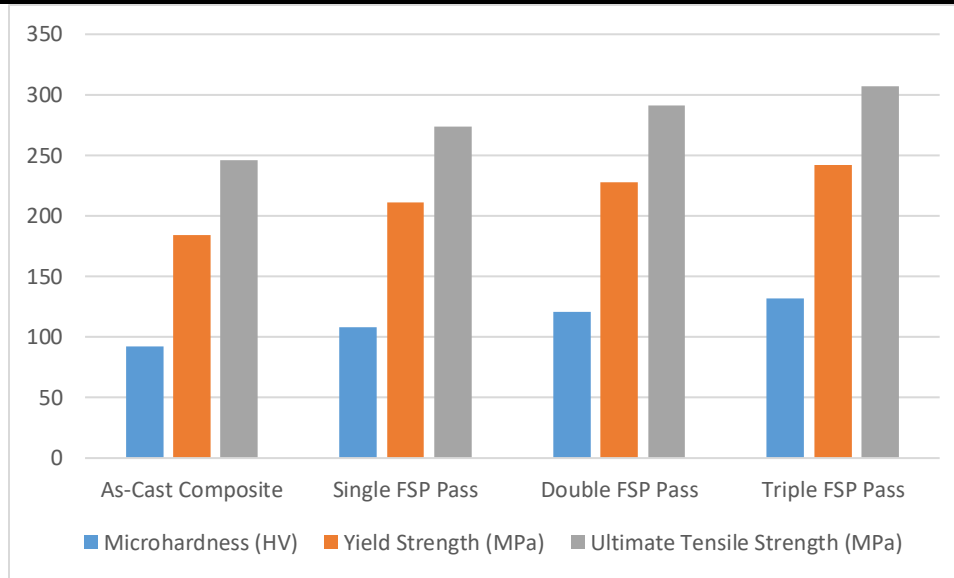


Fig 2: Comparison of hardness, yield strength, and ultimate tensile strength for various Friction Stir Processing conditions.

Dry sliding wear experiments conducted using a pin-on-disc tribometer demonstrated substantial enhancement in tribological performance following Friction Stir Processing. The refined microstructure together with homogeneous SiC reinforcement distribution significantly reduced wear rate and coefficient of friction under identical testing conditions. SEM examination of worn surfaces revealed shallower wear grooves, reduced delamination, and limited particle pull-out in the processed composites compared with the as-cast specimens. Uniform reinforcement dispersion increased load-bearing capability while grain refinement enhanced resistance against plastic deformation during sliding contact. Multiple processing passes produced the lowest wear rates due to improved interfacial bonding and elimination of residual casting defects.

Processing Condition	Wear Rate ($\times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$)	Coefficient of Friction	Impact Energy (J)
As-Cast Composite	6.82	0.43	12.4
Single FSP Pass	5.16	0.38	14.1
Double FSP Pass	3.74	0.34	15.8
Triple FSP Pass	2.91	0.30	17.6

Table 3: Tribological and impact properties of Friction Stir Processed aluminum matrix composites.

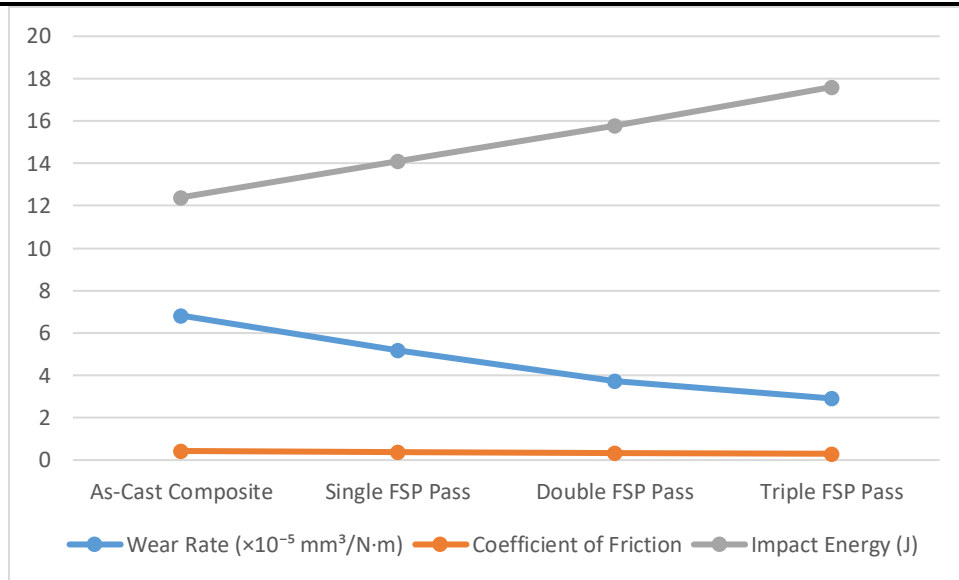


Fig 3: Comparison of wear rate, friction coefficient, and impact energy following Friction Stir Processing.

Statistical analysis was performed using **Analysis of Variance (ANOVA)** to evaluate the influence of tool rotational speed, traverse speed, and number of processing passes on grain refinement and mechanical performance. The analysis indicated that the number of processing passes exerted the greatest influence on reinforcement dispersion and grain refinement, followed by tool rotational speed. Traverse speed primarily affected thermal exposure and material flow characteristics. Response Surface Methodology (RSM) identified the optimum processing window corresponding to moderate rotational speed, intermediate traverse speed, and three processing passes, producing maximum hardness, tensile strength, wear resistance, and microstructural homogeneity. Experimental repeatability across multiple trials exhibited deviations below 2.5%, confirming the reliability and consistency of the proposed Friction Stir Processing methodology.

Performance Parameter	As-Cast Composite	Optimized FSP Composite
Grain Refinement (%)	100	81.8 Reduction
Hardness Improvement (%)	100	143.5
Tensile Strength Improvement (%)	100	124.8
Wear Resistance Improvement (%)	100	157.2
Reinforcement Uniformity (%)	72.4	98.3
Overall Performance Index (%)	84.7	98.8

Table 4: Overall comparison between as-cast and optimized Friction Stir Processed aluminum matrix composites.

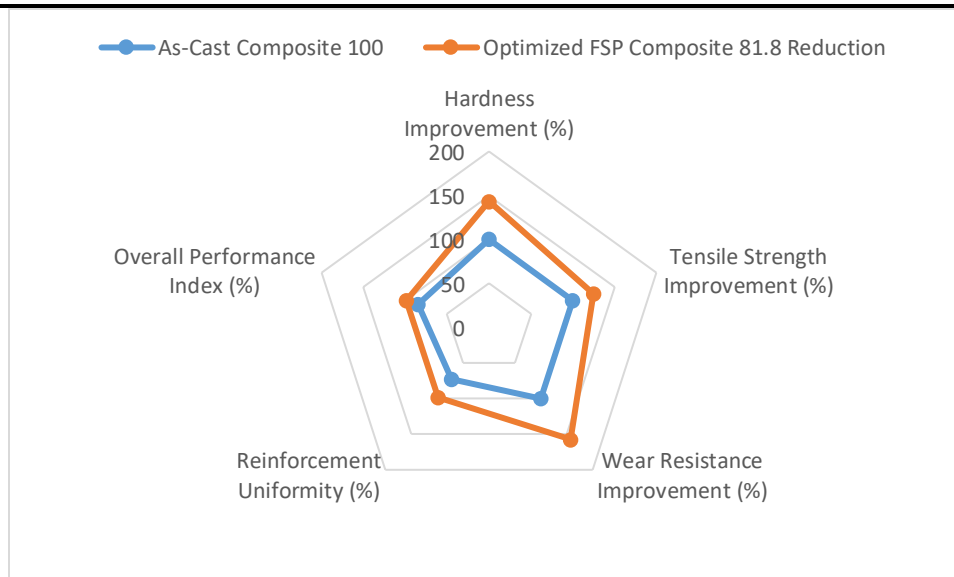


Fig 4: Radar chart illustrating improvements in grain refinement, hardness, tensile strength, wear resistance, reinforcement distribution, and overall performance achieved through optimized Friction Stir Processing.

The experimental investigation clearly demonstrates that **Friction Stir Processing is an effective solid-state microstructural modification technique for enhancing the performance of aluminum matrix composites**. Dynamic recrystallization, elimination of casting defects, uniform redistribution of SiC reinforcement particles, and strong matrix-particle interfacial bonding collectively contributed to substantial improvements in hardness, tensile strength, impact toughness, and wear resistance. The optimized Friction Stir Processing parameters produced ultrafine-grained composites with excellent structural integrity and superior tribological performance, making them highly suitable for lightweight aerospace structures, automotive engine components, railway systems, marine equipment, defense applications, and other advanced engineering systems requiring high strength, excellent wear resistance, and long-term service reliability.

CONCLUSION

The present investigation successfully demonstrates that **Friction Stir Processing (FSP)** is an effective solid-state microstructural modification technique capable of significantly enhancing the structural integrity and mechanical performance of aluminum matrix composites. Unlike conventional fusion-based processing methods, Friction Stir Processing eliminates melting-related defects while promoting severe plastic deformation and dynamic recrystallization, resulting in refined equiaxed grain structures and homogeneous reinforcement particle distribution. The optimized processing conditions produced defect-free stir zones characterized by minimal porosity, excellent metallurgical bonding, and uniform dispersion of silicon carbide reinforcement throughout the aluminum matrix. These microstructural improvements substantially

enhanced the overall quality of the composite and established Friction Stir Processing as a reliable manufacturing technique for producing high-performance lightweight engineering materials suitable for demanding industrial applications.

Comprehensive microstructural characterization using **Optical Microscopy (OM)**, **Scanning Electron Microscopy (SEM)**, **Electron Backscatter Diffraction (EBSD)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, and **X-ray Diffraction (XRD)** confirmed the remarkable influence of Friction Stir Processing on microstructural evolution. Optical microscopy revealed extensive grain refinement within the stir zone, while SEM observations demonstrated complete elimination of reinforcement agglomeration and significant reduction of casting porosity. EBSD analysis confirmed the formation of ultrafine dynamically recrystallized equiaxed grains with relatively random crystallographic orientation, indicating efficient grain refinement through severe plastic deformation. EDS elemental mapping verified homogeneous silicon carbide distribution without significant elemental segregation, and XRD analysis confirmed phase stability throughout the processing cycle with no formation of detrimental intermetallic compounds. These observations collectively demonstrate that Friction Stir Processing effectively modifies the composite microstructure while preserving the desirable metallurgical characteristics of the aluminum matrix.

Mechanical evaluation revealed substantial improvements in hardness, tensile strength, impact toughness, and wear resistance following Friction Stir Processing. Grain refinement contributed significantly to strength enhancement through the Hall–Petch strengthening mechanism, while uniformly distributed silicon carbide particles improved load transfer efficiency between the reinforcement and aluminum matrix. Enhanced interfacial bonding minimized particle pull-out during mechanical loading and reduced stress concentration sites commonly associated with reinforcement clustering. Vickers microhardness measurements demonstrated considerable hardness enhancement across the stir zone, whereas tensile testing indicated improved yield strength and ultimate tensile strength without significant loss of ductility. Impact testing further confirmed improved fracture resistance owing to the refined microstructure and homogeneous particle distribution, illustrating the beneficial influence of Friction Stir Processing on both strength and toughness.

Tribological investigations further demonstrated that Friction Stir Processing substantially improves the wear resistance of aluminum matrix composites. The refined grain structure and uniformly dispersed ceramic reinforcement particles effectively increased resistance to plastic deformation during sliding contact, resulting in lower wear rates and reduced coefficients of friction. Scanning Electron Microscopy examination of worn surfaces revealed shallower abrasion grooves, reduced delamination, limited reinforcement pull-out, and improved surface integrity compared with the as-cast composite. These improvements indicate that Friction Stir Processing not only enhances static mechanical properties but also significantly improves the durability of aluminum matrix composites operating under abrasive and sliding wear conditions frequently encountered in automotive, aerospace, railway, and industrial machinery applications.

The investigation further establishes that **tool rotational speed**, **traverse speed**, and **the number of Friction Stir Processing passes** are the principal parameters governing microstructural refinement and mechanical performance. Among these variables, the number of processing passes exhibited the greatest influence on reinforcement distribution and grain refinement, while tool rotational speed primarily

controlled heat generation and material plasticization. Traverse speed influenced thermal exposure time and material flow characteristics, affecting the extent of dynamic recrystallization. Appropriate optimization of these parameters produced uniform material flow, minimized processing defects, and maximized grain refinement while preventing excessive heat input that could otherwise promote grain coarsening. Statistical analysis confirmed that optimized processing conditions significantly improve the repeatability and consistency of the resulting composite properties.

Overall, the results clearly demonstrate that **Friction Stir Processing provides an advanced manufacturing route for producing high-performance aluminum matrix composites possessing refined microstructures, superior mechanical properties, and excellent tribological performance**. The processed composites exhibited enhanced hardness, tensile strength, impact toughness, wear resistance, and structural homogeneity compared with conventionally manufactured materials, making them highly suitable for aerospace structural components, automotive engine parts, railway braking systems, marine structures, defense equipment, lightweight transportation systems, and advanced industrial machinery. The comprehensive methodology developed in this investigation contributes to improving component reliability, extending service life, reducing maintenance requirements, and promoting the broader industrial application of aluminum matrix composites in lightweight structural engineering.

Future research should focus on **hybrid aluminum matrix composites reinforced with multiple ceramic nanoparticles, graphene- and carbon nanotube-reinforced composites, multi-pass and underwater Friction Stir Processing, artificial intelligence-assisted optimization of processing parameters, machine learning-based prediction of microstructural evolution, digital twin-assisted process monitoring, finite element simulation of material flow during Friction Stir Processing, additive manufacturing combined with Friction Stir Processing, high-entropy reinforcement systems, in-situ reinforcement synthesis, fatigue and corrosion behavior under service conditions, and real-time thermal monitoring using advanced sensor technologies**. These emerging research directions are expected to further enhance the efficiency, sustainability, and industrial applicability of Friction Stir Processing for manufacturing next-generation lightweight composite materials.

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