OPEN ACCESS

Indian Journal of Structure Engineering (IJSE)
ISSN: 2582-922X (Online), Volume-5, Issue-2, November 2025

In Situ Composites Prepared by Friction Stir Processing of Aluminium Alloy: A Review

Mustafa Sh. Aljanabi, Omar Hassan Mahmood

***Abstract:** This review examines the properties of aluminium matrix composites produced by friction stir processing and the types of reinforcements that have been explored recently. The demand for light yet strong parts appears to be growing, as regular aluminium alloys cannot provide sufficient strength, wear, or corrosion protection. Friction stir processing may offer a solid-state method for achieving finer grains and distributing particles more evenly, without the drawbacks of casting. Authors list a variety of filler types – ceramics like SiC or Al_2O_3, metals such as copper or scandium, carbon-based materials like graphene sheets, and even waste products like rice husk ash or eggshells. Those additions are reported to boost stiffness, hardness and resistance to corrosion. Yet, the exact influence often depends on the tool shape, spin speed, travel speed, and the number of passes made. Those process settings appear to control where particles end up, how well they adhere, and the overall performance. The paper highlights why these FSP composites may be significant for applications such as planes, cars, boats, and heat sinks, particularly when eco-friendly fillers are utilised. Still, some problems remain unsolved: particles can clump, bonds may break, and even tiny changes in parameters can disrupt the entire batch. Critics could argue that the current data are still scattered, making it hard to judge reproducibility. Looking ahead, the authors suggest mixing different reinforcements, utilising live monitoring of the stir zone, and incorporating more waste-derived materials. Those ideas could improve both the function and green grade of the composites, if they survive real-world testing. Nevertheless, the field lacks standardised tests, which can lead to conflicting results. Some labs use low tool speeds to avoid overheating; others push high rotations for finer grains. These choices entail trade-offs that readers should consider when evaluating the claimed benefits in practice.*

***Keywords:** Friction Stir Processing - Aluminum Metal Matrix Composites - Reinforcement Particles - Solid State Processing - FSP*

Nomenclature:

AMCs: Aluminum Matrix Composites
FSP: Friction Stir Processing
FSW: Friction Stir Welding
MMCs: Metal–Matrix Composites
UFSP: Upward Friction Stir Processing
GNPs: Graphene Nanoplatelets
CNTs: Carbon Nanotubes
UTS: Ultimate Tensile Strength
RHA: Rice Husk Ash

Manuscript received on 28 August 2025 | First Revised Manuscript received on 09 September 2025 | Second Revised Manuscript received on 16 October 2025 | Manuscript Accepted on 15 November 2025 | Manuscript published on 30 November 2025.

*Correspondence Author(s)

Mustafa Sh. Aljanabi*, Assistant Lecturer, College of Engineering, Mechanical Department, Tikrit University, Salah Aldin, Tikrit, Iraq. Email ID: mustafa.shaker@tu.edu.iq, ORCID ID: 0009-0007-8017-6186

Omar Hassan Mahmood, Assistant Lecturer, Dour Technical Institute, Mechanical Department, Northern Technical University, Salah Aldin, Dour, Iraq. Email ID: eng.omarhasan94@ntu.edu.iq, ORCID ID: 0009-0005-2131-7810

I. INTRODUCTION

Aluminium and its alloy families underpin a considerable fraction of contemporary structural engineering, earning favour due to low density, excellent strength-to-weight ratios, immunity to atmospheric corrosion, and favourable thermal and electrical conductivities [1]. At the same time, conventional wrought and cast alloys suffer from deficiencies in wear resistance, elevated-temperature strength, and hardness. Conventional alloys cannot satisfy the demand for integrated material components in aerospace, marine, and high-performance automotive applications [2]. Aluminum matrix composites (AMCs) are increasingly being adopted for such applications. Rein-forced with ceramic or metallic particulates, AMCs achieve superior macro- and microstructural properties relative to unreinforced composites and alloys. Friction Stir Processing (FSP) is being explored at several universities and national laboratories for the development of aluminium matrix composites for the same applications [3].

In recent years, a broad array of particulate reinforcements has been explored, such as:

Materials	Addition
Ceramics	Al_2O_3, SiC, ZrO_2, TiO_2, B_4C, TiC
metallics	Cu, W, Mo, Sc
carbon-based	graphite and graphene nanoplatelets
sustainable fillers	rice husk ash, eggshell particles, and bone-derived powders

These have been successfully compounded into a suite of aluminium alloys, namely AA2024, AA5052, AA5056, AA5083, AA6061, AA6082, and AA7075, by one or several passes of Friction Stir Processing [4]. The resulting composite materials, both as surface coatings and as bulk inserts, show remarkable improvements over unprocessed structures in microhardness, ultimate tensile strength, wear resistance, grain refinement, and corrosion resistance [5].

Much of the increase in performance is due to the ultrafine and uniform distribution of reinforcement particles and to the dynamically recrystallized, refined grains that form during processing [6].

This review compiles recent literature published over the past decade regarding the increasing demand for aluminium matrix composites that combine low mass with high strength.

The review is directed at three principal objectives:

Objective 1: Reinforcement Material Spectrum to catalogue the broad spectrum of reinforcement materials tested in the friction stir processing of aluminium matrix alloys, encompassing metallic, ceramic, and organic phases.

Objective 2: Strengths Spectrum to compare, in a quantitative manner, the respective impacts of these materials on tensile strength, fatigue life, microstructural stability, and corrosion resistance.

Objectives 3: Processing

Variables & Mixing Efficiency, and the quantity of overlapping passes on the achievement of:

- Uniform reinforcement dispersion
- Mechanical bonding strength between the matrix and the reinforcements. Analysis of these objectives leads to fruitful future research proposals, notably:
- Using a hybrid scheme of reinforcements.
- Incorporating biodegradable fibres.

These strategies will allow composites to maintain mechanical integrity while offering eco-friendly, "sustainable" pathways.

II. COMPOSITE FABRICATION BY FRICTION STIR PROCESSING (FSP)

Friction Stir Processing (FSP) leverages principles of Friction Stir Welding (FSW) to effect solid-state microstructural refinement and particulate reinforcement of metallic matrices. Although FSW was initially tailored for the joining of aluminium alloys, its basic principles have been adapted to create layered and bulk metal–matrix composites (MMCs), particularly those based on aluminium. The principal advantage of FSP lies in its capacity to embed hard particles into the matrix without surpassing solidus temperatures, thus circumventing the defects typically associated with liquid-phase processing, such as gas entrapment, agglomeration of the reinforcements, and weak reinforcement–matrix interfaces [3].

A. Principle and Process Description

The (FSP) uses a non-wearing rotating tool that has a shoulder and a pin to achieve a precise and controlled deformation mechanism. The tool is inserted vertically into a metallic substrate and then translated along a specified track. The superposition of angular rotation and downward pressure generates localised frictional energy that heats the surrounding matrix sufficiently to achieve plasticity without the incipience of melting [7]. The deformation is concentrated in a limited stirring zone, where the matrix is subjected to cyclic strain and internal dynamic recrystallisation, thereby producing a homogenised microstructural state and, in composite applications, a consistent dispersion of reinforcement particulates [8].

The primary methods by which reinforcement is incorporated into composite processing via FSP are threefold:

i. *Filling Grooves:* Pre-assembled groove arrays—linear hollows formed explicitly on the matrix surface—are loaded with reinforcement particles before processing. The FSP tool, moving over the grooves, mechanically shears the matrix and simultaneously drives the particles into the interstitial spaces, merging them into the recrystallised microregion [9].

ii. *Drilling Holes:* An alternative method entails drilling a series of small-diameter holes into the matrix in a specified order. These holes are filled with particles that act as reinforcements [10]. Next, a lateral stirring operation is performed to ensure the reinforcements are integrated into the matrix. The drilling and reinforcement methods, like those in the previous section, yield a fine distribution of the reinforcements. The following two layers introduce a different scheme and provide a better understanding of the types of particles that can be used as reinforcements [11].

iii. *Layered Sandwich* design or tape casting means putting a reinforcement sheet between two leaves of the matrix alloy before friction stir processing. This approach is used in upward friction stir processing (UFSP) to achieve a more uniform distribution of particles [12].

Key process parameters, such as tool rotation speed, travel speed, tilt angle, plunge depth, number of passes, and tool geometry, significantly influence how the material flows and bonds at the interface, as well as its microstructural evolution. For instance, subsuming an increase in the number of processing passes usually leads to a finer distribution of the reinforcement; however, increasing the number of passes also tends to result in a significant increase in thermal cycles. Thus, subsuming an increase in the no. of passes tends to also lead to a significantly larger increase in the number of thermal cycles [13].

B. Microstructural and Mechanical Characteristics

The stir zone of FSP-induced composites exhibits refined equiaxed grains, accompanied by strong interfacial bonding and uniform particle distribution. The processing deformation causes grain sizes to vary between sub-micrometres and a few micrometres based on the chosen parameters. The reinforcements function as grain pinning sites, which restrict grain growth and strengthen the material through Hall-Petch mechanisms [14].

The mechanical testing of FSP composites demonstrates improved microhardness, tensile strength, yield strength, and wear resistance. However, multiple tools pass, or high heat input, can cause grain coarsening or thermal softening. The two FSP passes in AA7075/TiC composites produced better hardness and wear resistance than single-pass samples due to improved grain refinement and uniform dispersion [15].

Friction Stir Processing has proven itself as a powerful method for creating aluminium matrix composites. FSP outperforms traditional fusion-based methods because it enables precise control of particle distribution and grain size, as well as localised mechanical properties. The combination of appropriate process parameters with reinforcement types and matrix alloys empowers the creation of customised composites for aerospace and marine applications, as well as biomedical and automotive applications.

III. REINFORCEMENTS USED IN FSP OF ALUMINUM ALLOYS

The aluminium matrix composite manufacturing process, utilising Friction Stir Processing (FSP), employs multiple reinforcement materials to achieve superior mechanical properties, as well as enhanced thermal and tribological performance. The reinforcement materials can be categorised into two main groups.

The most widely used ceramic particles for reinforcement applications include Al2O3, SiC, ZrO2,

Retrieval Number: 100.1/ijse.B132205021125
DOI: 10.54105/ijse.B1322.05021125
Journal Website: www.ijse.latticescipub.com

Published By:
Lattice Science Publication (LSP)

TiO_2, B_4C, TiC and WC. The addition of these materials enhances both the hardness and wear resistance, as well as the thermal stability, of the composites. The strength, electrical/thermal conductivity, and grain refinement of materials benefit from the use of Cu, Mo, W and Sc metallic reinforcements. The formation of Al_3Sc precipitates promotes fine-grained microstructures, which is attributed to Scandium.

The combination of Graphite, graphene nanoplatelets (GNPs), and carbon nanotubes (CNTs) provides wear resistance, self-lubricating properties, and enhanced electrical conductivity.

The combination of Gr + Al_2O_3, sic + TiO_2, and B_4C + Cr_2O_3 hybrid reinforcements is used to achieve synergistic effects that balance hardness, toughness, and corrosion resistance.

Rice husk ash, eggshell powder and chicken bone ash have been studied as sustainable and affordable ceramic-like reinforcement materials that enhance hardness while promoting sustainability.

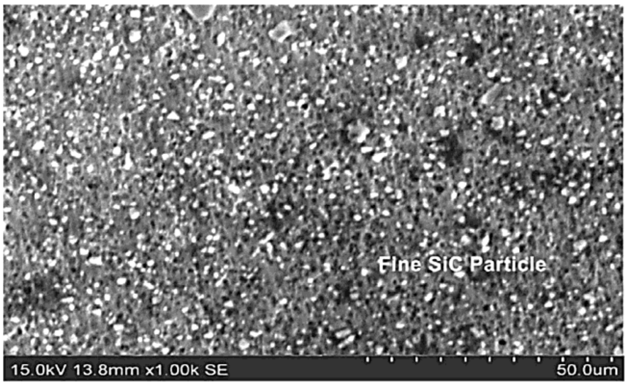
The various aluminium alloy matrices (e.g., AA6061, AA7075, AA5052) have incorporated these reinforcements through single or multi-pass FSP to create compo-sites for aerospace, automotive and marine applications.

A. Ceramic Particles

The most widely used reinforcement materials in aluminium matrix composites processed via Friction Stir Processing (FSP) are ceramic particles, as they possess high hardness and thermal stability, as well as excellent wear resistance. The addition of ceramic particles to aluminium matrices produces enhanced surface hardness, along with elevated tensile strength, refined grains, and improved durability, which makes these composites suitable for the aerospace, automotive, and marine industries.

The primary ceramic reinforcements employed in this process consist of aluminium oxide (Al_2O_3) [16]. silicon carbide (SiC) [17]. titanium dioxide (TiO_2) [18]. zirconium dioxide (ZrO_2) [19]. titanium carbide (TiC) [20]. and boron carbide (B_4C) [21]. These particles achieve their best results based on their weight percentage and size (micro or nano), dispersion level, and the processing parameters applied during FSP.

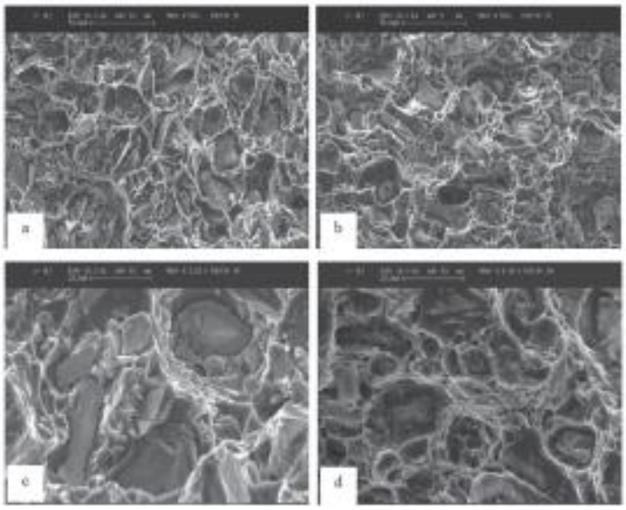
The reinforcement ratios range from 5 wt.% to 20 wt.%, which determines the required application needs. The combination of 10–15 wt.SiC in AA6061 and AA7075 alloys resulted in significant improvements in hardness and tensile strength through optimal multi-pass FSP dispersion. Research showed that adding 20 wt. the addition of Al_2O_3 to AA6061 resulted in a hardness increase from ~63 HV (base metal) to ~91 HV, thus demonstrating the significant impact of ceramic addition on mechanical properties. Figure 1 shows the distribution of SiC particles in the AA-10 wt. % SiCp metal matrix composites [17].



[Fig.1: SEM Micrographs of FSPed AA-10 wt. % SiCp Composites]

The quality of particle distribution and interface bonding in ceramic-reinforced materials depends heavily on the tool rotation speed (900–1200 rpm) and traverse speed (30–60 mm/min), as well as the tool geometry (usually thread-ed cylindrical tools). Multiple passes (2–3) are necessary to achieve uniform particle dispersion when working with significant reinforcement percentages. The improper control of processing parameters leads to the formation of particle clusters, along with voids and tunnel defects, which degrade the mechanical properties of the material. Multiple research findings indicate that nano-sized ceramic particles offer significant advantages in terms of both particle distribution and grain size reduction. Research revealed that nano-Al_2O_3 and nano-SiC particles created a more uniform stir zone and smaller average grain sizes, resulting in composites with superior strength-to-weight ratios. Figure 2 shows the SEM images of the friction stir-processed Al without/with nano-Al_2O_3 particle addition [16].

Ceramic particle reinforcement through FSP represents a well-established method for enhancing the surface and bulk properties of aluminium alloys. The development of defect-free, uniform reinforcement in composite structures requires the optimisation of particle type, along with size, percentage, and process parameters.



[Fig.2: SEM Images of the Friction Stir-Processed Al and Al with Nano-Al2O3 Particle Addition]

Table I: Summary of Ceramic Particle Reinforcements in FSP of Aluminium Alloys

Alloy	Reinforcement	wt.%	FSP Passes	Hardness (HV)	UTS (MPa)	Notable Outcomes
AA6061	SiC	30	1–2	↑ ~30–40%	↑ ~20–25%	Wear resistance, fine grains
AA6061-T6	Al_2O_3	~20	2	91 (↑ from 63)	↑ ~24%	Enhanced strength, uniform dispersion
AA2024	ZrO_2	----	2	↑ ~35%	↑ ~22%	Grain refinement, corrosion resistance
AA7075	TiC	2	1	↑ to 175	↑ to 337	High strength, minimal defects
AA6082	WC	6 - 18	2	↑ ~25%	↑ ~15%	Improved thermal properties

B. Metallic Reinforcements

The fabrication of Additive Manufacturing Composites (AMCs) through Friction Stir Processing (FSP) benefits from metallic reinforcements as an effective additive class, which outperforms ceramic particles. The aluminium matrix demonstrates better bonding properties with metallic particles compared to brittle ceramic phases, and exhibits enhanced ductility, along with improved electrical and thermal conductivity. The addition of metallic components strengthens the material through solid-solution strengthening and precipitation hardening mechanisms, as well as grain boundary pinning effects.

FSP applications use five metallic reinforcement materials, which consist of copper (Cu) [22]. molybdenum (Mo) [23]. tungsten (W) [24]. zirconium tungstate (ZrW2O) [25]. and scandium (Sc) [26]. The elements enhance both mechanical properties and structural refinement, as well as corrosion protection.

The amount of metallic reinforcements used in FSP applications ranges between 1 wt.% and 30 wt.%, depending on the desired mechanical or thermal properties, with the addition of 10 wt.%. Conversion of Cu to AA5056 alloy resulted in a substantial hardness enhancement, from 61 HV to 84 HV, while simultaneously increasing the ultimate tensile strength (UTS) through the formation of intermetallic phases and enhanced dislocation density—the addition of 5-15 wt.% Mo to Al-Mg-Sc alloy led to improved surface hardness and grain refinement because Mo has a high melting point and low diffusivity (Figure 3) [22].

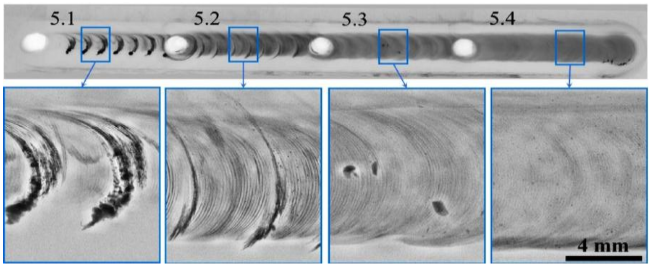
The effective dispersion and bonding of metallic particles within the stir zone depend heavily on the tool rotation speed, which ranges from 800 to 1200 rpm, and the traverse speed, which ranges from 20 to 60 mm/min, during FSP.

The stirring process improves with increased heat input when using lower traverse speeds and higher rotation speeds, especially for particles with high melting points, such as molybdenum (Mo) and tungsten (W). The tool geometry (typically threaded or tapered cylindrical) and the number of FSP passes (1–3) also play critical roles in achieving a uniform distribution and avoiding clustering.

Researchers have made significant progress by incorporating Scandium (Sc) into high-strength AA7075 alloys. The formation of fine Al3Sc precipitates becomes possible by adding 2 wt% Sc, which functions as an effective recrystallisation nucleation site to create ultrafine grain structures and enhance mechanical properties. AA7075–Sc composites underwent grain reduction to 2.3 µm while their UTS increased more than 20% [26].

ZrW2O stands out as a unique reinforcement material due to its negative thermal expansion properties. The addition of ZrW2O to AA5056 resulted in reduced residual stresses. It achieved a maximum hardness of 78 HV while maintaining a stable microstructure under thermal cycling conditions, thus showing promise for aerospace applications [25].

The mechanical, thermal, and corrosion resistance properties of aluminium alloys processed by FSP are significantly enhanced through the use of metallic reinforcement methods. Achieving defect-free high-performance composites requires the precise selection of metal type and reinforcement percentage, along with suitable process parameters.



[Fig.3: CT Images of the Processed Area of Al-Mg-Sc Alloy with Five wt.% Mo]

Table II: Summary of Metallic Reinforcements in FSP of Aluminium Alloy

Alloy	Reinforcement	wt.%	Passes	Hardness (HV)	UTS (MPa)	Notable Outcomes
AA5056	Cu	1.5 - 30	2	↑ to 84	↑ ~22%	Intermetallic, high dislocation density
AA5056	ZrW_2O_8	10	2	↑ to 78	↑ ~18%	Thermal stability, reduced residual stress
AA6xxx	Mo	5 - 10	2	↑ ~25%	↑ ~17%	Grain refinement, improved wear resistance
AA7075	Sc	2	1–2	↑ ~20%	↑ >20%	Al_3Sc phase, ultrafine grains (~2.3 µm)
Al matrix	W	10	2	↑ ~30%	↑ ~15%	High hardness, stable under high temp.

C. Carbonaceous Materials

The combination of low density and high thermal stability, along with excellent lubrication properties and outstanding mechanical strength, makes carbon-based materials suitable as reinforcements for Additive Manufacturing Composites (AMCs) processed by Friction Stir Processing (FSP). Researchers have incorporated various aluminium alloys with graphite (Gr) [27]. graphene nanoplatelets (GNPs) [28]. carbon nanotubes (CNTs)[29]. and carbon black to create composites which show enhanced wear resistance, friction reduction, and improved thermal and electrical conductivity.

Graphite stands out as the preferred choice because it occurs naturally and is less expensive, while offering built-in lubricating properties. The graphite content in aluminium alloys typically ranges from 2 wt.% to 10 wt.%, with additional ceramic particles added to maintain structural integrity. The wear rate of AA5083 decreased, and its microhardness increased by 20% when graphite was

Retrieval Number: 100.1/ijse.B132205021125
DOI: 10.54105/ijse.B1322.05021125
Journal Website: www.ijse.latticescipub.com

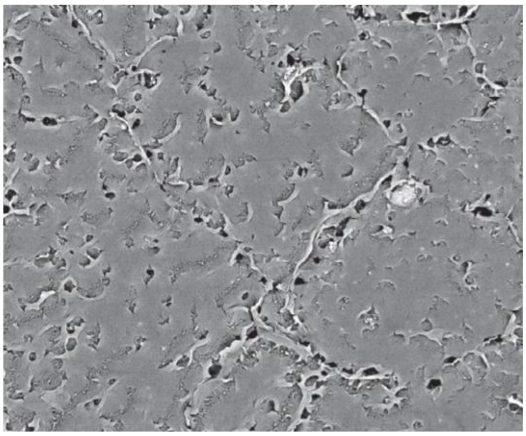
Published By:
Lattice Science Publication (LSP)

added, as it functions as a solid lubricant. The distribution of CNT reinforcement particles in Al5083/CNT composites, after the third FSP pass, is as shown in Figure 4 [30].

The combination of GNPs and CNTs yields superior mechanical and functional properties due to their nanoscale dimensions and elongated structures. The incorporation of GNPs into AA7075 material resulted in enhanced tensile strength, accompanied by grain refinement and substantial improvement in thermal conductivity. The proper distribution of nanocarbon materials proves difficult to achieve because they tend to cluster after multiple FSP passes, or hybrid reinforcement techniques are needed to prevent agglomeration [31].

The distribution and interfacial bonding of carbonaceous materials depend heavily on processing parameters, which include rotation speed (900–1200 rpm), traverse speed (30–60 mm/min) and tool design (threaded cylindrical or conical tools). The lightweight nature of these materials and Their tendency to cluster, similar to metallic or ceramic particles, leads researchers to use lower traverse speeds combined with multiple FSP passes (up to three) to achieve a uniform distribution.

The combination of graphite with ceramic reinforcements, such as Al2O3 or SiC, in hybrid systems yields improved strength and lubrication performance. The combination of 5 wt.% Gr with wt. 10% Al2O3 in AA5083 produces improved micro-hardness values, decreased wear depth, and enhanced surface integrity, which makes it appropriate for sliding contact applications [32].



[Fig.4: SEM Image of the Distribution of Reinforcements After the Third Pass in Al5083/CNTs Composites]

The addition of carbonaceous materials offers a beneficial method for modifying the properties of FSP-fabricated aluminium composites, which encompass both tribological and thermal characteristics. The optimal selection and processing of these materials need to balance dispersion difficulties with performance enhancement results.

Table III: Summary of Carbonaceous Reinforcements in FSP of Aluminium Alloys

Alloy	Reinforcement	wt.%	Passes	Hardness (HV)	Wear Rate	Notable Outcomes
AA5083	Graphite (Gr)	5	2	↑ ~20%	↓ ~30%	Lubrication effect, reduced friction
AA5083	Gr + Al_2O_3	25/75%	2	↑ ~28%	↓ ~40%	Hybrid synergy, better surface durability
AA6061	Graphene (GNPs)	10-May	3	↑ ~25%	↓ ~25%	Enhanced thermal/electrical conductivity
AA7075	GNPs	33.30%	2	↑ ~22%	↓ ~20%	Grain refinement, improved strength
AA6061	CNTs	06-Feb	2	↑ ~30%	↓ ~35%	Strong interface, low wear rate

D. Hybrid Reinforcements

Research on aluminium matrix composites (AMCs) produced by Friction Stir Processing (FSP) reveals an increasing interest in hybrid reinforcements to enhance multiple properties of these materials. Researchers combine different reinforcement materials, including ceramics with carbonaceous or metallic particles, to achieve a synergistic effect that surpasses the limitations of single reinforcement. The combination of hybrid composites enables superior hardness alongside enhanced tensile strength, wear resistance, thermal conductivity, and corrosion protection, without compromising ductility and toughness levels.

Researchers have explored different hybrid combinations such as SiC + TiO2 [33]. B4C + Cr2O3 [34]. Gr + Al2O3 [35]. Cu + Gr [36]. and Al2O3 + GNPs [37]. The hybrid particle selection process depends on both the application requirements and the properties that researchers want to improve. The combination of Gr + Al2O3 provides solid lubrication benefits together with high surface hardness [35]. While B4C + Cr2O3 combines improved wear and corrosion resistance properties. The weight percentage of hybrid reinforcement typically extends between 5 and 15 wt.%, with component ratios usually at 2:1 or 1:1 [35].

The processing parameters need proper optimisation cause multiple particle types interact during the processing. A typical hybrid reinforcement processing procedure involves tool rotation speeds of 900–1200 rpm and traverse speeds of 30–60 mm/min and 2–3 FSP passes to achieve proper distribution and mixing of both reinforcement particles. Tool geometry plays a crucial role because threaded or pin-profiled tools yield the best results for uniform multi-phase particle distribution.

Several research investigations have demonstrated significant performance enhancements through the implementation of hybrid reinforcement systems. The mechanical properties of 2- 6 wt.% Cr2O3 and B4C reinforced AA6061 material showed more than 35% Tensile strength improvement alongside better wear resistance through the combined hardening effect of ceramic and oxide phases [34].

Research on AA5083 material reinforced with Gr + Al2O3 resulted in enhanced surface quality, accompanied by decreased wear rates and increased microhardness. AA6061 alloys containing 2-6 wt.% Cu and Gr demonstrated enhanced mechanical strength and improved lubrication properties, which make the material suitable for

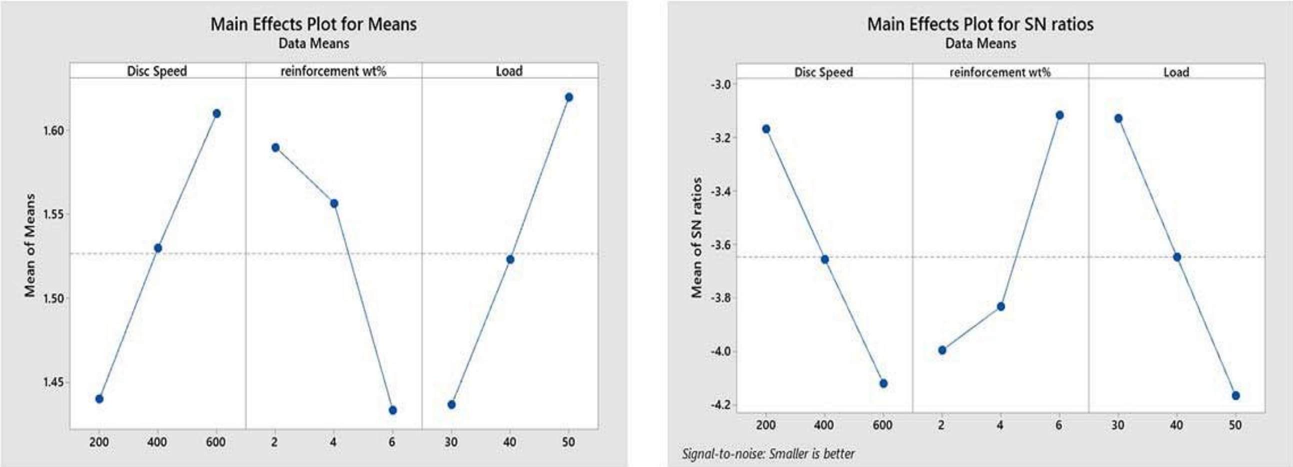
Retrieval Number: 100.1/ijse.B132205021125
DOI: 10.54105/ijse.B1322.05021125
Journal Website: www.ijse.latticescipub.com

Published By:
Lattice Science Publication (LSP)

applications requiring sliding and impact loading and Figure 5 (a) and (b) depict the Main Effects Plots for Means (showing the mean values of wear rate) and for S/N ratios (showing S/N ratios for wear rate), respectively [36].

Hybrid reinforcement systems pose challenges in maintaining particle dispersion and achieving optimal interfacial bonding. The issues become more manageable when FSP passes are increased, along with proper tool tilt angle optimisation and surface polishing or heat treatment post-processing methods.

The use of hybrid reinforcements represents an effective method for developing versatile aluminium-based composites through FSP technology. The maximum synergistic benefits from hybrid systems depend on selecting appropriate reinforcement materials with defined content ratios and optimising FSP parameters.



[Fig.5: (a), (b) Main Effects Plot for Means (and S/N Ratios, Respectively) for Factors on Wear Rate]

Table IV: Summary of Hybrid Reinforcements in FSP-Fabricated Aluminium Composites

Alloy	Reinforcements	wt.%	Passes	Hardness (HV)	Wear Rate	Key Improvements
AA6061	$B_4C + Cr_2O_3$	2 - 6	2	↑ ~35%	↓ ~40%	High hardness, improved wear behaviour
AA5083	$Gr + Al_2O_3$	-----	2	↑ ~28%	↓ ~45%	Lubricity + surface durability
AA6061	Cu + Gr	2 - 6	2	↑ ~30%	↓ ~25%	Strength + self-lubrication
AA7075	$SiC + TiO_2$	(15+15)	3	↑ ~32%	↓ ~30%	Better dispersion, wear resistance
AA6061	Al_2O_3 + GNPs	25/75%	3	↑ ~25%	↓ ~35%	Thermal + mechanical property boost

E. Bio-based/Sustainable Additives

The world has shifted its focus toward sustainability and environmental responsibility, so bio-based and waste-derived additives now receive attention for their use as reinforcements in advanced materials composites (AMCs) made through fibre spinning processes (FSP). These additives help decrease manufacturing expenses and environmental harm while providing competitive mechanical and tribological performance. Rice husk ash (RHA) [38]. together with eggshell powder [39]. and animal bone ash (chicken bones) [40]. serve as sustainable additives that contain naturally occurring ceramics such as silica, calcium carbonate and phosphates [41].

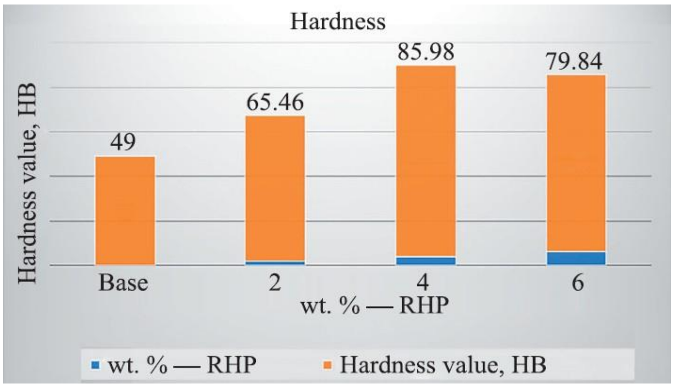
The performance of these materials depends heavily on their weight percentage, ranging from 2 to 15 wt.%, and their micro-scale particle size, with the addition of 5 wt..% RHA to AA6061 alloy resulted in a 22% hardness increase and superior wear resistance because silica in the ash acted like conventional ceramic particles. The microhardness and compressive strength of AA7075 alloys increased when eggshell powder, primarily composed of CaCO3, was used at 3–9 wt.% levels, while the composite became less dense [38].

Bio-based reinforcement integration requires optimal processing parameters to achieve successful results. The best results were achieved through tool rotation speeds between 900–1100 rpm combined with traverse speeds of 30–50 mm/min while performing 2 to 3 FSP passes to distribute the light particles uniformly. The unique morphology and thermal instability of bio-based particles require special attention when designing tools and controlling heat input during processing. The distribution and stirring of heterogeneous materials become more efficient when using threaded or pin-shaped tools. Proper processing enables these organic-derived reinforcements to develop strong bonds with the aluminium matrix material. The hybridization of bio-based materials with traditional ceramics through RHA-SiC combinations produces stronger materials with better micro-structural uniformity and surface quality [39].

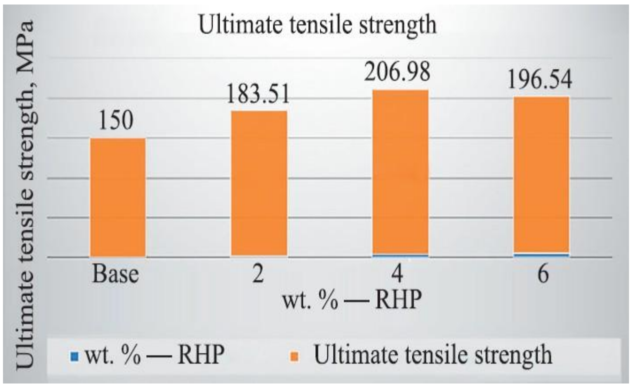
The use of sustainable materials demonstrates their potential to function both as replacements and as enhancers of strength when paired with standard reinforcement materials. The reinforcement used increases the material strength up to a point of 4 wt.%, but beyond that, it decreases its value when utilising 6 wt.%. % of RHP. Also, the maximum hardness achieved is 85.98 HB, with reinforcement of 2 wt. % SiC as well as four wt. % RHP is mixed with Al 6082 alloy as shown in Figure 6 [40].

Retrieval Number: 100.1/ijse.B132205021125
DOI: 10.54105/ijse.B1322.05021125
Journal Website: www.ijse.latticescipub.com

Published By:
Lattice Science Publication (LSP)



[Fig.6: Hardness of Fabricated Hybrid Composite AA6082/SiC/RHP]



[Fig.7: Ultimate Tensile Strength of Fabricated Hybrid Composite AA6082/SiC/RHP]

Table V: Summary of Bio-Based/Sustainable Additives in FSP of Aluminium Alloys

Alloy	Additive Type	wt.%	FSP Passes	Hardness (HV)	Key Results
AA6061	Rice Husk Ash (RHA)	5	2	↑ ~22%	Improved wear resistance, silica-based hardening
AA7075	Eggshell Powder	3 - 9	2	↑ ~25%	Increased compressive strength, eco-friendly
AA6082	Chicken Bone Ash	2 - 6	2	↑ ~18%	Lower density, good particle distribution
AA6082	RHA + SiC (Hybrid)	—	3	↑ ~28%	Hybrid synergy, enhanced surface integrity

IV. CHALLENGES AND APPLICATIONS FOR FSP-FABRICATED ALUMINUM COMPOSITES

FSP represents an effective fabrication method for high-performance AMCs, but industrial deployment needs to address multiple challenges. Achieving uniform distribution of reinforcement particles is a primary challenge because nano-scale and low-density materials, including graphene, CNTs and bio-based powders, need to be dispersed. The mechanical properties of materials degrade because localised weaknesses, along with clustering and interfacial debonding, appear due to inhomogeneous distribution. Each matrix-reinforcement combination requires extensive optimisation because the process parameters of tool geometry, rotation speed, traverse speed, and number of passes remain highly sensitive to specific combinations. The improper selection of process parameters leads to the formation of voids, along with tunnel defects and incomplete mixing, which compromise the integrity of the stir zone.

The main obstacle arises from the insufficient bonding between reinforcement particles and the aluminium matrix. The efficiency of load transfer decreases, and the benefits of reinforcement become limited because ceramic and carbon-based particles fail to bond correctly. The production of hybrid and bio-based reinforcements faces additional complexity because their chemical properties and thermal stability exist across a wide range. The processing of B4C and TiC hard particles presents critical challenges because the tool surface undergoes multiple-pass erosion, which negatively affects both cost efficiency and repeatability.

The challenges of FSP production have not prevented the remarkable applications of AMCs in various engineering applications. The aerospace and automotive sectors utilise SiC, Al2O3, and Sc reinforced composites for structural and semi-structural components because these materials provide better strength-to-weight ratios and fatigue resistance. AA5xxx- and AA6xxx-based composites with ceramic or hybrid reinforcements exhibit exceptional corrosion and wear resistance, making them suitable for ship hulls, propeller components, and offshore structures in marine environments. Thermal management systems consisting of carbonaceous-reinforced AMCs find applications in heat sinks and housings for electronics because they enhance thermal conductivity. Bio-based and sustainable composites are experiencing increasing demand for non-critical consumer goods, agricultural tools, and eco-friendly packaging applications due to their combination of moderate strength and cost-effectiveness.

The continuous development of tool design, along with parameter control and reinforcement technology, has been expanding the use of FSP-based composites despite the processing complexities and technical barriers. Their combination of performance capabilities, weight advantages, and sustainability makes them a competitive material solution for future industrial needs across different sectors.

V. FUTURE RESEARCH SCOPE

Research into aluminium matrix composites processed by Friction Stir Processing offers numerous new opportunities to provide lightweight yet robust materials. This is an emerging and fast-growing research area. Today's and tomorrow's researchers will focus on applying carbon nanotubes, together with graphene nano-plates and nano-sized ceramics, as reinforcement materials. They will also seek to address some crucial problems that recent research has suggested possible solutions for.

The emerging research trend concentrates on creating reinforcement hybrids that contain functionally graded structures.

Material properties are to be aimed at precise sites through the use of these materials. The best method for achieving clever layering involves a single FSP process that produces a ceramic surface with wear-resistant properties and a sufficiently ductile metal core.

FSP researchers have attained real-time monitoring and process-modelling

Published By:
Lattice Science Publication (LSP)

techniques that now bolster the reliability of field operations. Advanced simulation tools, including finite element modelling (FEM) and machine learning (ML) algorithms, are pivotal to this new era of field operations. If simulation tools succeed, then field operations will also grow.

The years to come will see even more development in the sustainability sector. To prepare the way, more research is warranted to evaluate the long-term effects—especially in an environmental context—of using rice husk ash, eggshells, and bone ash as biobased industrial waste materials in reinforcements for bio-composites. If such B-sit materials are to be put to critical use, they must prove chemically stable; they must not impart dangerous levels of toxicity to humans or the environment; and they must not corrode in ways that will significantly shorten the life of the structures that incorporate them.

FSP-AMCs hold great application potential but require further research to fully realise their potential. This young technology depends on more than the minimal test data it has to date. Several unanswered questions exist about FSP-AMCs regarding fundamental properties, such as durability and reliability, that would make them practical for use in high-stress environments. A few experiments, along with extensive work of a kind typically undertaken by a postdoctoral researcher, will be required to answer these fundamental questions and prove the viability of FSP-AMCs.

The next generation of engineering systems can utilise aluminium matrix composites that undergo FSP processes, once researchers resolve the various multidimensional facets of these materials. Material development must co-occur with process optimisation, as well as the assessment and practical application testing of these materials. To achieve the true next-generation potential of aluminium matrix composites, this is the path we must follow.

VI. CONCLUSION

Friction Stir Processing (FSP) has significantly advanced the fabrication of both surface and bulk aluminium matrix composites (AMCs), emerging as a powerful solid-state method for material modification. The process has enhanced the mechanical properties, as well as the tribological, thermal, and corrosion-related properties, of aluminium alloys. The assessment of aluminium alloys was conducted for AA6xxx, AA5xxx, AA7xxx, AA1050, and AA2024, along with various reinforcements that include ceramics, metallic elements, carbon-based materials, hybrid systems, and bio-derived sustainable additives. Ceramic particles with SiC, Al_2O_3, B_4C, and TiC show consistently outstanding enhancements in hardness, wear resistance, and microstructural refinement. Additional benefits from metallic additives such as Cu, Mo, Sc, and ZrW_2O_8 include thermal stability enhancement, solid-solution strengthening, and effective grain boundary pinning.

The addition of carbonaceous materials, including graphene and graphite, enhances both lubrication properties and electrical conductivity, while also reducing wear and tear. Hybrid reinforcement systems that contain different phases improve performance by offering multiple functions. At the same time, bio-based additives such as rice husk ash, eggshell, and bone ash serve as affordable and environmentally friendly options that will enhance mechanical properties.

The FSP process faces specific technical challenges. They are Particle agglomeration, uneven particle distribution, Interfacial debonding, and Sensitivity to critical processing parameters (e.g., rotation and traverse speeds, tool geometry, and the number of passes). Producing high-quality, defect-free composites with consistent structural integrity requires the implementation of advanced processing techniques, along with real-time control systems, to address these existing issues. FSP-AMCs have numerous industrial applications. Their properties are: 1. High strength-to-weight ratio, 2. Corrosion resistance, and 3. Surface durability.

This allows applications in aerospace, automotive, marine, thermal management systems, and environmentally friendly manufacturing. Future research on FSP-AMCs needs to focus on three areas: 1. Hybrid reinforcement system optimisation, 2. Practical service condition validation of performance, and 3. Sustainable behaviour: additive studies.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. Abtan, N. S., Jassim, A. H., & Al-Janabi, M. S. M. (2018). Tensile Strength, Micro-hardness and Microstructure of Friction-Stir-Welding AA6061-T4 Joints. Tikrit Journal of Engineering Science, 25(4), 50–55. DOI: https://doi.org/10.25130/TJES.25.4.09
2. O. H. Mahmood, M. Sh. Aljanabi, and F. M. Mahdi, "Effect of Cu nanoparticles on microhardness and physical properties of aluminium matrix composite prepared by PM," AIMS Materials Science, vol. 12, no. 2, pp. 245–257, Jan. 2025, doi: 10.3934/matersci. 2025013. Available: DOI: https://doi.org/10.3934/matersci.2025013
3. Sato, Y. (2015). Friction Stir Welding (FSW). Quarterly Journal of The Japan Welding Society, 84(8), 573–581. DOI: https://doi.org/10.2207/JJWS.84.573
4. Moustafa, E. B. (2017). Effect of Multi-Pass Friction Stir Processing on Mechanical Properties for AA2024/Al2O3 Nanocomposites. Materials, 10(9), 1053. DOI:https://doi.org/10.3390/MA10091053
5. H. Eskandari, R. Taheri, and F. Khodabakhshi, "Friction-stir processing of an AA8026-TiB2-Al2O3 hybrid nanocomposite: Microstructural developments and mechanical properties," Materials Science and Engineering A-structural Materials Properties Microstructure and Processing, vol. 660, pp. 84–96, Apr. 2016, Available:

https://www.sciencedirect.com/science/article/pii/S0921509316301976

6. Vidal, C., Ferreira, P. M., Inácio, P. L., Ferreira, F., Silva, R. J. C., & Santos, T. G. (2023). Enhancement of particle distribution in aluminium-based composites produced by upward friction stir processing. The International Journal of Advanced Manufacturing Technology, 127, 2745–2757. DOI: https://doi.org/10.1007/s00170-023-11664-y
7. Sanusi, K. O., & Akinlabi, E. T. (2017). Friction-stir processing of a composite aluminium alloy (AA 1050) reinforced with titanium carbide powder. Materiali in Tehnologije, 51(3), 427–435. DOI: https://doi.org/10.17222/MIT.2016.021
8. Zhang, R. Y., Wang, P., Han, X. W., Shi, Z. M., & Zhao, G. (2016). Effect of the Deformation Parameters on the Microstructure of TiC-Al2O3P/Al Composites. Materials Science Forum, 877, 237–244. DOI: https://doi.org/10.4028/WWW.SCIENTIFIC.NET/MSF.877.237
9. Pasha, Md. A. (2022). Fabrication of Surface Metal Matrix composite of AA7075 using Friction Stir Processing. *International Journal of Scientific Research in Science and Technology*, 551–555. DOI: https://doi.org/10.32628/ijsrst2293108
10. Zykova, A., Vorontsov, A. V., Chumaevskii, A., Gurianov, D. A., Savchenko, N. L., Gusarova, A., Kolubaev, E., & Tarasov, S. Yu. (2022). In Situ Intermetallics-Reinforced Composite Prepared Using Multi-Pass Friction Stir Processing of Copper Powder on a Ti6Al4V Alloy. Materials, 15(7), 2428. DOI: https://doi.org/10.3390/ma15072428
11. Tashkandi, M. A., Al-jarrah, J. A., & Ibrahim, M. (2017). Increasing the Mechanical Properties of Friction Stir Welded Joints of 6061 Aluminium Alloy by Introducing Alumina Particles. Advances in Materials Sciences, 17(2), 29–40. DOI: https://doi.org/10.1515/ADMS-2017-0009
12. Inácio, P. L., Nogueira, F., Ferreira, F. B., Vidal, C., Schell, N., Tero, T., Vilaça, P., Oliveira, J. P., & Santos, T. G. (2021). Functionalized material production via multi-stack Upward Friction Stir Processing (UFSP). Materials and Manufacturing Processes, 1–14. DOI: https://doi.org/10.1080/10426914.2021.1942909
13. Refat, M., et.al. (2016). Microstructure, Hardness and Impact Toughness of Heat-Treated Nanodispersed Surface and Friction Stir-Processed Aluminium Alloy AA7075. Journal of Materials Engineering and Performance, 25(11), 5087–5101. DOI: https://doi.org/10.1007/S11665-016-2346-3
14. Olaniran, O., Uwaifo, O., Bamidele, E., & Olaniran, B. A. (2019). *An investigation of the mechanical properties of an organic silica, bamboo leaf ash, and rice husk-reinforced aluminium hybrid composite*. *3*(4). DOI: https://doi.org/10.15406/MSEIJ.2019.03.00103
15. García-Vázquez, F., Vargas-Arista, B., Muñiz, R., Ortiz, J., Hernández García, H., & Acevedo, J. (2016). The Role of Friction Stir Processing (FSP) Parameters on TiC-Reinforced Surface of Al7075-T651 Aluminium Alloy. *Soldagem & Inspeção*, *21*(4), 508–516. DOI: https://doi.org/10.1590/0104-9224/SI2104.10
16. Kumar, R. A., et al. (2019). Effect of Hybrid Reinforcement on the Stirred Zone of Dissimilar Aluminium Alloys during Friction Stir Welding. Metallurgical Research & Technology, 116(6), 631. DOI: https://doi.org/10.1051/METAL/2019062
17. Li, P., & Chen, T. J. (2016). Effect of SiCp volume fraction on the microstructure and tensile properties of SiCp/2024 Al-based composites prepared by powder thixoforming. Journal of Materials Research, 31(18), 2850–2862. DOI: https://doi.org/10.1557/JMR.2016.293
18. Yu, Z., Zhu, H., Huang, J., Li, J., Xie, Z., & Xie, Z. (2017). Processing and characterisation of in-situ ultrafine TiB2-Cu composites from the Ti-B-Cu system. Powder Technology, 320, 66–72. DOI: https://doi.org/10.1016/J.POWTEC.2017.07.036
19. Ammal, M. A., & Sudha, J. (2022). Microstructural Evolution & Mechanical Properties of ZrO2/GNP and B4C/GNP reinforced AA6061 Friction Stir Processed Surface Composites - A Comparative study. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *237*, 1149–1160. DOI: https://doi.org/10.1177/09544054221126942
20. Ahmadifard, S., Momeni, A., Bahmanzadeh, S., & Kazemi, S. (2018). Microstructure, tribological and mechanical properties of Al7075 / Ti3AlC2 MAX-phase surface composite produced by friction stir processing. *Vacuum*, *155*, 134–141. DOI: https://doi.org/10.1016/J.VACUUM.2018.06.002
21. Yelamasetti, B., G V. R., Saxena, K. K., Msomi, V., M V. H., & Behera, A. (2022). Surface modification of aluminium alloy 6061 by embedding B4C particles via friction stir processing. *Materials Research Express*, *9*(5), 056511. DOI: https://doi.org/10.1088/2053-1591/ac6da7
22. Agureev, L. E., Kostikov, V. I., Yeremeyeva, Zh. V., Barmin, A. A., Rizakhanov, R. N., Ivanov, B. S., Ashmarin, A. A., Laptev, I. N., & Rudshteyn, R. I. (2016). Powder aluminium composites of the Cu system with micro-additions of oxide nanoparticles. *Inorganic Materials: Applied Research*, *7*(5), 687–690. DOI: https://doi.org/10.1134/S2075113316050026
23. Kalashnikova, T., et.al (2022). Structure, Mechanical Properties and Friction Characteristics of the Al-Mg-Sc Alloy Modified by Friction Stir Processing with the Mo Powder Addition. *Superalloys*, *12*(6), 1015. DOI: https://doi.org/10.3390/met12061015
24. Mourad, A.-H. I., Mousa, E. S., & Kandil, A. (2020). *Fabrication of AA6082/WC nanocomposite by friction stir processing and optimisation using the Taguchi approach*. *15*(57), 1030–1039. DOI: https://doi.org/10.21608/AUEJ.2020.120375
25. Chumaevskii, A., et al. (2023). In-Situ Al-Mg Alloy Base Composite Reinforced by Oxides and Intermetallic Compounds Resulted from Decomposition of ZrW2O8 during Multipass Friction Stir Processing. *Materials*, *16*(2), 817. DOI: https://doi.org/10.3390/ma16020817
26. Mandal, P. K. (2021). *Surface Modification of Aluminium Alloy (7xxx Series) by Multipass Friction Stir Processing* *6*(2), 008–017. DOI: https://doi.org/10.30574/GJETA.2021.6.2.0127
27. R. Zaekova, D. Gradinarov, P. Tashev, and Y. Hadjitodorov, Modification of 5083 aluminium alloy with graphene via friction stir processing. (2023). *Vide. Tehnoloģija. Resursi*, *3*, 276–280. DOI: https://doi.org/10.17770/etr2023vol3.7196
28. Abushanab, W. S., et al. (2023). Impact of Hard and Soft Reinforcements on the Microstructure, Mechanical, and Physical Properties of the Surface Composite Matrix Manufactured by Friction Stir Processing. *Coatings*, *13*(2), 284. DOI: https://doi.org/10.3390/coatings13020284
29. Akçamlı, N., Gökçe, H., & Uzunsoy, D. (2016). Processing and characterisation of graphene nano-platelet (GNP) reinforced aluminium matrix composites. *Materials Testing-Materials and Components Technology and Application*, *58*, 952. DOI: https://doi.org/10.3139/120.110944
30. Boromei, I., Ceschini, L., Morri, A., & Garagnani, G. L. (2016). Friction Stir Welding of Aluminium-Based Composites Reinforced with L2O3 Particles: Effects on Microstructure and Charpy Impact Energy. *Metallurgical Science and Technology*, *24*(1), 12–21. https://www.fracturae.com/index.php/MST/article/download/1117/1069
31. Khoshaim, A. B., Moustafa, E. B., Alazwari, M. A., & Taha, M. A. (2023). An Investigation of the Mechanical, Thermal and Electrical Properties of an AA7075 Alloy Reinforced with Hybrid Ceramic Nanoparticles Using Friction Stir Processing. *Superalloys*, *13*(1), 124. DOI: https://doi.org/10.3390/met13010124
32. A. Mostafapour and S. T. Khandani, "Fabrication of AL/Graphite/AL2O3 surface hybrid nano composite by friction stir processing and investigating the wear and microstructural properties of the composite," DOAJ (DOAJ: Directory of Open Access Journals), Oct. 2017, https://doaj.org/article/33c956ececba4f2abe06ed54c89c59ba
33. Pasha, Md. A. (2022). Fabrication of Surface Metal Matrix composite of AA7075 using Friction Stir Processing. *International Journal of Scientific Research in Science and Technology*, 551–555. DOI: https://doi.org/10.32628/ijsrst2293108
34. N, U. K., & G, R. (2023). Analysis of tensile strength on friction stir-welded Al 6061 composite reinforced with B4C and Cr2O3 using RSM and ANN. *Engineering Research Express*, *5*(1), 015018. DOI: https://doi.org/10.1088/2631-8695/acb6d1
35. Heidarpour, A., Ahmadifard, S., & Kazemi, S. (2017). On the fabrication and characterisation of Al5083/Al2O3 surface nanocomposite via friction stir processing. *Journal of Advanced Materials and Processing*, *5*(2), 11–24. https://jmatpro.iaun.ac.ir/article_594940.htm
36. Saxena, P., Bongale, A., Kumar, S., & Jadhav, P. R. (2023). Microstructural and sensor data analysis of friction stir processing in fabricating Al6061 surface composites. *Engineering Research Express*, *5*(1), 015065. DOI: https://doi.org/10.1088/2631-8695/acc158
37. Şenel, M. C., & Gürbüz, M. (2020). Investigation on Mechanical Properties and Microstructures of Aluminium Hybrid Composites Reinforced with Al2O3/GNPs Binary Particles. *Archives of Metallurgy and Materials*, 97–106. DOI: https://doi.org/10.24425/amm.2021.134764
38. Fatchurrohman, N., Farhana, N., & Marini, C. D. (2018). *Investigation on the effect of Friction Stir Processing Parameters on Micro-structure and Micro-hardness of Rice Husk Ash reinforced Al6061 Metal Matrix Composites*. *319*(1), 012032. DOI:

https://doi.org/10.1088/1757-899X/319/1/012032
39. Srivastava, A. K., Nag, A., Dwivedi, S. P., Dixit, A. R., & Hloch, S. (2023). Effect of eggshell powder on the microstructural and thermal behaviour of Al7075/waste eggshell surface composites produced by solid-state friction stir processing developed for potential thermal applications. *The International Journal of Advanced Manufacturing Technology*, *127*(3–4), 1243–1261. DOI: https://doi.org/10.1007/s00170-023-11600-0
40. Kumar, N., Singh, R. K., Srivastava, A. K., Nag, A., Petrů, J., & Hloch, S. (2022). Surface Modification and Parametric Optimization of Tensile Strength of Al6082/SiC/Waste Material Surface Composite Produced by Friction Stir Processing. *Coatings*, *12*(12), 1909. DOI: https://doi.org/10.3390/coatings12121909
41. Kumar, N. S. S., Gupta, P., & Singh, R. K. (2022). Fabrication and characterization of hybrid composite of Al6082/SiC/rice husk powder using friction stir processing. *Naučno-Tehničeskij Vestnik Informacionnyh Tehnologij, Mehaniki i Optiki*, *22*(6), 1119–1126. DOI: https://doi.org/10.17586/2226-1494-2022-22-6-1119-1126

AUTHOR'S PROFILE

Mustafa Shakir Marmoos Aljanabi is an Assistant Lecturer at the Department of Mechanical Engineering, College of Engineering, Tikrit University, Iraq. He obtained his B.Sc. degree in Mechanical Engineering from Tikrit University in 2015 and his M.Sc. degree in Mechanical Engineering (with a specialisation in Production and Metallurgy) from the same university in 2019. He is currently preparing for his PhD studies in Mechanical Engineering. His research interests include friction stir welding (FSW), friction stir processing (FSP), and composite materials, with a particular focus on enhancing the microstructural and mechanical performance of aluminium-based systems. He has authored and co-authored three research papers that have been published in international journals.

Omar Hassan Mahmood Al-Douri is an Assistant Lecturer at the Department of Mechanical Technologies, Technical Institute of Dour, Northern Technical University, Iraq. He obtained his M.Sc. degree in Mechanical Engineering from Tikrit University in 2019, with a focus on advanced materials and manufacturing processes. Currently, he is preparing for his PhD studies in Mechanical Engineering. His research interests include powder metallurgy, friction stir processing, freeze casting, fibre distribution in composites, and tribological performance of reinforced Al-Fe matrix composites. He has authored and co-authored several research papers in international journals. Additionally, he contributes to curriculum development, teaching, and supervising student projects.