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# Mechanical Properties of Friction Stir Processed Aluminum Composite Surfaces

**Hasabe Pradeepkumar Tukaram[1] and Dr. Nikhil Janardan Rathod[2]**
[1]Research Scholar, Department of Mechanical Engineering
[2]Research Guide, Department of Mechanical Engineering
Vikrant University, Gwalior, M.P, India

**Abstract:** *Friction Stir Processing is an advanced solid-state surface modification technique derived from friction stir welding and is increasingly used to manufacture aluminum-based surface composites with improved mechanical and tribological performance. Unlike conventional fusion-based processing, FSP produces intense plastic deformation and frictional heating without melting the substrate, thereby promoting dynamic recrystallization, grain refinement, particle fragmentation, and more homogeneous distribution of reinforcement particles. This paper examines the mechanical properties of friction stir processed aluminum composite surfaces, with particular emphasis on hardness, tensile strength, yield strength, ductility, wear resistance, and the relationship between processing parameters and microstructural development. Published research from 2010–2025 indicates that reinforcements such as SiC, $Al_2O_3$, $TiB_2$, graphite, carbon nanotubes, and hybrid particles can significantly improve surface hardness and wear resistance when appropriately dispersed.*

**Keywords:** Friction Stir Processing, Aluminum Matrix Composites, Surface Composites, Mechanical Properties, Hardness.

## I. INTRODUCTION

Aluminum alloys are widely employed in aerospace, automotive, marine, transportation, and structural engineering because of their low density, good corrosion resistance, favorable machinability, and high specific strength. Nevertheless, conventional aluminum alloys may exhibit inadequate surface hardness, wear resistance, and load-bearing capability when exposed to severe mechanical contact or abrasive environments. Aluminum matrix composites provide an effective approach for overcoming these limitations by incorporating hard ceramic, metallic, or carbon-based reinforcement phases into an aluminum matrix. However, conventional casting and powder-metallurgy approaches may result in particle segregation, porosity, weak interfacial bonding, and undesirable reactions. Friction stir processing has therefore emerged as an attractive solid-state technique for producing surface-modified aluminum composites.

FSP is based on the principles of friction stir welding but is employed primarily to modify the microstructure and properties of a material rather than join two separate components. A rotating tool consisting of a shoulder and pin is plunged into the aluminum surface and traversed along the processing direction. Friction between the tool and workpiece generates heat, while the rotating pin produces intense plastic flow. Because the temperature generally remains below the melting temperature of aluminum, solid-state processing minimizes melting-related defects. Severe plastic deformation and dynamic recrystallization produce fine, equiaxed grains, while reinforcement particles introduced into a groove or hole can become mechanically incorporated into the surface layer.

The mechanical properties of an FSP surface composite depend on several interacting variables. These include tool rotational speed, traverse speed, axial force, tool tilt angle, pin geometry, number of passes, reinforcement type, reinforcement concentration, particle size, and cooling conditions. The relationship is not necessarily linear. Increasing rotational speed can improve particle distribution and material flow up to an optimum point, but excessive heat input may promote grain growth and reduce hardness. Similarly, additional FSP passes generally improve particle dispersion

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and grain refinement, although excessive processing may increase heat exposure and reduce certain precipitation-strengthened properties.

The objective of this research paper is to critically examine the mechanical behavior of friction stir processed aluminum composite surfaces based on research published between 2010 and 2025. Particular attention is given to the mechanisms responsible for improvement in hardness, strength, ductility, and wear resistance.

## II. FRICTION STIR PROCESSING OF ALUMINUM COMPOSITE SURFACES

The basic FSP process involves four major stages: tool plunging, tool dwelling, tool traversing, and tool withdrawal. During processing, frictional heat softens the aluminum, while the rotating tool causes severe plastic deformation. The material is transported around the pin and consolidated behind the tool. Reinforcement particles placed in a surface groove can consequently be distributed throughout the stir zone.

The heat generated during FSP can be approximately related to frictional work as:

$$Q \approx 2\pi\mu P\omega R^2$$

where Q represents heat generation, μ is the coefficient of friction, P is the applied pressure, ω is angular velocity, and R is the effective tool radius.

The final properties are determined by the balance between heat generation and material flow. Insufficient heat can produce inadequate plasticization and tunnel defects, whereas excessive heat can cause grain coarsening or degradation of strengthening precipitates.

Surface composites produced by FSP commonly employ SiC, $Al_2O_3$, $TiB_2$, graphite, CNTs, graphene, and hybrid reinforcements. A review by Sharma et al. emphasized that FSP can enhance surface hardness, strength, ductility, wear resistance, corrosion resistance, fatigue behavior, and formability.

## III. MICROSTRUCTURAL EVOLUTION DURING FSP

The improvement in mechanical properties is strongly associated with microstructural refinement. Aluminum alloys subjected to FSP experience severe plastic deformation and dynamic recrystallization. The original coarse grains are transformed into fine equiaxed grains within the stir zone.

The Hall–Petch relationship can be expressed as:

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

where σy is yield strength, σ0 is the friction stress, ky is the Hall–Petch constant, and d is average grain diameter.

Thus, decreasing grain size generally increases yield strength. Reinforcement particles provide an additional strengthening contribution through load transfer, Orowan strengthening, dislocation generation, and grain-boundary pinning.

Research on AA5083/n-SiC composites demonstrated this relationship clearly. FSP produced fine recrystallized grains and improved the distribution of nanosized SiC particles. A 2 wt% n-SiC composite processed by FSP achieved a yield strength of 224 MPa and hardness of 84 HV, compared with 152 MPa and 75 HV for FSPed unreinforced AA5083. Excessive SiC content of 3 wt% produced agglomeration and consequently reduced mechanical performance.

Similarly, studies of AA7075/$TiB_2$ composites have shown that FSP can convert clustered reinforcement particles into a more homogeneous intragranular distribution. Particle fragmentation and redistribution during processing contribute to improved mechanical and wear properties.


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## IV. MECHANICAL PROPERTIES OF FSP ALUMINUM COMPOSITE SURFACES

### 1. Hardness

Hardness is one of the most consistently improved properties following FSP surface modification. Ceramic reinforcements such as SiC and $Al_2O_3$ are significantly harder than aluminum and can therefore increase resistance to localized plastic deformation.

Izadi (2013) reported that FSP increased the hardness of powder-metallurgy Al–SiC composites. For 4 vol% and 8 vol% SiC composites, hardness increased from 130 HV and 145 HV to approximately 171 HV and 177 HV, respectively.

The increase can be attributed to:

1. Grain refinement.
2. Dispersion strengthening.
3. Increased dislocation density.
4. Load transfer from aluminum to reinforcement.
5. Orowan strengthening.
6. Particle-induced restriction of grain boundary movement.

However, hardness does not always increase simply with increasing FSP intensity. In precipitation-hardened aluminum alloys, excessive heat can dissolve or coarsen strengthening precipitates. Research on AA2014/SiC indicated that although the reinforcement increased surface hardness, FSP alone could reduce hardness relative to the base alloy because precipitation hardening may be more influential than grain refinement in some conditions.

### 2. Tensile and Yield Strength

Tensile strength depends on grain size, reinforcement distribution, matrix-reinforcement bonding, defects, and thermal history. Uniformly distributed particles improve load transfer and restrict plastic deformation.

The tensile behavior can be represented through the engineering stress relationship:

$$\sigma = \frac{F}{A_0}$$

where σ is engineering stress, F is applied tensile force, and A0 is the original cross-sectional area.

The FSPed AA5083–2 wt% SiC nanocomposite reported by recent research demonstrated a yield strength of 224 MPa compared with 152 MPa for the FSPed unreinforced alloy. This represents approximately a 47% increase in yield strength.

Another investigation of AA6061/$Al_3Fe$ composites found that FSP resulted in homogeneous redistribution and fragmentation of $Al_3Fe$ particles, substantial grain refinement, and considerable improvement in tensile strength.

### 3. Ductility

Strength and ductility frequently exhibit a trade-off in metal matrix composites. The incorporation of hard ceramic particles can increase strength while potentially reducing elongation if particle clusters or interfacial defects develop.

FSP can partially overcome this problem because severe plastic deformation breaks up particle clusters and improves matrix homogeneity. Therefore, an optimized reinforcement concentration may provide a better strength–ductility combination than either an unprocessed composite or an excessively reinforced material.

The AA5083–SiC study provides an important example: 2 wt% SiC produced favorable strength–ductility synergy, whereas 3 wt% SiC caused particle agglomeration and inferior mechanical properties.

### 4. Wear Resistance

Wear resistance is particularly important for aluminum surface composites used in sliding, abrasive, and contact applications. Hard ceramic particles provide resistance against material removal, while grain refinement increases the resistance of the aluminum matrix to plastic deformation.

The specific wear rate can be expressed as:

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$$K_s = \frac{V}{WL}$$

where K_s is specific wear rate, V is wear volume, W is applied load, and L is sliding distance.

FSP can reduce wear by producing a harder and more homogeneous surface. A 2020 investigation of AA2024 reinforced with $Al_2O_3$ nanoparticles showed that additional FSP passes improved wear resistance by approximately 39–70%, while a third FSP pass increased ultimate tensile strength and Young's modulus by approximately 40% and 20%, respectively. The incorporation of $Al_2O_3$ nanoparticles increased hardness by approximately 42%.

## V. EFFECT OF MAJOR PROCESS PARAMETERS

| Process parameter | Effect on microstructure | Expected mechanical effect | Major concern |
|---|---|---|---|
| Tool rotational speed | Controls heat and material flow | Moderate increase can improve strength/hardness | Excessive heat may cause grain growth |
| Traverse speed | Controls heat input and processing time | Higher speed can refine grains under suitable conditions | Too high may cause tunnel defects |
| Number of FSP passes | Improves particle dispersion and refinement | Generally improves hardness and strength initially | Excessive passes can cause thermal softening |
| Reinforcement content | Changes dispersion strengthening | Moderate addition improves hardness and strength | Excessive particles cause agglomeration |
| Particle size | Influences strengthening and distribution | Nano-sized particles can produce strong strengthening | Nanoparticle clustering |
| Tool pin profile | Controls material flow | Better distribution and defect reduction | Poor flow may produce defects |
| Tool tilt angle | Improves consolidation | Can improve surface integrity | Excessive tilt may disturb material flow |
| Cooling | Controls peak temperature | Can preserve refined grains and precipitates | Excessive cooling may reduce plastic flow |

A review of aluminum surface composites reported that multiple FSP passes, cooling, tool design, and reinforcement selection substantially affect grain size and mechanical properties. In AA7075/$TiB_2$ systems, for example, very substantial reductions in grain size and increases in strength and hardness have been reported under optimized processing conditions.

## V. STRENGTHENING MECHANISMS

The mechanical improvement of FSP aluminum composites results from several simultaneous mechanisms.

**1. Grain Boundary Strengthening**

Dynamic recrystallization produces fine grains. According to the Hall–Petch relationship, smaller grains provide greater resistance to dislocation movement.

**2. Dispersion Strengthening**

Hard particles distributed within the aluminum matrix obstruct dislocation motion. This is particularly important for nanosized SiC and $Al_2O_3$.

**3. Load Transfer**

When strong bonding exists between the aluminum matrix and reinforcement, part of the applied load can be transferred from the relatively soft aluminum to the stronger reinforcement.

**4. Orowan Strengthening**

Small particles force dislocations to bow around them. The resulting strengthening contribution increases as particle spacing decreases.

**5. Thermal and Precipitation Effects**

FSP can alter the precipitation state of age-hardenable aluminum alloys. Consequently, mechanical performance reflects both grain refinement and changes in precipitation strengthening. This explains why some FSPed alloys may exhibit reduced hardness despite significant grain refinement.

## VI. DISCUSSION

The available literature demonstrates that FSP is highly effective for engineering the surface properties of aluminum alloys. Its principal advantage is the simultaneous occurrence of severe plastic deformation, dynamic recrystallization, and reinforcement redistribution. Compared with conventional composite manufacturing, the solid-state nature of FSP reduces the likelihood of melting-related defects and can improve interfacial characteristics.

The selection of reinforcement is nevertheless critical. SiC provides excellent hardness and wear resistance, $Al_2O_3$ provides strong dispersion strengthening, $TiB_2$ provides high-temperature stability and hardness, while graphite and carbon-based reinforcements can provide favorable tribological characteristics. Hybrid reinforcements can potentially combine these advantages, but they also increase processing complexity.

One of the most important findings across the literature is that more reinforcement does not necessarily mean better mechanical properties. The AA5083/n-SiC investigation showed that 2 wt% reinforcement produced excellent performance, whereas 3 wt% resulted in severe agglomeration and inferior properties. Therefore, the optimum reinforcement concentration must balance particle strengthening against agglomeration.

Similarly, increasing the number of FSP passes can improve homogeneity. Research on $Al_2O_3$-reinforced AA2024 demonstrated substantial improvements in wear, tensile strength, Young's modulus, and hardness with additional processing. However, excessive passes may increase thermal exposure and cause precipitation changes or grain coarsening.

Recent reviews published in 2025 continue to identify particle agglomeration, process-parameter optimization, tool wear, and the development of hybrid reinforcement systems as important research challenges.

## VII. CONCLUSIONS

The following conclusions can be drawn from the research published during 2010–2025:

1. Friction Stir Processing is an effective solid-state technique for producing mechanically enhanced aluminum surface composites.
2. Grain refinement and dynamic recrystallization are major contributors to improved yield strength and hardness.
3. Ceramic reinforcements such as SiC, $Al_2O_3$, and $TiB_2$ can substantially increase surface hardness and wear resistance.
4. Uniform particle distribution is more important than simply increasing reinforcement concentration. Excessive reinforcement can generate particle agglomeration and reduce strength and ductility.
5. Multiple FSP passes generally improve particle dispersion and microstructural homogeneity, although excessive passes may introduce undesirable thermal effects.
6. Tool rotational speed and traverse speed must be carefully optimized because heat generation strongly influences grain size, precipitation state, material flow, and defect formation.
7. FSP can produce an attractive combination of strength, hardness, ductility, and wear resistance, making aluminum surface composites suitable for aerospace, automotive, marine, and other engineering applications.
8. Future work should focus on hybrid nanoparticles, cryogenic/cooling-assisted FSP, artificial intelligence-based parameter optimization, multiphysics modeling, and long-term fatigue and wear evaluation.

The evidence from 2010–2025 establishes FSP as a promising route for tailoring the mechanical properties of aluminum composite surfaces. The strongest results are obtained when reinforcement content, particle size, tool geometry, rotational speed, traverse speed, number of passes, and thermal conditions are simultaneously optimized rather than considered independently.

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