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Microstructural Evolution of Aluminum Composite Surfaces during Friction Stir Processing

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Abstract: *Friction stir processing has emerged as an effective solid-state surface modification technique for developing refined, homogenized, and reinforced aluminum composite layers without melting the substrate. The process combines frictional heating, severe plastic deformation, material flow, dynamic recovery, and dynamic recrystallization, thereby producing substantial changes in grain morphology, grain size, particle distribution, crystallographic texture, dislocation density, and grain-boundary character. These effects become particularly important when ceramic, metallic, or hybrid reinforcement particles are introduced into aluminum alloys to form surface metal-matrix composites. Unlike conventional liquid-state composite processing, FSP can reduce porosity and reinforcement agglomeration while simultaneously refining the aluminum matrix.*

Keywords: Friction stir processing, aluminum matrix composite, surface composite, microstructural evolution, dynamic recrystallization, grain refinement, reinforcement dispersion, hardness.

I. INTRODUCTION

Aluminum alloys are extensively used in aerospace, automobile, transportation, marine, and structural applications because of their low density, good corrosion resistance, high specific strength, and excellent manufacturability. However, conventional aluminum alloys may exhibit inadequate surface hardness, wear resistance, stiffness, and resistance to localized degradation when exposed to severe tribological or mechanical environments. Aluminum matrix composites provide an attractive solution because reinforcing phases such as SiC, Al_2O_3, B_4C, TiC, graphene, carbon-based particles, and metallic particulates can be incorporated into the aluminum matrix to improve surface and bulk performance. Nevertheless, conventional liquid-state composite fabrication may suffer from porosity, interfacial reactions, reinforcement agglomeration, segregation, and poor particle distribution. FSP has consequently attracted substantial interest as a solid-state route for manufacturing aluminum surface composites. The process modifies only a selected region of the material while largely retaining the properties of the underlying substrate.

FSP is derived from friction stir welding and uses a rotating non-consumable tool consisting generally of a shoulder and a cylindrical, threaded, tapered, or otherwise profiled pin. The tool is plunged into the aluminum surface and traversed along a predetermined path. Friction between the shoulder and workpiece generates heat, while the rotating pin introduces severe plastic deformation and facilitates material movement. Because the processing temperature normally remains below the melting temperature of aluminum, the material undergoes intense deformation in a solid or highly plasticized state. The combination of heat and deformation produces a characteristic stir zone with refined grains and modified particle morphology.

The principal significance of FSP for aluminum composites is therefore not simply the incorporation of reinforcement but the simultaneous modification of the matrix microstructure. During processing, the original coarse grains are fragmented and transformed through recovery and recrystallization. Reinforcement particles can act as obstacles to grain-boundary movement and as potential nucleation sites for recrystallized grains. The resulting structure may

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contain fine equiaxed grains, increased high-angle grain-boundary fractions, modified crystallographic texture, and more homogeneous reinforcement distributions. Reviews of FSP-based aluminum composites have emphasized that the evolution from deformed grains through dislocation structures and subgrains to new recrystallized grains is central to the final microstructure.

The basic heat-generation relationship can be represented conceptually as:

$$Q \approx \mu P \omega$$

where Q represents frictional heat generation, μ is the effective friction coefficient, P is the contact force, and ω\omega is the angular velocity of the tool. The actual thermal history is more complex because heat is also affected by plastic deformation, tool geometry, traverse speed, material properties, and heat dissipation to the workpiece and backing plate.

The microstructural response is consequently governed by the balance between heat input and plastic strain. A simplified representation of the thermal-mechanical condition is:

$$\text{Microstructural evolution} = f(\omega, V, F, T, \varepsilon, \dot{\varepsilon}, N, P)$$

where ω is tool rotational speed, V is traverse speed, F is axial force, T is temperature, ε is plastic strain, ε is strain rate, N is the number of passes, and P represents reinforcement characteristics.

Recent research confirms that multiple processing passes can substantially alter the microstructure. In Al6061-T6/SiC composites, increased FSP passes have been associated with finer grains, improved particle dispersion, reduced agglomeration, and increased microhardness. Similarly, multi-pass processing of AA2024/Al_2O_3 surface composites produced improved dispersion and grain refinement, with reported increases in tensile strength and hardness. These findings establish microstructural evolution as a central mechanism controlling the performance of FSP-produced aluminum composite surfaces.

II. RESEARCH OBJECTIVES

The major objectives of this research paper are:

1. To examine the mechanisms responsible for microstructural evolution in aluminum composite surfaces during FSP.
2. To analyze the influence of FSP parameters on grain refinement and recrystallization.
3. To evaluate the role of reinforcement particles in controlling grain growth and particle dispersion.
4. To discuss the effects of multiple FSP passes on surface microstructure.
5. To establish relationships between microstructural characteristics and surface mechanical properties.
6. To identify research challenges and future directions for FSP-based aluminum surface composites.

III. FRICTION STIR PROCESSING OF ALUMINUM COMPOSITE SURFACES

FSP produces a characteristic processed region consisting broadly of the stir zone, thermo-mechanically affected zone, and heat-affected zone, although the exact morphology depends on alloy composition, processing parameters, and tool design. The stir zone experiences the most severe deformation and consequently exhibits the strongest microstructural transformation. The TMAZ experiences both thermal exposure and deformation, whereas the HAZ is principally affected by temperature. The base material remains relatively unaffected. Understanding these regions is essential because mechanical and tribological properties are strongly dependent on the spatial distribution of grain size and reinforcement.

During FSP, the rotating tool generates a combination of shear deformation and material flow. The aluminum matrix becomes sufficiently plasticized to flow around the tool pin. Reinforcement particles embedded in the surface layer are mechanically transported and redistributed by this flow. Large particle clusters may be broken apart, while individual

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particles can become more uniformly dispersed. The effectiveness of this process depends on tool rotational speed, traverse speed, reinforcement concentration, particle size, tool geometry, and the number of passes.

The ratio of tool rotational speed to traverse speed is often used as a useful qualitative indicator of heat and material-flow conditions:

$$R = \frac{\omega}{V}$$

A higher value of R generally indicates greater heat generation per unit traverse distance, although the actual thermal condition depends on tool geometry, contact conditions, axial force, and material properties. Excessively high heat input may encourage grain growth, whereas insufficient heat can cause inadequate material flow, tunneling, voids, or incomplete particle distribution.

IV. MECHANISMS OF MICROSTRUCTURAL EVOLUTION

1. Severe Plastic Deformation

Severe plastic deformation is the fundamental mechanism responsible for modifying the aluminum matrix. The rotating pin imposes intense shear deformation, producing high dislocation densities and fragmentation of the original grains. Initially, deformation generates dislocation cells and tangles. Continued deformation causes these structures to reorganize into subgrain boundaries. With increasing thermal activation, subgrain boundaries progressively develop into high-angle grain boundaries.

The overall transformation can be represented as:

$$\text{Coarse grains} \rightarrow \text{Dislocation cells} \rightarrow \text{Subgrains} \rightarrow \text{Recrystallized grains}$$

This process explains why the stir zone frequently possesses much finer grains than the base material. Research on FSP-based in-situ composites has identified the sequence of dislocation walls, subgrains, dislocation multiplication, and new grain formation as an important pathway for microstructural refinement.

2. Dynamic Recovery

Dynamic recovery occurs during deformation at elevated temperatures and involves rearrangement and partial annihilation of dislocations. Aluminum has relatively high stacking-fault energy, which facilitates recovery processes. However, because FSP simultaneously imposes severe plastic deformation, recovery does not eliminate all defects. Instead, it contributes to the formation of stable subgrain structures that subsequently participate in recrystallization.

3. Dynamic Recrystallization

Dynamic recrystallization is one of the most important mechanisms governing grain refinement during FSP. New grains develop during deformation and thermal exposure, replacing highly distorted regions with relatively equiaxed grains. The resulting structure generally contains a high proportion of high-angle grain boundaries.

The average grain size can be conceptually related to the competition between nucleation and growth:

$$d \propto \frac{1}{\sqrt{N_g}}$$

where d represents characteristic grain size and Ng represents the effective density of recrystallized grain nuclei. This is a simplified relationship rather than a universal predictive equation.

Recent investigations of SiC-reinforced aluminum composites have specifically attributed grain refinement to dynamic recrystallization and reported progressively improved microstructural uniformity with multiple FSP passes.

4. Particle-Stimulated Nucleation

Reinforcement particles can strongly influence recrystallization. Relatively large particles may generate deformation zones around themselves, producing high dislocation densities. These regions can become favorable sites for recrystallization, a phenomenon commonly associated with particle-stimulated nucleation.

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At the same time, finely distributed particles can restrict grain-boundary migration. Consequently, reinforcement particles perform two important microstructural functions: they can facilitate nucleation of new grains and suppress subsequent grain growth.

V. ROLE OF REINFORCEMENT PARTICLES

The reinforcement phase is critical to the final microstructure of FSP aluminum composites. Ceramic particles such as SiC and Al_2O_3 have high hardness and thermal stability and can resist deformation during processing. When appropriately dispersed, they restrict grain-boundary movement and contribute to grain stabilization.

A simplified Zener-pinning relationship is:

$$D \approx \frac{4r}{3f}$$

where D represents the limiting grain size, r is reinforcement particle radius, and f is particle volume fraction. The relationship illustrates that smaller and more numerous particles can provide stronger resistance to grain-boundary movement.

However, excessive reinforcement concentration can produce clustering. Agglomerated particles may behave as defects rather than strengthening features. Therefore, the objective of FSP is not merely to increase reinforcement content but to achieve a stable and homogeneous distribution.

A study of Al6061-T6/SiC composites found that increasing the number of FSP passes improved the dispersion of SiC and reduced agglomeration, while grain refinement contributed to increased microhardness. Similar observations have been reported for Al_2O_3-reinforced AA2024 composites, where multi-pass FSP promoted homogeneous dispersion and finer grains.

VI. INFLUENCE OF FSP PARAMETERS ON MICROSTRUCTURE

The principal process variables and their expected microstructural effects are summarized below.

FSP Parameter	Increase in Parameter	Expected Microstructural Effect	Possible Limitation
Tool rotational speed	Higher heat and stirring	Improved plastic flow and particle redistribution	Excessive grain growth/thermal exposure
Traverse speed	Faster processing	Lower heat input and shorter exposure	Incomplete mixing or defects
Number of passes	Repeated deformation	Greater grain refinement and particle homogenization	Excessive thermal cycling
Reinforcement content	Higher particle fraction	Greater pinning and strengthening potential	Particle agglomeration
Particle size	Smaller particles	More uniform dispersion and stronger grain-boundary pinning	Difficult dispersion at very high surface area
Tool pin profile	More intense stirring	Improved material flow	Greater tool wear and heat generation
Axial force	Greater contact	Enhanced heat generation and consolidation	Excessive deformation or dimensional effects
Cooling condition	Greater heat extraction	Suppressed grain growth	Possible inadequate plasticization

Experimental research supports the importance of these variables. Studies of AA2014/SiC composites have shown that rotational speed and traverse speed affect grain refinement and microhardness, demonstrating that appropriate parameter selection is essential for controlling the processed microstructure.

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VII. EFFECT OF MULTIPLE FSP PASSES

Multi-pass FSP is particularly important for aluminum surface composites because one pass may not provide complete particle dispersion. Repeated tool movement introduces additional plastic deformation and breaks down particle clusters. At the same time, successive passes repeatedly modify the grain structure.

For example, research on AA2024/Al_2O_3 nanocomposites showed that second and third passes produced finer grains and improved particle dispersion. The study reported approximately 80% grain refinement compared with the base metal and increases in tensile strength and hardness.

Similarly, research on AA6061 reinforced with stainless-steel particles found that increasing the number of passes from one to four enhanced grain refinement, particle refinement, dispersion, and dislocation density. The resulting microstructural modifications were associated with improved hardness, tensile strength, impact toughness, corrosion resistance, and wear behavior.

Recent 2025 research on hybrid B_4C–Al_2O_3 aluminum surface composites further demonstrated the importance of multi-pass processing. Increasing the number of passes from one to six reduced mean grain size from 7.32 μm to 2.31 μm and increased the fraction of high-angle grain boundaries from 74.13% to 94.61%. These results illustrate that repeated FSP can fundamentally modify both grain size and grain-boundary character.

VIII. MICROSTRUCTURAL CHARACTERIZATION TECHNIQUES

A comprehensive investigation of FSP aluminum composites requires multiple characterization methods because no single technique can fully describe the processed microstructure.

Characterization Technique	Major Information Obtained	Relevance to FSP
Optical microscopy	Grain morphology and processed-zone structure	Identification of SZ, TMAZ and HAZ
SEM	Grain/particle morphology and defects	Particle dispersion and agglomeration
EDS	Elemental composition	Identification of reinforcement and reaction products
EBSD	Grain orientation and boundary character	Grain size, texture and recrystallization
XRD	Phase identification and residual stress	Phase transformation and crystallographic changes
TEM	Nanoscale grains and particles	Dislocations, interfaces and nanoscale precipitation
Microhardness testing	Local hardness distribution	Correlation with grain refinement and reinforcement
Wear testing	Friction and material loss	Evaluation of surface-performance improvements

EBSD is particularly valuable because it permits quantitative evaluation of grain size, crystallographic orientation, low-angle and high-angle grain boundaries, and texture. Recent FSP studies have used EBSD together with SEM and EDS to connect grain refinement and particle redistribution with changes in mechanical properties.

IX. MICROSTRUCTURE–PROPERTY RELATIONSHIP

The improvement in surface performance after FSP can be explained through several strengthening mechanisms. Grain refinement increases resistance to plastic deformation according to the Hall–Petch relationship:

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

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

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Reinforcement particles additionally contribute through load transfer, Orowan strengthening, dislocation strengthening, thermal-expansion mismatch, and grain-boundary pinning. Therefore, the final strength and hardness can be considered as a combined response:

$$\sigma_y = \sigma_0 + \Delta\sigma_{GB} + \Delta\sigma_P + \Delta\sigma_D + \Delta\sigma_{LT}$$

where the additional terms represent grain-boundary, particle, dislocation, and load-transfer strengthening, respectively. The relationship between microstructure and hardness has been demonstrated experimentally. Three-pass processing of Al6061-T6/SiC composites produced refined grains and improved particle distribution and was associated with a 41.79% increase in microhardness in the reported system. In another study, reinforced FSP aluminum composites exhibited an 81.26% increase in microhardness and a 65.20% reduction in grain size relative to the base material.

X. DEFECTS AND PROCESSING CHALLENGES

Despite its advantages, FSP does not automatically produce defect-free composite surfaces. Inadequate heat generation or poor material flow can result in tunnel defects, voids, incomplete consolidation, or heterogeneous particle distribution. Excessive rotational speed can generate unnecessary heat and potentially promote grain growth. Similarly, very high reinforcement concentrations can lead to particle clustering and poor interfacial bonding.

Tool wear is another important problem when processing hard ceramic-reinforced composites. SiC, B_4C, and Al_2O_3 particles can impose substantial abrasive loads on the tool. Tool degradation changes pin geometry during processing, which subsequently alters material flow and heat generation. The 2015 review of FSP surface composites identified defect-free fabrication, microstructure tailoring, tool durability, and strengthening mechanisms as important areas requiring further investigation.

Consequently, optimization should consider multiple responses simultaneously. A useful conceptual objective function is:

$$J = w_1 H + w_2 S + w_3 W^{-1} - w_4 D$$

where H represents hardness, S represents strength, W represents wear rate, D represents defect fraction, and wi are weighting coefficients. Such multi-objective optimization can help identify process conditions that balance grain refinement, reinforcement distribution, productivity, and defect minimization.

XI. CONCLUSION

Friction stir processing provides an effective solid-state approach for controlling the microstructure and surface properties of aluminum composites. The process generates severe plastic deformation and frictional heating without requiring complete melting, enabling extensive grain refinement, dynamic recrystallization, reinforcement redistribution, and microstructural homogenization. The stir zone normally exhibits the most pronounced transformation, characterized by refined equiaxed grains and modified grain-boundary structures. Reinforcement particles further contribute to refinement through particle-stimulated nucleation and grain-boundary pinning, while also providing opportunities for load transfer and wear resistance.

The number of FSP passes, rotational speed, traverse speed, reinforcement type, particle size, particle concentration, and tool geometry collectively determine the final microstructure. Evidence from SiC-, Al_2O_3-, B_4C-, and metallic-particle-reinforced aluminum systems indicates that carefully controlled multi-pass FSP can reduce particle agglomeration, refine grains, increase high-angle grain-boundary fractions, and improve hardness and other surface properties. However, excessive heat input, inappropriate processing conditions, and reinforcement clustering can compromise the benefits of FSP. Therefore, future development should focus on quantitative process–structure–property models, advanced characterization, optimized tool design, multi-objective parameter optimization, and scalable manufacturing strategies.

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