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Review Article

Methods for Incorporating Reinforcement Particles in Friction Stir Processing: A Review

Sanjeev Kumar[1], Anuradha Sinha[2], Guru Sewak Kesharwani[2]

1. Associate Professor & HoD.
2. Research Scholar
Department of Mechanical Engineering, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh

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Abstract

Friction stir processing (FSP) is progressively recognized as a promising solid-state technique for enhancing both surface and bulk material properties by incorporating reinforcement particles into metallic matrices, thereby achieving improved mechanical, tribological, and corrosion-resistant properties. This review systematically examines the principal methods employed for particle introduction in FSP, including groove filling, drilled hole filling, pre-sintered inserts, and surface coating-assisted approaches. The influence of these techniques on particle dispersion, microstructural evolution, mechanical and tribological behaviours are critically discussed. A comparative assessment highlights the challenges associated with each method, emerging future trends and the potential integration of machine intelligence for process optimization and performance prediction..

Keyword*:* Friction Stir Processing, Particle Reinforcement, Composite Materials, Incorporation Techniques, Process parameters.

Address for Correspondence: Sanjeev Kumar, Department of Mechanical Engineering, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh. 250005

E-mail: placid.san@gmail.com **Contact:** +91-87328 19621

Introduction:

A microstructural modification technology called Friction Stir Processing (FSP) is derived from Friction Stir Welding (FSW) and uses severe plastic deformation and stirring action to enhance material characteristics. Both friction stir welding (FSW) and friction stir processing (FSP) are solid-state processes that produce plastic deformation and frictional heat using a rotating tool. But their aim and applications diverge most fundamentally[1]. By stirring two or more distinct materials together along a joint line, FSW is mainly used for joining them. It may produce a flawless weld without melting the base elements. FSP, on the other hand, is meant to improve the mechanical and microstructural characteristics of a specific material or restricted area rather than to join. Metal matrix composites with enhanced hardness, wear resistance, or grain refinement are frequently produced by inserting reinforcement particles into the surface or subsurface[2]. While the tools and working concepts of the two processes are similar, FSP differs in that it focuses on material modification rather than material joining.

FSP is primarily helpful for producing localized surface composites because it can smooth out grain structures, remove casting flaws, and evenly distribute reinforcing particles[3]. FSP minimises residual stresses and distortion by avoiding melting, in contrast to traditional fusion-based techniques, which produce better mechanical, tribological, and corrosion-resistant qualities. Consequently, FSP has been widely used in the defence, automotive, marine, and aerospace industries, where there is a need for high-performance materials with exceptional surface properties. Additionally, it serves as a sustainable alternative to advanced material processing and component life enhancement[4]. The various process parameters, such as rotational speed, traverse speed, tool tilt angle, plunge depth, and workpiece material, generate heat and cause the flow of plasticised material, which in turn affects the joining.

The present study discusses the impact of different particle incorporation techniques in friction stir processing (FSP), such as surface coating, groove filling, powder preplacement, and hybrid methods, on reinforcement distribution, bonding integrity, and resulting property enhancement is the main focus This study's unique consolidation and critical evaluation.

2. Methods of Reinforcement Incorporation in FSP:

Several methods have been developed to introduce reinforcement particles into the matrix during FSP, aiming to achieve enhanced material properties, homogeneous dispersion, and strong interfacial bonding[5].

2.1 Groove Filling Technique:

A widely adopted method for incorporating reinforcement particles in Friction Stir Processing (FSP) is the grooving technique. It involves three main steps: machining a groove of defined dimensions into the base material, filling it with reinforcement particles (e.g., ceramics, metallics, or nanoparticles), and subsequently sealing the groove using a pinless tool. FSP follows this with a pinned tool to ensure uniform dispersion and strong interfacial bonding of the particles within the matrix, and Figure 1 illustrates the sequential steps of this

groove-filling technique. Multiple FSP passes are often employed to minimize agglomeration and enhance mechanical and tribological performance.
Kumar et al.[6] demonstrated that multi-groove FSP of Cu/SiC composites enhanced SiC dispersion, interfacial bonding, grain refinement, hardness, and wear resistance, while moderately improving strength and reducing ductility compared to single-groove and base copper. Ashokkumar et al.[7] observed that finer grains and better particle dispersion from multi-pass processing, as well as AlO_3-reinforced AZ61 Mg surface composites made via FSP, demonstrated increased mechanical characteristics, with a UTS of up to 630 MPa and a hardness of 300 HV at 15% reinforcement. Kundurti et al.[8] produced AA7075 surface composites reinforced with rGO and rGO + MWCNT using optimized FSP parameters. These composites demonstrated improved hardness, impact strength, thermal conductivity, tribological properties, and refined grain structure, confirming notable improvements over the base metal through microstructural modification. Using friction stir processing and T6 heat treatment, Ravi et al.[9] showed that AA6061 composites reinforced with AlCoFeNiMn high-entropy alloy particles had refined equiaxed grains, improved surface hardness (115 HV), increased tensile strength (315 MPa), and a lower wear rate (1.04×10^{-3} mm^3/Nm), indicating strong interfacial bonding and appropriateness for automotive and aerospace applications. Balmiki et al.[10] incorporated MWCNTs of ABS and PS, improved joint strength by 39.16%, with optimal conditions at 900 rpm and 0.1 mm/s, demonstrating enhanced performance over non-reinforced joints.

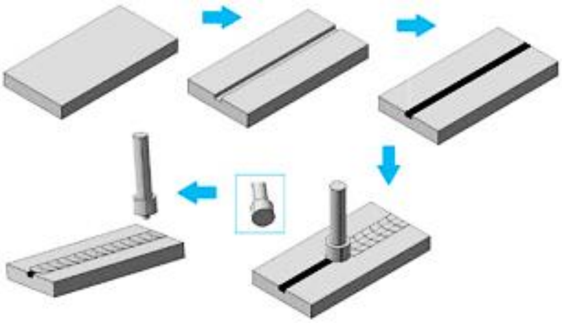

Fig.1. Grooving technique using FSP [11]

2.2 Drilled Hole Filling Techniques

By adding reinforcement particles to a metal matrix, the powder preplacement process in FSP produces surface composites. Using this method, a pre-machined groove or hole on the workpiece surface is filled with a defined amount of powder, such as SiC, AlO_3, or graphene, as shown in Figure 2. The material is then stirred with a revolving tool, producing plastic deformation and frictional heat without melting. The reinforcements' hardness, wear resistance, and corrosion resistance are improved by this method, which also allows for homogeneous dispersion and strong metallurgical bonding. As a result, it can be used in biomedical, automotive, and aerospace applications.

Abdullah et al. [12] investigated the effect of Cu nanoparticle reinforcement by FSP on AA7075, revealing that it increased corrosion resistance, mechanical properties, and grain structure. Cu nanoparticles' strengthening and protecting function was confirmed by samples C1 and C2, which showed maximum hardness (111 HV), superior corrosion resistance ($R_p = 4.12\ k\Omega \cdot cm^2$), and the greatest UTS (460 MPa), respectively. Dubey et al. [13] presented a single-stage Incremental Hole Flanging (IHF) method using a conical tool, reducing production time while enabling successful flange formation with optimized tool angles and validated deformation behavior through FEA on AA1050. Pham et al. [14] conducted a comprehensive study on the variability of Hole Expansion Ratio (HER) in DP800 steel, identifying pre-strain and pre-damage from hole punching as dominant factors. Using a surrogate model trained via neural networks and Monte Carlo simulations, they quantified HER uncertainty and provided insights for improving edge crack resistance. Chen et al.[15] systematically analyzed pin-hole occlusion failure in D25TCIF steel pistons, identifying thermo-mechanical stress concentration and oil film rupture as key causes. An optimization strategy improved oil film thickness by up to 15.36%, offering effective predictive accuracy and practical solutions for piston durability. Zhang et al. [16] developed a nonlinear FEM dynamic model for BTA deep-hole drilling, incorporating drill rod elasticity and tool–workpiece interaction. Their findings reveal guide bar wear sensitivity, chip morphology issues, and offer optimized tool geometry and feed strategies for enhanced machining quality and vibration control.

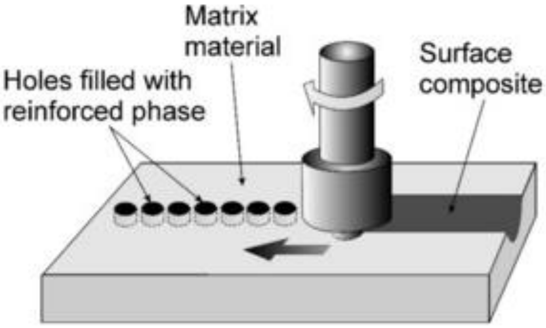

Fig.2. Reinforcement placement through the hole technique in FSP [11]

2.3 Surface Coating Approach:

FSP surface coating has grown into a vital tool for improving engineering materials' surface qualities without reducing their bulk properties. The requirement for this particular kind of approach develops from the limitations of traditional surface coating methods like thermal spraying, electroplating, and laser cladding, which frequently entail melting and are vulnerable to flaws like porosity, cracking, delamination, and undesired phase changes. On the other hand, FSP is a solid-state method that refines the surface microstructure and plastically deforms it by using the frictional heat produced between a rotating tool and the workpiece. By using this technique, reinforcement particles like

SiC, AlO_3, TiC, or graphene can be included in the surface layer, producing a uniform particle distribution and a metallurgically bonded composite coating free of defects as shown in Fig.3. Using plasma spraying or adhesive, a small coating of reinforcing material is applied to the base metal's surface. FSP ensures better retention and dispersion by stirring the coated layer into the substrate.

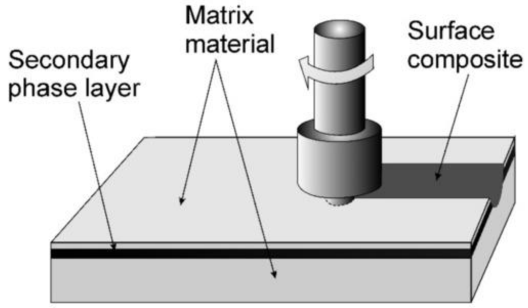

Fig.3. Surface coating method used in FSP

Bhojak et al.[17] friction stir processed the magnesium-based composites, enhancing biocompatibility and mechanical properties and offering controlled degradation, thereby minimizing the need for secondary implant removal. Naumov et al. [18] found that nanoparticle-reinforced AA 2024 processed through FSP shows significant improvement in mechanical performance and microstructure, effectively mitigating corrosion and toughness issues common in conventional aluminum alloys. Gopal et al.[19] revealed that CRT-reinforced magnesium surface composites, optimized using the Taguchi–Entropy–COPRAS method, demonstrated improved hardness and machinability with accurate control over material removal rate, surface roughness, and kerf width. Wang et al. [20] confirmed that optimizing FSP parameters substantially improves the wear resistance of 7075 aluminum alloy by refining the grain structure and inducing nano-twin formations within the weld seam. Kosaraju et al. [21] revealed that the mechanical properties of the nano-SiC reinforced AA8011 alloy were much improved by modified FSP parameters, with ANOVA identifying important affecting process variables and SEM demonstrating ductile fracture. Karmakar et al. [22] observed that hybrid FSS-FSP processing minimized heterogeneity and achieved 96.60% joint efficiency, which greatly enhanced tensile strength and interlayer integrity and made it appropriate for cyclic loading applications. Moonngam et al.[23] observed that the FSP and post-heat treatment of Al–3Zn alloy anodes improved microstructure and crystal orientation to increase corrosion resistance and attain a stable discharge potential of 1.53 V. Samal et al.[24] reinforced epoxy composites supplemented with banana pseudostem fibre and AlO_3 particles demonstrated enhanced mechanical strength and thermal stability, with the best results at 30% fibre input.

2.4 Pre-sintered Inserts or Composite Sheets

Surface composites can be uniformly and precisely reinforced by using FSP using pre-sintered inserts or composite sheets. Before processing, the substrate is embedded with these inserts, which are usually composite laminates or sintered pellets. The material is stirred by the rotating tool during FSP, which evenly integrates the reinforcement into the matrix. Better mechanical qualities and a constant reinforcement volume are guaranteed by this technique. However, it presents difficulties for tool design and process efficiency because it requires exact alignment of inserts and may result in greater tool wear because of the hardness of the pre-sintered materials.

Patel et al.[25] demonstrated that ZrO_2-reinforced AZ91D composites fabricated via multi-pass FSP exhibited superior microhardness, tensile strength, and corrosion resistance, making them promising candidates for biodegradable implant applications. Muribwathoho et al. [26] systematically optimized FSP parameters using Taguchi and ANOVA to enhance tensile strength and hardness in AA5083/SiC composites, achieving cost-effective, high-performance material fabrication. Mohankumar et al. [27] optimized FSP parameters via GA and RSM, significantly reducing wear loss to 2.953 mg, with uniform reinforcement dispersion, enhanced grain refinement, and desirability of 0.8675, confirming model robustness. Bharti et al. [28] FS Processed of AA2014/SiC composites optimized by RSM (50 mm/min, 1000 rpm, 1° tilt, 2 passes) reduced grain size (16.7 μm vs 26.9 μm), increasing microhardness by 6.25–15.36% for improved aerospace/automotive performance. Using FSP, Ardalanniya et al.[29] fabricated two-layer Al-Zn composites; GNPs changed the shape of the Alclad layer and decreased the stir zone temperature, while micro-Cu particles increased UTS by 26.3%. Prasomthong et al.[30] optimized FSP parameters and significantly enhanced the properties of AA6061-T6, resulting in high hardness and 15.80 J impact energy with a GRG of 0.905, supporting the crucial role of TiO_2 volume.

3. Challenges in Particle Incorporation

In FSP, particle reinforcement presents several difficulties that have a significant impact on the final composite's performance and quality. Particle agglomeration is a significant issue due to its high surface energy; fine nanoparticles tend to group, creating weak spots and uneven dispersion within the stirring zone. Furthermore, using hard reinforcements accelerates tool wear, particularly when employing traditional tool materials. This might cause contamination and inaccurate dimensional measurements in the processed area. Achieving a strong interfacial bond between the reinforcing particles and the matrix is another critical difficulty. Metallurgical bonding can be hindered by factors such as oxidation, insufficient heat input, or inadequate stirring, which compromise the mechanical integrity.

4. Future Trends and Research Directions

The aim of recent developments in friction stir processing (FSP) has been to enhance composite performance through innovative methods. One such advancement is the use of nano- and hybrid reinforcements, in which the combination of micro- and nanoparticles, like graphene and Al_2O_3, has a synergistic effect that significantly increases mechanical strength and wear resistance. Particles may be more evenly distributed with fewer efforts thanks to predictive modeling for optimal process parameters, made possible by the convergence of machine learning and artificial intelligence, which has also reduced the time spent experimenting. Another noteworthy advancement is the creation and use of novel tool materials and geometries. On the one hand, AI and ML have reduced the need for extensive experimentation by promoting uniform particle dispersion; on the other hand, they have enabled predictive modeling for optimal process parameters. The development and application of innovative tool materials and geometries represent yet another significant breakthrough. Tools made with sophisticated composite or ceramic-based coatings exhibit increased resistance to wear, enhancing processing consistency and durability. The investigation of environmentally friendly FSP processes, such as the use of recycled reinforcing particles and green processing materials, has also been prompted by initiatives toward sustainable manufacturing. This aligns composite development with the objectives of both economic and environmental sustainability.

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