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Review

Recent advances in friction stir processing (FSP) for microstructural refinement and surface property enhancement

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Abstract: Friction stir processing (FSP) has emerged as an advanced solid-state metalworking technique derived from the principles of friction stir welding (FSW). Originally developed for aluminum alloys, FSP enables controlled modification of the near-surface microstructure of metallic components through localized severe plastic deformation, material stirring, and frictional heating. These combined effects promote significant grain refinement, improved homogeneity, and densification within the processed zone, resulting in enhanced mechanical and surface performance. In recent years, FSP has been widely applied to produce ultrafine-grained structures, fabricate surface metal–matrix composites, and support the in situ formation of reinforcing phases, such as intermetallic compounds. Owing to its effectiveness in tailoring surface characteristics, FSP has strong potential for industrial implementation across the aerospace, automotive, marine, and biomedical sectors, particularly in applications requiring wear-resistant surfaces, lightweight structural elements, and high-performance materials. This review highlights recent progress in FSP research and provides insights into current developments and future directions of the technique.

Keywords: friction stir processing; aluminum alloys; surface modification; hardening with strengthening particles; hybrid in situ surfaces

1. Introduction

Friction stir welding (FSW) and friction stir processing (FSP) have significantly advanced materials engineering by enabling efficient solid-state joining and microstructure modification techniques [1]. Developed at The Welding Institute (TWI) in 1991, FSW has been widely implemented in aerospace, automotive, and shipbuilding industries because it can produce high-quality, defect-free joints with excellent mechanical performance [1].

FSW is considered a modern welding technique, and its working principle is commonly illustrated through a schematic representation (**Figure 1**), demonstrating its effectiveness for joining metallic components. In contrast to conventional rotary friction welding, which requires rotation of at least one of the workpieces during bonding [1–9], FSW overcomes several practical constraints associated with component geometry. Traditional rotary friction welding is typically limited to parts with regular shapes—most commonly circular cross-sections—and is generally restricted by component length. Typical examples include short tubes or round bars with similar diameters, where rotation can be readily applied without compromising alignment or process stability.

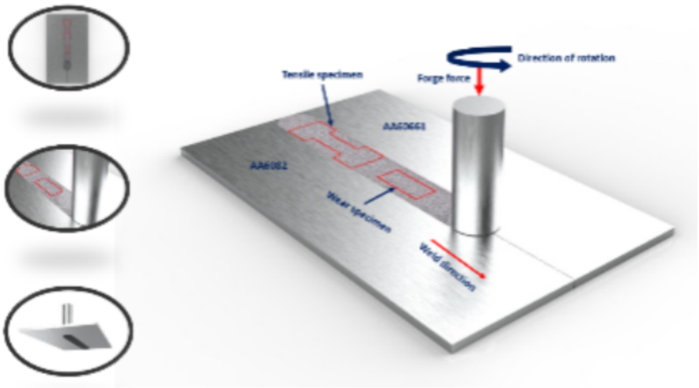

Figure 1. Schematic of the friction stir welding process.

Friction stir processing (FSP), an extension of friction stir welding (FSW), further improves material performance by enabling microstructural refinement, increasing hardness, and providing effective surface modification. This literature survey examines the growing influence of FSW and FSP in modern manufacturing and highlights their continuous development driven by ongoing technological progress [2–4]. Since its introduction, FSW has progressed into a highly efficient and versatile joining technique, particularly for aluminum alloys [4]. In contrast to conventional fusion welding, FSW is performed below the melting temperature of the base material, thereby minimizing common welding defects such as porosity, distortion, and solidification cracking.

Several notable advancements reported in recent studies [5–7] have contributed to the improved effectiveness and wider adoption of the technique, including:

- Advanced tool designs: The development of multi-shoulder and threaded-pin tools has enhanced material flow and mixing, resulting in stronger and more reliable joints.
- Automation and process control: Integration of FSW with robotic and CNC systems has improved precision, repeatability, and productivity, supporting its application in large-scale industrial manufacturing.
- Hybrid joining approaches: The combination of FSW with conventional arc-based welding methods has been shown to improve mechanical performance while increasing overall process efficiency.

The effectiveness of FSW in joining dissimilar materials, such as Al/Mg and Al/Steel, has further broadened its application scope, allowing for lightweight, high-strength components in automotive and aerospace engineering. FSP has emerged as a promising technique for localized microstructural modification. By subjecting metals to severe plastic deformation and controlled thermal exposure, FSP induces grain refinement, enhances hardness, and improves fatigue resistance. Recent developments [8,9] highlight:

- Surface composite fabrication: FSP enables in-situ synthesis of metal matrix composites by incorporating reinforcing particles such as SiC and Al_2O_3.
- Grain refinement mechanisms: The Hall-Petch relationship indicates that finer grain structures, achieved through FSP, result in superior strength and toughness.
- Application in high-performance materials: Titanium alloys and high-strength

steels have significantly improved ductility and wear resistance through FSP.

Machine learning integration in FSW and FSP: The emergence of artificial intelligence and machine learning has significantly influenced the optimization of FSW and FSP. Predictive models using deep learning can accurately forecast weld quality from input parameters, reducing trial-and-error experimentation. Key contributions [8, 10] include:

- Process parameter optimization: Artificial neural networks (ANN) and genetic algorithms (GA) enhance weld quality by identifying optimal tool rotation speeds and traverse rates.
- Defect detection and prevention: Real-time monitoring systems integrated with AI can detect anomalies and adjust parameters dynamically to prevent defects.
- Fatigue life prediction: Machine learning models have been employed to estimate the fatigue life of FSW joints, improving reliability assessments in critical applications.

Friction stir welding (FSW) is a relatively modern solid-state joining technique. As illustrated schematically in **Figure 1**, the process has proven to be highly effective for welding metallic components. In conventional rotary friction welding, at least one workpiece must rotate during joining, which imposes practical limitations on the types of components that can be processed. Specifically, this method is generally restricted to regularly shaped parts—typically those with circular cross-sections—and is often constrained by component length. Typical examples include short tubes or round bars with similar diameters, where rotation can be readily applied without compromising process stability.

2. Literature

Friction stir welding (FSW) has gained substantial recognition as a solid-state joining technique across a wide range of industrial sectors since its introduction in 1991 [11–14]. In particular, it has attracted increasing attention due to its capability to join materials that are difficult or unreliable to weld using conventional fusion-based approaches. Compared with traditional welding techniques, FSW offers several advantages, including the ability to join dissimilar or metallurgically incompatible materials and the elimination of additional joining elements such as adhesives, self-piercing rivets, or other mechanical fasteners, thereby reducing overall manufacturing cost and complexity.

Conventional fusion welding methods can negatively affect joint quality by introducing microstructural heterogeneity, residual stresses, and property degradation within the weld region during melting and solidification. In contrast, FSW operates at temperatures well below the melting points of the base materials, making it particularly effective for joining dissimilar materials while minimizing typical welding defects [15,16].

Owing to its low heat input, use of a non-consumable tool, and ability to produce joints with improved fatigue resistance and tensile strength, FSW has contributed notably to the advancement of the automotive manufacturing sector [17].

The technique supports lightweight design strategies, enhances resource efficiency, reduces environmental impact, and lowers operational costs, making it an increasingly important joining solution for sustainable and high-performance vehicle production.

Friction stir welding (FSW) is a rapidly evolving technology with strong potential for expanded implementation in the marine industry [18, 19]. Recent developments have improved weld quality and productivity, increasing its attractiveness for industrial applications. Advanced tool designs incorporating multiple shoulders and modified pin geometries have been shown to reduce welding stresses and enhance joint strength [20–23]. In addition, automated FSW systems have improved process consistency and efficiency, particularly when welding large-scale or complex structures. Hybrid approaches that integrate FSW with complementary techniques, such as arc-based welding, have also demonstrated improvements in weld integrity and process efficiency under specific operating conditions [24–27].

FSW is currently applied in a wide range of marine-related operations, including shipbuilding and offshore structural repair. The process is particularly effective for joining aluminum alloy panels used in ship hulls and deck structures, as well as for repairing damaged components. Offshore applications also include welding aluminum alloy parts in installations such as oil platforms and wind turbines. Beyond the marine sector, FSW has been widely adopted in the automotive industry due to its relatively low heat input and ability to join materials with similar or dissimilar properties. It enables reliable joining of challenging material combinations such as Al/Mg, Al/steel, and Al/Ti, highlighting its versatility and industrial relevance [28,29].

In recent years, machine learning (ML) has emerged as a valuable modeling and optimization tool across manufacturing systems [30–34], and its application has increasingly expanded into the field of FSW. ML methods have shown strong relevance in numerous engineering areas, including fracture mechanics [35–37], structural engineering [38], composite materials [39–43], laser cutting [28], and friction stir processing [44]. Because FSW involves multiple interacting parameters and diverse welding configurations, developing accurate predictive models using conventional approaches can be complex and time intensive. Machine learning techniques are therefore well suited for FSW process modeling, as they can learn nonlinear relationships between process inputs and performance outputs through data-driven training and error minimization [45].

This review summarizes recent progress in FSW for maritime applications and emphasizes its advantages over conventional joining techniques. Key areas of advancement include improvements in joint strength, corrosion resistance, fatigue performance, welding equipment design, material selection, corrosion mitigation strategies, and surface protection methods, as well as the growing integration of machine learning tools for process prediction and optimization. Finally, the study highlights the need for further research and stresses the importance of considering economic feasibility and environmental sustainability to support wider industrial adoption of FSW technology.

3. Methods

Friction stir welding (FSW) is an advanced solid-state joining technique that produces high-strength, defect-minimized joints without melting the base materials. The process employs a specially designed non-consumable tool consisting of a rotating shoulder and a protruding pin [46–48]. As the tool is plunged into the joint interface, frictional heat and severe plastic deformation soften the surrounding material below its melting temperature, creating a highly plasticized zone. This thermomechanical action promotes grain refinement and enables intimate contact between the joining surfaces.

During welding, the tool's rotation and translational motion mechanically stir and consolidate the softened material, resulting in a continuous, robust weld along the joint line [49]. FSW is particularly well-suited for aluminum alloys, as it produces joints with excellent mechanical performance while minimizing distortion and common fusion-related defects. These characteristics have contributed to its widespread adoption in industrial manufacturing and other high-performance engineering applications [49–54]. **Table 1** summarizes the key processing parameters of friction stir welding (FSW) and friction stir processing (FSP), together with their primary effects on weld quality and material performance.

Table 1. Summarizing and outlining the key parameters of friction stir welding (FSW) and friction stir processing (FSP).

Parameter	Friction stir welding (FSW)	Friction stir processing (FSP)	Effects
Tool Rotation Speed	Higher speeds improve material flow but may cause defects at excessive values.	Higher speeds enhance plastic deformation but can lead to excessive heat.	Affects grain refinement, material flow, and defect formation.
Tool Traverse Speed	Higher speeds reduce heat input but may cause defects.	Controls processing time and material refinement.	Influences weld quality, grain size, and mechanical properties.
Tool Tilt Angle	It helps consolidate the weld material; improper tilt can lead to voids.	Affects the depth of the processed layer and material mixing.	Enhances material flow and interlayer bonding.
Axial Force	Ensures proper material consolidation; too high can cause excessive flash.	Controls penetration depth and microstructural refinement.	Affects material flow, bonding, and residual stresses.
Tool Design (Pin & Shoulder)	Influences material flow and heat generation.	Determines the extent of plastic deformation and stirring.	Affects weld strength, microstructure, and defect formation.
Material Type	Aluminum alloys are widely used; more complex materials require specialized tools.	Suitable for a range of materials, including composites.	Determines tool wear, heat input, and processing feasibility.
Cooling/Lubrication	It can help control heat input and reduce residual stresses.	Used for controlling heat input and achieving finer microstructures.	Affects grain size, hardness, and residual stress levels.
Passes (Single/Multiple)	Typically, a single pass for joining.	Multiple passes may be required for more profound material modification.	Improves microstructural uniformity and mechanical properties.

The FSW tool consists primarily of two functional elements—the shoulder and the pin—each designed to meet specific welding requirements. The shoulder, which is larger and typically flat, generates most of the frictional heat and applies the downward forging force required to constrain the workpieces and maintain intimate contact during welding. In contrast, the pin is generally designed according to the thickness of the materials being joined and plays a central role in stirring and transporting the plasticized material within the joint region [55,56].

To withstand the severe thermo-mechanical conditions during processing, the shoulder is commonly manufactured from heat- and wear-resistant materials. In demanding applications, materials such as tungsten carbide are frequently employed, and some advanced tool systems incorporate cooling mechanisms to dissipate heat, thereby extending tool life and reducing friction-related degradation [57–62].

The pin is a smaller protrusion with a contoured or threaded profile that penetrates the joint interface. It is critical for controlling material flow, enhancing mixing, and ensuring the formation of sound weld characteristics [62]. The pin is typically fabricated from durable, heat-resistant materials, and its design parameters—such as geometry, rotational speed, and rotation direction—strongly influence the quality and consistency of the weld produced [63–65]. Modern tool configurations may also include retractable pins, which enable adjustment of penetration depth and improve adaptability when welding materials with varying thicknesses. Threaded pin designs are particularly effective for enhancing material transport and improving joint integrity [64].

During welding, the rotating tool generates sufficient frictional heating to soften the surrounding material and create a highly plasticized zone, in which significant grain refinement occurs. Because the process is conducted below the melting temperature, FSW avoids many defects commonly associated with fusion welding, including voids, inclusions, and solidification-related imperfections. As the tool advances along the joint line, the stirred material consolidates and re-solidifies behind it, forming a dense weld region—often referred to as the weld "nugget"—characterized by a refined microstructure and high mechanical strength [66].

The weld quality achieved in friction stir welding (FSW) is strongly governed by a set of critical process parameters that must be carefully optimized for each application. Appropriate adjustment of these variables is essential for producing defect-free joints with the required mechanical performance and structural integrity [66–69]. This ability to tailor processing conditions also makes FSW a highly adaptable technique for joining a wide range of materials and component geometries.

Tool rotational speed plays a major role in controlling heat generation, material plasticization, and flow behavior within the stirred zone. Although increasing rotational speed can enhance productivity and improve material mixing, excessively high speeds may accelerate tool wear and reduce material flow stability. Traverse speed (welding speed) also significantly influences weld formation by regulating the time available for stirring and consolidation. Lower traverse speeds generally increase heat input and promote effective material mixing, but they can extend cycle time and may lead to excessive softening. In contrast, higher traverse speeds reduce heat input and improve productivity; however, insufficient heat and stirring may result in incomplete bonding and reduced joint quality [69–73].

Tool material selection is another crucial factor, as FSW tools must withstand severe mechanical loading and elevated temperatures while maintaining resistance to wear and deformation. Common tool materials include tungsten carbide, tool steels, and cermets, which are chosen based on the hardness and thermal conductivity of the workpiece materials. Selecting an appropriate tool material is important not only to prevent tool failure but also to avoid contamination and ensure stable material flow during welding. In addition, tool design—particularly the geometry of the pin and shoulder—directly affects heat generation, material transport, and joint soundness [74–77]. Pin profiles and shoulder dimensions are typically customized according to joint configuration and material thickness. At the same time, tool tilt angle can further improve forging pressure and enhance joint consolidation in certain applications [78–81].

The applied downward (axial) force is equally important, as it governs the contact conditions between the tool and workpieces and directly affects frictional heating and consolidation pressure. This force must be controlled to maintain stable material flow and prevent defects such as tunneling or void formation. Furthermore, the weldability and thermal behavior of the base material influence the required process window, often demanding parameter modifications for thicker sections, high-strength alloys, or complex joint geometries. By systematically tuning these factors, FSW can achieve consistent, high-quality welds across diverse industrial applications.

Overall, FSW relies on a rotating pin–shoulder tool that generates frictional heat and severe plastic deformation to soften the material without melting it. This produces a plasticized region where efficient mixing and grain refinement occur, enabling the formation of sound joints with refined microstructures. The selection of tool materials, tool geometry, and operational parameters—such as rotational speed, traverse speed, and axial force—collectively determines weld quality, efficiency, and the resulting mechanical properties of the joint.

Friction stir welding (FSW) is a solid-state joining technique capable of producing pronounced microstructural and mechanical modifications within welded joints. The intense stirring action promotes grain refinement and microstructural evolution, which directly influences key mechanical properties such as hardness, tensile strength, and fracture toughness, making FSW joints suitable for demanding industrial applications [82–84]. Therefore, a detailed evaluation of the microstructural development and mechanical response of FSW joints is essential for understanding weld performance and reliability. Texture formation within the stirred region is primarily associated with the combined effects of severe plastic deformation and elevated temperatures during processing [85–87]. In addition, precipitate fragmentation, dissolution, and subsequent coarsening are commonly observed within and adjacent to the stirred zone, further contributing to property variations across the weld [88–90]. Owing to the strong correlation between local microstructural changes and post-weld mechanical behavior, numerous studies have investigated the evolution of microstructure during FSW [89–94].

The severe deformation and frictional heat generated during FSW result in a refined microstructure in the stirred region, with the most prominent transformation occurring in the weld nugget zone (WNZ). At the interface between the dynamically recrystallized nugget and the base material, a more gradual transition is typically observed on the advancing side, whereas a sharper boundary is often present on the retreating side [95]. The nugget morphology generally appears in two common forms: (i) a basin-shaped structure that widens toward the upper surface and (ii) an elliptical or oval-shaped nugget. The final nugget geometry is governed by several interacting factors, including welding parameters, tool design, workpiece temperature, and the thermal conductivity of the weld material.

Dynamic recrystallization during FSW is widely recognized as the primary mechanism responsible for producing fine, equiaxed grains in the weld nugget [96–98]. The resulting recrystallized grain size is strongly dependent on process conditions, including tool rotation and traverse speeds, tool geometry, alloy composition, axial load, local thermal history, and cooling rate within the stirred zone. In many cases, grains in the upper region of the nugget are relatively larger due to increased heat input, while grain size decreases with increasing distance from the weld centerline as the thermal and deformation intensity diminish.

Several investigations have reported that hardness evolution following FSW differs significantly between precipitation-hardened and solid-solution-hardened aluminum alloys. In precipitation-strengthened systems, a distinct thermomechanically affected zone (TMAZ) typically forms around the weld centerline [99–104]. The observed reduction in hardness in these alloys is mainly attributed to the dissolution, fragmentation, and coarsening of strengthening precipitates under the thermal cycle imposed during FSW [105–111].

Sato et al. [102] and Wang and Shivkumar [112], for example, studied hardness profiles in FSW 6063Al-T5 and concluded that precipitate distribution had a more dominant influence on hardness than grain size. Similarly, Svensson et al. [103] and Zhang and Zheng [113] examined the microstructure and mechanical behavior of FSW 5083Al-O and reported that the nugget zone exhibited fine equiaxed grains, accompanied by a reduced fraction of large particles and an increased presence of smaller particles.

Beyond welding, friction stir processing (FSP) introduces severe plastic deformation and material mixing within the processed region, enabling microstructure tailoring and surface composite formation. The effective strain during FSP has been estimated to reach high levels, allowing the incorporation of reinforcement particles into metallic substrates and the production of surface metal–matrix composites [114]. Chang et al. [115] reported early results on fabricating SiC particle–reinforced aluminum surface composites using FSP. In their approach, SiC powder was dispersed in a small amount of methanol to improve handling, then deposited onto the plate surface as a thin, relatively uniform layer. Subsequent friction stir processing facilitated particle incorporation into the substrate. Using optimized tool designs and processing parameters, a composite layer approximately 100 μm thick was successfully produced on 6061 aluminum alloy, exhibiting uniform particle distribution and strong bonding with the substrate [116, 117]. Further studies demonstrated that by adjusting FSP conditions, the SiC content could be increased from approximately 5 to 27 vol.% within the aluminum matrix. As expected, the addition of SiC significantly enhanced the hardness of the processed surface layer, with hardness increasing with increasing reinforcement volume fraction, particularly in SiCp/5083Al surface composites [116].

4. Result and discussion

Applying FSP produces considerable frictional heating and severe plastic deformation, leading to recrystallization in the dynamic agitated zone. In this instance, equiaxed, fine-grained, uniform-size grain recrystallization was generated in the Vasava et al. [108] present a representative microstructure of FSP 7075Al-T651. A refined microstructure of approximately 7.5 μm was generated at a tool rotation speed of 400 rpm and a traverse velocity of 102 mm/min. Despite ongoing disputes over the grain-refining mechanism in the SZ, it is widely accepted that grain refinement results from dynamic recrystallization [118–121]. Consequently, the nucleation and dynamic recrystallization development parameters will dictate the SZ's final grain microstructure. The size of the recrystallized grains in the SZ is greatly influenced by the FSP parameters, tool geometry, material chemistry, workpiece temperature, vertical pressure, and active cooling. Data is current as of October 2023. Ma and Mishra present transmission electron microscopy (TEM) micrographs of FSP Al-4Mg-1Zr samples processed under various FSP conditions. FSP parameters and tool geometries can be changed to alter the grain size of FSP samples, resulting in an ultra-fine-grained microstructure of 0.4 to 0.7 μm [122].

The friction stir process (FSP), including friction stir welding (FSW), is a solid-state joining technique extensively used for metals and alloys, particularly aluminum, magnesium, and other nonferrous materials. Its ability to produce defect-free welds and modify microstructures without melting the base material has garnered significant attention in the aerospace, automotive, and shipbuilding industries. This document explores how mechanical properties and microstructure influence the friction stir process. Mechanical properties such as the base material's strength, hardness, ductility, and toughness directly affect FSP. These properties determine the material's behavior under the intense thermal and mechanical loads induced during the process. High-strength materials, such as specific grades of aluminum or titanium alloys, pose challenges for FSP due to their resistance to deformation. The tool must withstand high forces and temperatures to effectively plasticize the material. Conversely, softer materials like magnesium alloys require lower forces but are more susceptible to surface defects, such as flash or voids, due to their low hardness.

Ductility plays a crucial role in determining the material flow during FSP. Materials with high ductility exhibit smooth material flow around the tool, resulting in uniform welds with fewer defects. Conversely, low-ductility materials may fracture or form voids under the same conditions. The thermal conductivity of the base material impacts heat dissipation during FSP. High-thermal-conductivity materials, such as aluminum alloys, dissipate heat rapidly, requiring higher rotational and traverse speeds to maintain sufficient plasticization. Thermal expansion affects residual stresses and distortions in the weld zone. The friction stir process profoundly alters the microstructure of the base material due to the combined effects of plastic deformation, dynamic recrystallization, and heat generation. These changes typically result in a fine-grained microstructure in the stirred zone (SZ), which enhances mechanical properties.

Dynamic recrystallization is the primary mechanism responsible for grain refinement during FSP. The intense plastic deformation and high strain rates cause the original coarse grains to break into smaller, equiaxed grains. Due to the Hall-Petch effect, fine grains in the SZ contribute to improved strength and toughness. FSP can significantly alter the material's crystallographic texture. Severe plastic deformation aligns grains along specific orientations depending on the tool rotation and traverse direction. This texture evolution can affect anisotropic properties, such as directional strength and corrosion resistance.

Depending on temperature and cooling rate, FSP can induce phase transformations in alloys. For example, precipitates such as Mg_2Si or Al_2Cu in aluminum alloys can dissolve and reprecipitate during FSP, altering the mechanical properties. Similarly, changes in α and β phases can occur in titanium alloys, affecting the weld zone's strength and toughness. The mechanical properties of the friction-stir weld differ significantly from those of the base material due to microstructural modifications. The weld zone can be divided into the stirred zone (SZ), the thermomechanically affected zone (TMAZ), and the heat-affected zone (HAZ), each with distinct characteristics. The SZ, known as the nugget zone, experiences intense plastic deformation and dynamic recrystallization. This results in a fine-grained microstructure with improved mechanical properties, including tensile strength, hardness, and fatigue resistance. However, the SZ's properties depend on the material and process parameters, including tool geometry, rotational speed, and traverse speed.

The TMAZ lies adjacent to the SZ and experiences both thermal and mechanical effects, though to a lesser degree. The grains in this zone are plastically deformed but not fully recrystallized. The mechanical properties of the TMAZ are typically lower than those of the SZ and base material due to the presence of elongated grains and potential residual stresses. The HAZ undergoes thermal exposure without significant plastic deformation. This zone often exhibits reduced mechanical properties due to precipitate coarsening or over-aging in precipitation-strengthened alloys. Proper control of process parameters can minimize the adverse effects of the HAZ. Defects such as voids, tunnel defects, and surface flash can compromise the mechanical properties of the weld. These defects typically arise due to improper process parameters or tool design. Tunnel defects are elongated voids that form due to insufficient material flow. They can act as stress concentrators, reducing tensile strength and fatigue resistance. Excessive heat or material flow can cause surface flash, leading to material wastage and aesthetic concerns. This defect does not significantly affect mechanical properties but does affect weld quality and post-processing requirements. Root defects occur due to inadequate penetration or improper tool tilt. These defects can compromise weld integrity, particularly under dynamic loading conditions.

The mechanical properties and microstructure of the weld are heavily influenced by tool design and process parameters. Tool geometry, rotational speed, traverse speed, and tilt angle all play a vital role in determining weld quality. The tool's shoulder and pin profile affect material flow and heat generation. Tools with complex pin profiles, such as threaded or tapered pins, enhance material mixing and reduce defects. The shoulder design controls heat input and surface finish. Optimal rotational and traverse speeds ensure adequate heat generation and material plasticization. High rotational speeds generate more heat, promoting dynamic recrystallization, while low traverse speeds allow sufficient time for material flow. A slight tilt of the tool enhances material consolidation and reduces the formation of voids. However, excessive tilt can lead to improper penetration and defects.

The ability of friction stir processing (FSP) to precisely tailor microstructures and mechanical performance has significantly expanded its range of applications. Ongoing progress in tool design, parameter optimization, and real-time monitoring technologies is enabling FSP to meet increasingly complex and demanding industrial requirements. In particular, FSP has attracted attention in the aerospace and automotive sectors for improving the performance of lightweight alloys, such as aluminum and magnesium. The resulting refined microstructures and enhanced mechanical properties contribute to improved structural efficiency, reduced weight, and better fuel economy. In addition, FSP is widely used for surface modification, enabling controlled processing conditions to produce engineered surface layers with superior wear resistance, corrosion resistance, and fatigue performance.

Despite these advantages, several technical challenges still limit large-scale adoption. These include difficulties in processing high-melting-point and high-strength materials (e.g., steels and titanium alloys), controlling defect formation, and achieving consistent scalability for industrial production. Recent innovations in tool materials and protective coatings, hybrid FSP techniques, and computational modeling approaches are actively addressing these issues, thereby supporting broader implementation of FSP across engineering applications.

During FSP, a fine and homogeneous densified microstructure is typically produced due to the intense shearing, fragmentation, and stirring action generated by the rotating threaded pin [123–125]. This capability enables FSP to serve as an effective microstructure-modification tool for heterogeneous metallic systems, including aluminum-based composites and nanophase aluminum alloys fabricated via powder metallurgy (PM) routes [19,126]. Under severe plastic deformation, extremely high strain rates (on the order of 10^2–10^3 s^{-1}) and cumulative strains approaching 40 have been reported, promoting accelerated diffusion, enhanced material mixing, and effective breakdown of coarse secondary phases [127–129]. Sharma et al. [130] noted that the material flow around the pin during friction stir processing exhibits similarities to conventional metal milling, highlighting the strong mechanical stirring nature of the process.

FSP's ability to induce intense plastic deformation also makes it promising for in-situ material synthesis. Mechanical alloying has long been used to fabricate nanostructured materials by repeatedly welding, fracturing, and re-welding powders [131]. Similarly, the severe deformation and thermal exposure generated during FSP can promote diffusion-driven reactions between constituent elements, creating favorable conditions for in-situ formation of composite reinforcements and intermetallic compounds.

Although many studies have examined FSW and FSP as independent processes, each technique presents limitations when applied alone. Recent research has therefore explored integrated hybrid approaches that combine friction stir welding and processing concepts to achieve more reliable optimization outcomes and to resolve conflicting design objectives [132–167]. Such hybrid frameworks can serve as scalable decision-support tools for optimizing friction-stir processes while reducing reliance on extensive experimental trials. By advancing both FSW and FSP methodologies, these approaches provide practical guidance for producing high-quality welded joints and consistently modified microstructures, offering a valuable benchmark for future research and industrial applications [168–177].

Overall, FSP produces a thin, homogeneous, and pore-free wrought-like structure by breaking down coarse dendrites and second-phase particles, refining matrix grains, closing porosity, and dissolving or redistributing precipitates under the combined effects of frictional heating and severe plastic deformation [1, 178–205]. This makes FSP an energy-efficient, environmentally sustainable, and highly versatile solid-state technique capable of generating fine-grained structures, developing surface composites, modifying heterogeneous materials, and enabling in-situ synthesis of composites or intermetallic phases. With continued research and improved understanding of processes, FSP is expected to evolve into a general-purpose metalworking technique for localized microstructure control and near-surface property enhancement. Although challenges remain, the method offers substantial commercial and technological potential across advanced engineering industries.

Finally, while friction stir welding (FSW) and friction stir processing (FSP) are based on the same thermomechanical principles—namely plastic deformation and frictional heating induced by a rotating tool—their purposes differ fundamentally. FSW is primarily applied for solid-state joining of two or more components, with joint strength, fatigue resistance, and defect minimization being the main performance targets. In contrast, FSP is applied to a single workpiece to locally refine microstructure and enhance properties, improving surface or bulk characteristics such as hardness, wear resistance, corrosion resistance, and fatigue performance without creating a joint.

In contrast, friction stir processing (FSP) is primarily used to refine microstructure and enhance surface or near-surface properties within a single workpiece. Rather than producing a joint, FSP modifies the processed region through intense plastic deformation and controlled thermal exposure, typically resulting in a homogeneous, fine-grained microstructure with improved mechanical and surface performance. The tooling and processing conditions in FSP are selected to maximize material mixing and flow within the processed zone while avoiding overheating and ensuring uniformity across the treated area.

Tool design plays a critical role in both techniques, but the design objectives differ. In FSW, tool geometry—particularly the shoulder features and pin profile—is optimized to promote balanced stirring between the two workpieces, ensuring defect-free bonding and high joint strength. In FSP, tool design and parameters are tailored to achieve the desired level of microstructural modification and property improvement, such as grain refinement or the distribution of reinforcement particles in surface composites.

From a functional perspective, FSW is used to join two or more components, and performance evaluation is centered on joint strength, fatigue resistance, and reliability. Conversely, FSP is used to enhance the mechanical properties of a localized region, improving hardness, ductility, wear resistance, and corrosion resistance without forming a joint. Overall, although both processes operate based on similar thermo-mechanical principles, FSW is primarily a joining technique, whereas FSP is a microstructure-engineering method aimed at improving the performance of existing materials.

5. Conclusion

Intense plastic deformation and frictional heating during friction stir processing (FSP) produce pronounced microstructural transformations in metallic materials. The process effectively fragments coarse dendritic structures and second-phase particles, refines the matrix grains, eliminates porosity, and promotes the dissolution and redistribution of precipitates. As a result, the processed zone typically exhibits a fine-grained, homogeneous, and pore-free wrought-like structure with improved integrity and performance. The successful use of FSP in producing ultrafine-grained microstructures, fabricating surface composites, modifying heterogeneous materials, and enabling in-situ formation of composites or intermetallic phases demonstrates its energy efficiency, environmental friendliness, and broad applicability.

Despite these advantages, several barriers must be addressed to support large-scale industrial implementation. Key challenges include severe tool wear when processing high-strength or hard-to-deform alloys, limited scalability for large components, and difficulties in maintaining stable material flow and uniform processing quality in complex geometries. Future research should prioritize the development of advanced tool materials and protective coatings to extend tool life, alongside systematic optimization of processing parameters to reduce defects and improve repeatability. In parallel, implementing real-time monitoring and feedback control systems will be essential for achieving reliable quality assurance. Moreover, coupling computational modeling with experimental investigations can provide deeper insight into thermo-mechanical behavior during FSP, enabling improved prediction and control of microstructural evolution.

With continued progress, FSP is expected to mature into a robust and standardized metalworking technology capable of precise near-surface microstructure tailoring. Emerging hybrid approaches—such as integrating FSP with additive manufacturing routes or laser-assisted processing—may further extend its functionality and application range. Through sustained innovation and process optimization, FSP has the potential to significantly influence the future of metallic material fabrication, processing, and performance enhancement across aerospace, automotive, biomedical, and other advanced engineering sectors.

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