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Friction Stir Processing: A Novel Approach for Strengthening and Surface Engineering

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A B S T R A C T

Friction stir processing (FSP) is an advanced metalworking technique derived from friction stir welding (FSW) that enables precise microstructural modification of metallic surfaces. Initially developed for aluminium alloys, FSP utilizes intense plastic deformation, material mixing, and localized heating to enhance mechanical properties, improve uniformity, and increase density in treated regions. This technique has proven effective in refining grain structures, enhancing surface characteristics, and facilitating the in-situ synthesis of composites and intermetallic compounds. This review explores the latest advancements, key insights, and emerging applications of FSP in modern material engineering.

1. Introduction

FSW is an innovative solid-state joining method developed by The Welding Institute (TWI) in Cambridge, UK, in 1991[1]. The fundamental principle behind FSW is relatively straightforward. A non-consumable rotating tool, including a uniquely made shoulder and pin, is positioned into the edges of the plates that must be joined. The tool moves along the joint line as the shoulder contacts the plates. This movement generates heat through friction between the workpieces and the tool and plastic deformation into the material. As a result of the localized heating, the material surrounding the pin enables the mix of the tool's rotation and its movement to shift the substance that runs from the pin's front to its back. Consequently, a solid-state welded joint is formed. The fundamental principle behind FSW is relatively straightforward. A specially designed, non-consumable rotating tool with a pin and shoulder is inserted into the edges of the plates to be joined [2], [3], [4]. The shoulder contacts the plates as the tool moves along the joint line. This action generates heat through friction and the deformation of plastic material, allowing the workpieces to soften around the pin [5], [6], [7]. The combination of the tool's rotation and its movement causes the material to shift from the front to the back of the pin, resulting in a welded joint in a solid state [5].

Additionally, FSP is gaining traction as an effective solid-state technique for targeted alteration and regulation of microstructures in metallic component surface layers [8], [9]. Since its inception, the range of applications for the use of FSP in the synthesis, processing, and manufacturing of metallic materials has been growing quickly. This research reviews the present comprehension and advancement of FSP, highlighting its increasing significance in the field [8], [10].

2. Literature Review

FSW has achieved considerable acclaim as a joining of a solid-state technique across multiple sectors since its introduction in 1991 [11], [12], [13], [14]. Fusion welding (FW) technology is garnering interest because of its capacity to unite materials that are challenging to bond with conventional procedures. FSW provides numerous benefits compared to traditional welding methods, including the efficient joining of incompatible materials and reduced expenses associated with adhesives, self-piercing of rivets, or alternative fasteners. Conventional welding methods may adversely impact joint characteristics due to variations in all properties. The FSW styles are especially effective for joining dissimilar materials because they operate at a considerably lower temperature than the melting point of the base material [15], [16]. This approach, which has several advantages such as lower prices, improved fatigue and strength of tensile, a tool non-consumable, little environmental effect, and heightened sustainability, has significantly advanced the automobile manufacturing sector [17]. This method has become critically important in automotive manufacturing because of its advantages, including enhanced fatigue and tensile strength, resource efficiency, environmental sustainability, and reduced operational expenses.

FSW is a quickly advancing technology with significant potential in the marine industry [18], [19]. Recent innovations have improved the quality of the weld and overall productivity, making it increasingly attractive for industry applications. Cutting-edge tool designs featuring multiple shoulder pins reduce welding stress and boost joint strength. [20], [21], [22], [23] Automated FSW systems further enhance the uniformity and efficiency of welding complex and large structures. Integrated FSW techniques, which mix FSW with other methods such as arc, have been shown to improve both the quality of weld and efficiency of the process in specific scenarios [24], [25], [26], [27].

FSW is widely utilized across different industrial applications, including the repair of ships and structures offshore. It is particularly effective for joining aluminium alloy panels and panels of the deck and repairing damaged components. Offshore applications include welding aluminium alloy parts in structures like oil platforms and turbines of wind. Beyond the marine sector, FSW is extensively applied in the automotive industry, particularly for materials with similar or differing properties due to its lower thermal input. It enables the seamless joining of different materials, like Al/Mg, Al/steel, and Al/Ti, demonstrating its versatility across various applications [28], [29].

Machine learning (ML) methods have garnered much focus as effective models for many manufacturing systems in recent years [30], [31], [32], [33], [34]. Applications for machine learning have also been observed in the field of FSW. Machine learning methodologies have exhibited notable applicability across diverse engineering domains, such as fracture mechanics [35], [36], [37], structural engineering [38], composite materials [39], [40], [41], [42], [43], laser cutting [28], and friction stir processing [44], among others. Various FSW methods possess distinct welding settings and conditions, rendering the modelling process complex and time-consuming. Learning Machine techniques are recommended for modelling FSW because they can be used to comprehend the correlation between model control factors and process responses via error-based learning during training [45]. This review highlights the developments in FSW for maritime applications, showcasing its benefits over traditional techniques. Key areas of improvement include strength of joint, resistance of corrosion, fatigue performance, welding equipment, selection of material, prevention of corrosion, and surface protection, alongside the integration of machine learning approaches. The study advocates more investigation and highlights the importance of addressing economic and environmental aspects in the broader adoption of FSW technology.

3. Methods

FSW is a cutting-edge solid-state welding method that joins metals to form sturdy, superior connectors without melting them. It uses a specific tool that has a revolving pin and a shoulder [46], [47], [48]. As the tool enters the joint., the frictional heat softens the material without liquefying it, forming a malleable plasticized region, allowing grain refinement and material fusion. The rotating motion of the tool mixes the softened material, resulting in a seamless and robust weld along the joint line [49]. This method is particularly effective for joining aluminium, offering the strength of superior and minimal distortion, making it highly valuable in industries such as industrial manufacturing [49], [50], [51], [52], [53], [54].

The shoulder and the pin, the two primary parts of the FSW tool, are each made for a particular welding application. The larger, flat shoulder applies a downward force to secure the materials, while the pin is tailored for welding materials thinner [55]. Typically, heat-resistant and resistant wear materials make up the shoulder. Materials like carbide of tungsten and many FSW tools include cooling systems to dissipate heat, extending tool life and reducing friction [57], [59], [60], [61], [62]. The pin, a small, contoured, or threaded part, penetrates the joint and is critical in regulating material flow and guaranteeing the appropriate joint characteristics [62]. Constructed from durable, heat-resistant materials, the pin's design, including its profile, rotational speed, and direction, is crucial for achieving optimal weld quality [63], [64], [65]. Advanced FSW tools may feature retractable pins to adjust penetration depth, which benefits materials of varying thicknesses. Threaded pins [64] are often utilized to improve material combination and joint quality. The tool's rotation generates sufficient heat to soften the surrounding material, creating a plasticized zone where grain structures are refined. This eliminates common defects like voids and inclusions found in traditional fusion welding. As the tool progresses, the material solidifies behind it, forming a strong weld with a refined " nugget of weld " that achieves maximum strength [66].

The quality of welds in the Friction Stir Welding (FSW) process is determined by critical parameters that must be optimized for specific applications. Proper adjustment of these factors is essential to produce superior welds without flaws and with the required mechanical qualities [66], [67], [68], [69]. Flexibility in modifying these parameters makes FSW a flexible technique for combining a variety of materials and components.

The speed of rotational FSW tools affects the generation of heat, material plasticity, and flow dynamics. While higher speeds can improve welding efficiency, they may also accelerate the tool's wear and reduce control over material flow. Traverse speed ensures thorough mixing and material flow, but it increases heat input and extends the welding cycle. Conversely, speeds of traverse faster reduction heat input, however, may compromise the quality of joint [69], [70], [71], [72], [73].

The choice of tool material is critical to the welding process. FSW tools must be made from materials with higher resistance to wear and withstand the mechanical and thermal stresses of welding. Common materials include tungsten carbide, tool steel, and cermet. The right tool material is crucial to avoid contamination and ensure efficient material flow. Additionally, the tool's design, particularly the pin and shoulder geometry, has a significant impact on material flow, heat generation, and joint integrity [74], [75], [76], [77]. The profile of the pin and dimensions of the shoulder are customized for specific applications, while tilt angles can improve performance for certain materials and configurations of joints [78], [79], [80], [81].

The downward force applied by the FSW machine is another vital factor, as it governs the interaction and friction between the workpieces and the instrument. This force must be closely monitored to maintain proper material flow and ensure joint integrity. The type of material being welded also affects the FSW process, requiring adjustments to tool parameters for thicker materials or complex geometries. The FSW process can achieve optimal results across diverse applications by fine-tuning these variables. FSW employs a specialized tool with a rotating pin and shoulder that generates frictional heat, softening the materials without melting them. This process creates a plasticized zone that facilitates material mixing and grain refinement, producing high-quality welds. The tools, including pin and shoulder geometry, materials, and cooling systems—are tailored to specific welding applications, influencing weld quality and efficiency. Key parameters like speed of rotation, traverse speed, and tool material are optimized to achieve defect-free joints with desirable mechanical properties.

FSW is a solid-state welding technique that can induce microstructural and mechanical alterations in FSW joints. The agitation process enhances grain refinement, leading to microstructural alterations that influence the mechanical properties of the weld [82], [83], [84]. The mechanical qualities, including hardness, strength of tensile, and toughness, are influenced, rendering FSW joints appropriate for industrial applications. Consequently, examining the mechanical and microstructural characteristics of joint FSW is essential. The texture formation in the zone stirred through FSW is attributed to the combined impacts of significant deformation of plastic and elevated temperature exposure [85], [86], [87]. Likewise, the disintegration of precipitates and their ensuing coarsening are noted within and adjacent to the agitated region [88], [89], [90]. The variations in microstructure across different regions significantly influence the mechanical properties observed post-welding. As a result, many researchers have examined microstructural change that transpires during FSW [89], [91], [92], [93], [94].

Because of the intense plastic deformation and frictional heat production, FSW creates a refined microstructure in the stirred zone. The most significant area affected is the zone of nugget, commonly called the weld nugget. At the interface between the recrystallized nugget zone and the base material, there is a gradual transition on the advancing side of the tool and a more distinct boundary on the retreating side [95]. The nugget zone can be categorized into two shapes: a basin-shaped nugget broadening toward the upper surface and an elliptical nugget with an oval configuration. The shape of the nugget zone is influenced by several factors, including the welding process parameters, tool geometry, the temperature of the workpiece, and the thermal conductivity of the material being welded.

Recrystallization of dynamics through FSW is recognized to result in the development of equiaxed, fine granules in the zone of nugget [96], [97], [98]. The dimensions of returned to crystal form grains in FSW materials are substantially affected by multiple factors, encompassing parameters of FSW, the geometry of the tool, the composition of the workpiece, temperature of the workpiece, vertical pressure, and cooling of active. The grain size within the zone of weld increases in the upper region, whereas it diminishes as one proceeds away from the zones of weld centerline.

A few studies have shown that the variations in hardness resulting from FSW differ amidst precipitation-hardened aluminium alloys and those hardened by solid solution. In precipitation-hardened aluminium alloys, FSW creates a thermomechanical affected zone (TMAZ) encompassing the centre of the weld [99], [100], [101], [102], [103], [104]. Previous studies indicate that the noted diminish in hardness is primarily due to the breakdown and dissolution of fortifying precipitates during the cycle of the thermal FSW process [105], [106], [107], [108], [109], [110], [111].

Sato et al. [112] investigated the hardness profiles of the microstructure in FSW 6063Al-T5. They found that the distribution of precipitates had a more significant impact on the hardness profile than grain size. Similarly, Svensson et al. [113] studied the microstructure and properties of FSW 5083Al-O. They observed that the zone of nugget contained fine equiaxed grains, characterized by a decreased presence of large particles and a grew concentration of small particles.

Applying the FSP method leads to significant deformation of plastic and material blending inside the treated area. It was estimated that the actual strain during FSP reached [114]. In this instance, it is feasible to integrate the metallic substrate plate with the ceramic particles—composites of the surface. Mishra et al. [115] documented the initial findings on producing a SiCp-Al surface composite by Friction Stir Processing (FSP). The powder of SiC was incorporated into a small quantity of methanol, blended, and subsequently applied to the plate surfaces to create a uniform thin layer of SiC particles. The aluminium plates with an applied SiC particle coating underwent Friction Stir Processing. Utilizing the tool design of optimized and processing conditions, a layer of a composite approximately 100 μm thick, including uniformly distributed particles and strong adhesion to the aluminium substrate, was produced on the 6061 Al aluminium alloy substrates [116], [117]. Modifying the FSP parameters could integrate 5 to 27 volume % of particles SiC into the aluminium matrix. The hardness value of the surface layer of aluminium substrates was markedly improved with the addition of SiC particles, and it grew when the FSP SiCp/5083Al surface composite's volume percentage of SiC particles rose [116].

4. Results and Discussion

Applying FSP produces considerable heating of frictional and severe deformation of plastic, leading to recrystallization in the dynamic agitated zone. In this instance, grain recrystallization that is equiaxed and fine of uniform size was generated in the SZ. Vasava A. et al. [118] 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 on the grain-refining mechanism in the SZ, it is widely accepted that grain refinement results from the recrystallization of dynamic [119], [120][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 Z and Mishra R et al. present transmission electron microscopy (TEM) micrographs of FSP Al-4Mg-1Zr samples subjected to various FSP settings. 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 aluminium, 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. Influence of Mechanical Properties on 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 behaviour under the intense thermal and mechanical loads induced during the process. High-strength materials like certain grades of aluminium or titanium alloys pose challenges in FSP due to their resistance to deformation. The tool must withstand high forces and temperatures to plasticize the material effectively. Conversely, softer materials like magnesium alloys require lower forces but are more susceptible to surface defects like flashes 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 like aluminium alloys rapidly dissipate heat, requiring higher rotational and traverse speeds to maintain sufficient plasticization. Thermal expansion affects residual stress 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 crystallographic texture of the material. The severe plastic deformation aligns the 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 the temperature and cooling rate, FSP can lead to phase transformations in alloys. For example, precipitates such as Mg_2Si or Al_2Cu in aluminium alloys can dissolve and re-precipitate 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 are significantly different from those of the base material due to microstructural modifications. The weld zone can be divided into the stirred zone (SZ), thermo-mechanically affected zone (TMAZ), and 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 such as 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 the coarsening of precipitates 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 flashes, leading to material wastage and aesthetic concerns. This defect does not significantly impact mechanical properties but affects 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 play a vital role in determining the quality of the weld. 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 void formation. However, excessive tilt can lead to improper penetration and defects.

The ability to control and tailor mechanical properties and microstructures through FSP has expanded its applications. Advances in tool design, process optimization, and real-time monitoring systems are enabling the use of FSP in more complex and demanding applications. FSP joins lightweight materials like aluminium and magnesium alloys in the aerospace and automotive industries. The enhanced mechanical properties and defect-free welds improve performance and fuel efficiency. FSP is increasingly used for surface modification to enhance wear resistance, corrosion resistance, and fatigue properties. By controlling the process parameters, surface layers with superior properties can be engineered. Challenges in FSP include processing high-melting-point materials like steel and titanium, minimizing defects, and ensuring scalability for industrial applications. Innovations in tool materials, hybrid FSP techniques, and computational modelling are addressing these challenges, paving the way for broader adoption of FSP.

A fine, homogeneous structure of density is produced during FSP by the revolving pin's severe breaking and mixing impact with a threaded design [123], [124], [125]. The microstructure of heterogeneous metallic materials, including aluminium and nanophase aluminium alloys made using the PM process, can thus be altered using FSP as a general tool [126], [127]. 100 to 103 s^{-1}strains per minute [128] and a strain of up to ~40 [129], as was previously mentioned, FSP causes thermal exposure and severe plastic deformation, which hastens the diffusion of components and significantly breaks up the coarse, secondary phase and material mixing [130]. During FSW, material flows around the pin may be comparable to conventional metal milling, according to Biallas et al. [131] Mechanical alloying has been a popular method for creating nanostructured materials. It involves repeatedly deforming powder particles (welding, fracturing, and rewelding) [132]. Therefore, using FSP to induce in-situ reactions between elements is likely thriving.

Existing studies have employed either FSW or FSP independently, but these methods have limitations when used alone. This future work study bridges these gaps by integrating FSWA and FSP into a hybrid approach, offering a more reliable and comprehensive optimization framework that effectively handles conflicting objectives [133-170]. A scalable and practical tool for decision-makers to optimize FSW processes without extensive experimental trials or traditional methods. This article advances FSW and FSP methodologies and provides valuable insights into achieving high-quality FSW joints and FSP, setting a benchmark for future research and industrial applications [171-180].

FSP produces a thin, homogeneous, and pore-free wrought structure by breaking up refining matrix grains, second-phase particles, coarse dendrites, closing porosity, and dissolving precipitates due to intense plastic deformation and heat exposure [181-205]. FSP has proven to be an energy-efficient, environmentally friendly, and versatile metalworking technique that can produce fine-grained structures and surface composites, modify the microstructure of nonhomogeneous materials, and synthesize composites and intermetallic compounds in situ. It can also be developed into a generic metalworking technique providing localized microstructure alteration and regulation of the treated metallic components' near-surface layers. As more research is conducted and the FSP process is better understood, FSP will find more and more uses in the synthesis, processing, and production of metallic materials. FSP presents tremendously alluring opportunities for commercial success, even though there are still many obstacles to overcome.

Friction Stir Welding (FSW), and Friction Stir Processing (FSP) are closely related techniques that utilize the same principles of plastic deformation and heat generation through a rotating tool. However, their purposes, applications, and specific processes differ significantly. FSW is primarily a joining technique. Used to weld two or more pieces of material together in a solid-state manner and commonly employed in joining aluminium alloys, magnesium alloys, and other metals, particularly for high-strength and defect-free joints. FSP is a surface or bulk material modification technique. It aims to refine the microstructure, eliminate defects, or enhance properties like wear resistance, hardness, and corrosion resistance. It is often used to improve material properties in localized regions rather than join components. Aerospace, automotive, and shipbuilding industries for welding panels, structural parts, and lightweight materials. Joining dissimilar materials that are challenging to weld using conventional methods. FSP, Surface modification of materials to improve fatigue resistance, thermal stability, or mechanical properties. Grain refinement for superplastic forming. Healing casting defects such as porosity.FSW requires two or more workpieces to be aligned and clamped together. The tool traverses along the joint line, stirring the material into a solid-state weld from both sides. FSP, Applied to a single workpiece. The tool moves over the targeted region, modifying the material beneath without joining separate components.

FSW Creates distinct zones: Stirred Zone (SZ), Thermo-Mechanically Affected Zone (TMAZ), and Heat-Affected Zone (HAZ). Focuses on maintaining weld integrity and avoiding defects such as voids or cracks. FSP Focuses on microstructure refinement and property enhancement in the processed area—resulting in a uniform and fine-grained microstructure in the modified zone. FSW Tool design is optimized for creating strong welds with adequate mixing of materials from both sides. Tool features like shoulder and pin profiles are crucial for defect-free welding.

FSP, Tool geometry, and parameters are tuned to maximize material flow and achieve targeted modifications. Process control is focused on avoiding overheating while achieving uniform surface properties. FSW Produces a joint between two or more materials. Mechanical properties like tensile strength and fatigue resistance of the joint are of primary importance. FSP Enhances the mechanical properties of the processed region, such as hardness, ductility, and resistance to wear or corrosion. It does not join materials but instead improves the characteristics of a single workpiece. In summary, while FSW and FSP rely on similar principles of plastic deformation and heat generation, FSW focuses on solid-state joining. FSP targets microstructural and property enhancements within a material.

5. Conclusion

Intense plastic deformation and exposure to heat during Friction Stir Processing (FSP) lead to significant changes in material structure. This process breaks down coarse dendrites and second-phase particles, refines matrix grains, closes porosity, and dissolves precipitates, resulting in a fine, uniform, and pore-free wrought structure. The wide-ranging successful applications of FSP—from producing fine-grained structures and surface composites to modifying the microstructures of heterogeneous materials and creating in-situ composites or intermetallic compounds—highlight its energy efficiency, environmental benefits, and versatility. FSP has the potential to evolve into a standard metalworking technique that enables precise modification and control of microstructures in the near-surface layers of metallic components. As research progresses and our understanding of the FSP process deepens, we can expect to uncover many applications in the fabrication, processing, and synthesis of metallic materials.

Despite some existing challenges, the potential for FSP to achieve commercial success remains highly promising.

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