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FRICTION STIR WELDING IN THE JOINING OF LIGHT METAL ALLOYS: A REVIEW

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Abstract: *Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) are solid-state joining processes in which bonding occurs below the melting temperature of base materials. These techniques are increasingly applied to non-ferrous metals such as aluminum, titanium, magnesium, and copper, as well as to dissimilar material combinations like Al-Ti and Al-Mg. Their growing use is driven by industrial demands, particularly in the aerospace and automotive sectors, where high strength and low weight are essential. This paper presents an overview of conventional and advanced FSW techniques, focusing on the mechanical and microstructural properties of the resulting joints. Experimental studies and industrial applications demonstrate that high-quality joints in aluminum and titanium alloys can be achieved through proper selection of process parameters and tool geometry. Due to the complex thermomechanical and metallurgical processes involved, careful control of welding parameters such as tool rotational speed, welding speed, and dwell time is crucial. These parameters significantly influence joint quality and the formation of intermetallic compounds, such as Ti_3Al. FSW continues to attract research interest because of its efficiency and potential in joining light metal alloys. Additionally, it is an energy-efficient and environmentally friendly process, contributing to sustainable engineering practices.*

Keywords: *Friction Stir Welding (FSW), Friction Stir Spot Welding (FSSW), aluminum, titanium.*

1. INTRODUCTION

Friction Stir Welding (FSW) is an advanced solid-state joining technology that has gained increasing importance across a wide range of industrial applications. This process enables the reliable joining of materials while providing superior joint properties in both similar and dissimilar metal combinations. FSW was invented and patented by The Welding Institute (TWI), United Kingdom, in 1991, and was initially developed as an alternative to conventional fusion welding for aluminum alloys. The technology was rapidly adopted in the aerospace industry, including NASA space programs, where weight reduction and high structural integrity are of primary importance. Over time, the application of FSW has expanded beyond aluminum alloys to include titanium, magnesium, copper, nickel, lead, zinc, and even steels, demonstrating its versatility for joining a broad range of engineering materials [1].

The development and industrial implementation of FSW have been predominantly associated with the welding of aluminum and its alloys, accounting for approximately 99% of its applications. Butt joints represent the majority of FSW joints because of their excellent mechanical properties, as demonstrated by numerous studies [2]. The weldability of aluminum alloys by conventional fusion welding processes is often limited; however, FSW has provided an effective solution for joining these alloys and related materials. Aluminum alloys, particularly those of the 2xxx, 5xxx, 6xxx, and 7xxx series, are widely used in various industrial sectors, including the automotive, aerospace, space, shipbuilding, construction, bridge engineering, and military industries. Their widespread application is primarily attributed to their low density, favorable mechanical properties, and excellent corrosion resistance [3].

The increasing demand for advanced engineering structures has created a growing need for joining both similar and dissimilar materials. In particular, combinations such as Al-Ti, Al-Mg, Cu-Al, and Al-steel have attracted considerable attention due to their potential for achieving an optimal balance between mechanical

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performance, weight reduction, and functional properties. However, joining materials with significantly different melting temperatures by conventional fusion welding processes remains a major challenge. High-strength aluminum and titanium alloys, which are widely used in aerospace applications, are particularly difficult to join using fusion welding because of the metallurgical incompatibilities and defects associated with melting-based processes.

The continued development of FSW has led to significant advances in a number of process variants, including multi-pass FSW, multi-tool FSW, tandem friction stir welding, and Friction Stir Spot Welding (FSSW). These developments have expanded the capabilities of the process and improved its applicability to a wider range of engineering materials and joint configurations. This paper provides an overview of these FSW techniques and discusses their main characteristics. Their implementation has resulted in improved joint performance and significantly broadened the range of compatible alloy systems that can be successfully joined using friction stir welding.

2. FUNDAMENTALS OF THE FSW PROCESS

Friction Stir Welding (FSW) differs from conventional friction welding in that it employs a non-consumable rotating tool to produce the joint. For this reason, FSW is often referred to as tool-assisted friction welding. Unlike conventional fusion welding processes, FSW is a solid-state joining process in which the base materials are joined without melting. During the process, the rotating tool generates frictional heat and severe plastic deformation, softening the material around the tool and enabling its plastic flow. The tool performs a combined rotational and translational motion (Fig. 1). It rotates about its own axis while simultaneously traversing along the joint line, which may be either straight or curved, depending on the joint geometry.

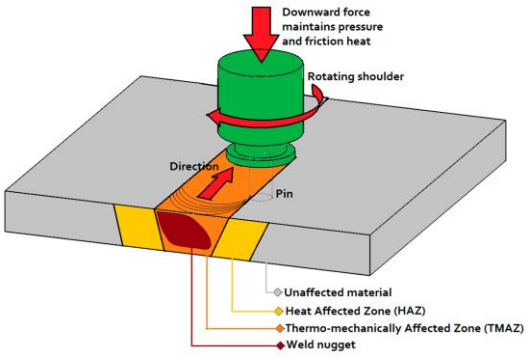


Figure 1. Schematic illustration of the Friction Stir Welding (FSW) process [4]

During the welding process, frictional heat is generated, raising the temperature of the material to approximately 0.8 of its melting temperature, which is sufficient to promote plastic deformation without melting. For most aluminum alloys, the maximum process temperature does not exceed 450 °C [5]. The FSW tool consists of two main components: a shoulder and a pin (Fig. 2). The threaded pin promotes continuous stirring and plastic flow of the softened material around the rotating tool, while the rotating tool typically operates at rotational speeds ranging from 100 to 1500 rpm.

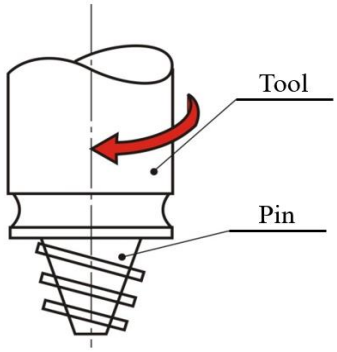


Figure 2. Schematic illustration of the FSW tool [6]

As the tool traverses along the joint line, the softened material undergoes intense plastic deformation and is transported from the leading edge to the trailing edge of the tool. Upon cooling, the plastically deformed material consolidates, forming a sound solid-state joint. At the beginning of the welding process, the tool pin penetrates the workpieces until the tool shoulder comes into contact with the upper surface of the material. After tool withdrawal, a characteristic exit hole, commonly referred to as the keyhole, remains at the end of the weld. The primary function of the shoulder is to apply forging pressure, contain the softened material within the welding zone, and generate the majority of the frictional heat. Tools with profiled shoulder surfaces, such as concentric grooves, spiral features, or scrolls, enhance heat generation and material flow. These surface features facilitate the transport of softened material around the tool, thereby improving material flow, joint formation, and the overall weld quality.

3. FSW-BASED TECHNIQUES

Over a relatively short period, the development of Friction Stir Welding (FSW) has led to the emergence of a broad family of friction stir-based technologies that continue to evolve. These developments have expanded the application of FSW not only as a joining technology but also as a material processing technique. The continuous development of new process variants has expanded the application of FSW to increasingly complex joint geometries and diverse engineering applications. In addition, advances in tool design have contributed to higher process efficiency, improved joint quality, and increased productivity.

The most widely used FSW-based technologies include:

- ✓ Friction Stir Lap Welding (FSLW);
- ✓ Friction Stir Processing (FSP);
- ✓ Friction Stir Dovetailing (FSD);
- ✓ Friction Stir Spot Welding (FSSW);
- ✓ Refill Friction Stir Spot Welding (Refill FSSW);
- ✓ Stationary Shoulder Friction Stir Welding (SSFSW);
- ✓ Underwater Friction Stir Welding (UFSW);
- ✓ Friction Stir Deposition (FSD),

as well as numerous other variants of friction stir-based processing and joining technologies.

Friction Stir Lap Welding (FSLW) is a solid-state joining process primarily used for lap joints in lightweight materials, including aluminum and magnesium alloys, as well as certain polymers [7].

Friction Stir Processing (FSP) is a versatile solid-state processing technique used to refine the microstructure and improve the mechanical properties of metallic materials. It is widely employed in the fabrication of surface composites and has also been successfully combined with ultrasonic vibration-assisted processing to enhance alloying and material modification [8].

Friction Stir Dovetailing (FSD) is a recently developed joining technique for dissimilar materials, particularly aluminum and steel. The incorporation of an aluminum alloy interlayer (AA6061) has been shown to improve the mechanical performance of the joint by increasing both load-bearing capacity and ductility, thereby effectively suppressing the formation of brittle intermetallic compounds [8].

Friction Stir Spot Welding (FSSW) (Fig. 3) is a solid-state spot joining process developed as an alternative to resistance spot welding. The technology is capable of producing high-quality spot welds through precise control of the process parameters and provides excellent mechanical performance, particularly in terms of joint strength. Consequently, FSSW has found widespread application in the automotive and aerospace industries [9].

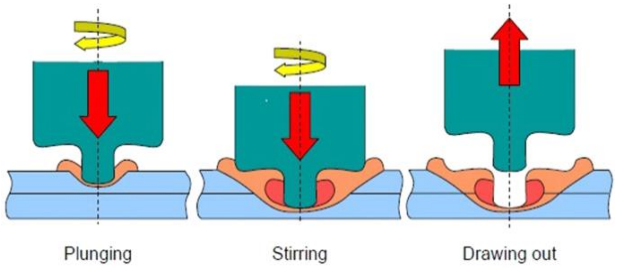


Figure 3. Schematic illustration of the Friction Stir Spot Welding (FSSW) process [10]

Stationary Shoulder Friction Stir Welding (SSFSW) has been shown to provide improved mechanical properties and a more refined microstructure compared with conventional FSW. Owing to its ability to reduce heat input while maintaining excellent joint quality, SSFSW is considered a promising technique for manufacturing lightweight structures [8].

Underwater Friction Stir Welding (UFSW) is an emerging variant of FSW in which the welding process is performed in a water environment. The presence of water creates unique thermal boundary conditions that promote rapid heat dissipation, resulting in a finer microstructure and enhanced joint strength [11]. Owing to these advantages, UFSW has recived increasing attention for joining materials that are difficult to weld using conventional fusion welding processes.

The continuous development of FSW has been driven not only by the need to improve joint quality but also by the demand for higher process efficiency, increased productivity, reduced energy consumption, and greater process flexibility. Consequently, several innovative process configurations have been developed, including multi-tool and double-sided FSW techniques.

Double-sided FSW employs two tools positioned on opposite sides of the workpiece with a slight offset in the welding direction (Fig. 4). Simultaneous counter-rotating operation offers several advantages, including reduced reaction torque and improved weld symmetry. Although the tool pins do not necessarily come into contact, they are positioned sufficiently close to promote effective material flow and mixing throughout the thickness of the joint, ensuring complete weld formation. This configuration also minimizes the asymmetry of lateral forces, resulting in improved process stability and tool balance. Double-sided FSW has been successfully applied to the welding of plates with thicknesses of up to 100 mm.

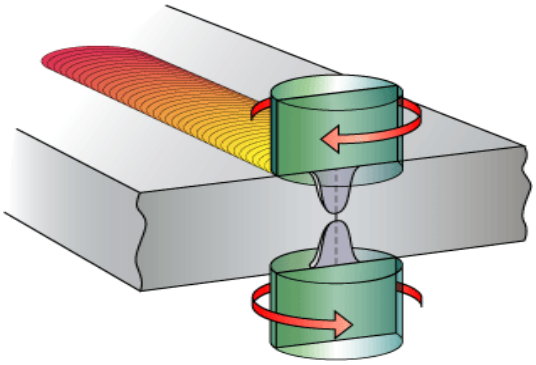


Figure 4. Schematic illustration of the double-sided FSW process [12]

Multi-tool Friction Stir Welding (FSW) enables the simultaneous joining of multiple plates, thereby increasing process productivity and efficiency (Fig. 5).

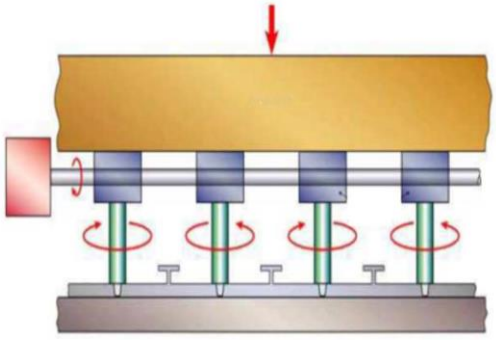


Figure 5. Schematic illustration of the multi-tool FSW process [13]

Several dual-tool FSW configurations have been developed to improve productivity, weld quality, and process efficiency. The three most common configurations are:

1. Parallel twin-tool FSW;
2. Tandem FSW;
3. Staggered twin-tool FSW.

The parallel twin-tool FSW configuration employs two tools that travel simultaneously along parallel welding

paths. This arrangement enables higher welding speeds, threby improved productivity by reducing the overall welding time. Figure 6 illustrates the schematic configuration of this process applied to a lap joint.

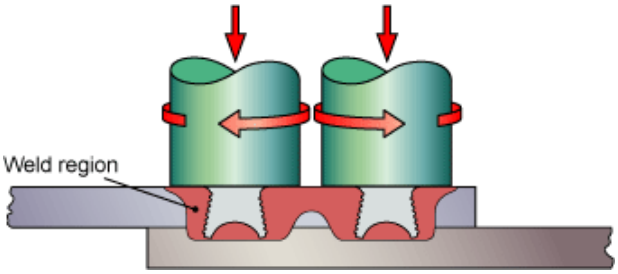


Figure 6. Schematic illustration of the parallel twin-tool FSW configuration [13]

Tandem FSW employs two or more tools positioned sequentially along the welding direction (Fig. 7). The leading tool generates the initial heat input and performs the primary plasticization and stirring of the material while overcoming most of the mechanical resistance. The trailing tool subsequently traverses the softened material, promoting additional material mixing, disrupting residual oxide layers, and refining the weld microstructure. In tandem FSW, the tools are commonly counter-rotating to reduce reaction torque and improve process stability.

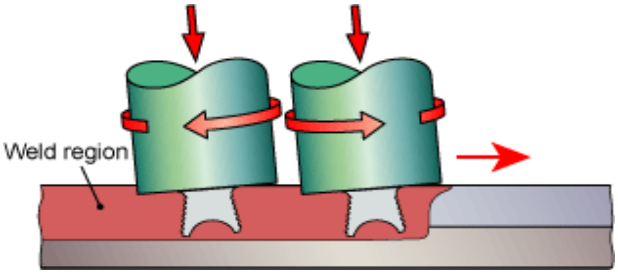


Figure 7. Schematic illustration of the tandem FSW configuration [13]

Tandem FSW has found widespread application in high-performance industries, including aerospace, automotive, and railway engineering. Typical applications include the fabrication of aircraft fuselage panels, rocket propellant tanks, battery enclosures for electric vehicles, and large extruded aluminum profiles used in high-speed railway vehicles [13]. The process is primarily employed for joining aluminum, magnesium, and copper alloys. In shipbuilding, for example, tandem FSW is used for welding thick aluminum alloy plates, particularly those of the 5xxx, 6xxx, and 7xxx series, with thicknesses exceeding 20 mm.

The staggered twin-tool FSW configuration utilizes two tools positioned sequentially with a lateral offset, allowing the second tool to partially overlap the weld produced by the first tool (Fig. 8). This arrangement creates a wider weld region, making it particularly suitable for lap joints where higher joint strength is required. Furthermore, the second tool promotes additional fragmentation and dispersion of residual oxide layers while improving material flow within the thermo-mechanically affected region. Another important advantage of this configuration is its ability to compensate for local thickness reduction that may occur during the first welding pass.

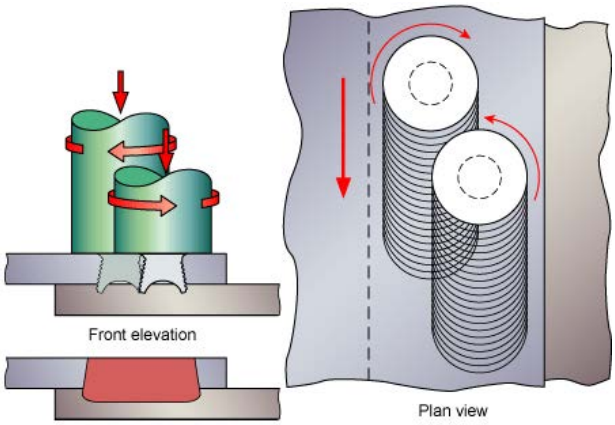


Figure 8. Schematic illustration of the staggered twin-tool FSW configuration [13]

4. WELDABLE MATERIALS

In principle, Friction Stir Welding (FSW) can be applied to joining of nearly all engineering metals, ranging from low-melting-point materials such as aluminum and magnesium to high-melting-point metals including titanium, copper, nickel, and steels. Successful welding depends primarily on the appropriate selection of process parameters and tool geometry, which largely determines the versatility and broad industrial applicability of the process.

Aluminum and its alloys are by far the most extensively welded materials using FSW. All major aluminum alloy series can be successfully joined, making aluminum the primary material group for which FSW was originally developed and remains the most widely adopted in industrial applications.

Magnesium alloys are also highly suitable for FSW. Aluminum-zinc alloys of the AZ series, particularly AZ31 and AZ91, exhibit excellent weldability and are widely used in the automotive and aerospace industries. Similarly, zinc-zirconium alloys of the ZK series produce high-quality welds. FSW has been successfully applied to magnesium components ranging from thin sheets with a thickness of approximately 1 mm to thick plates exceeding 20 mm.

FSW of titanium and its alloys offers an effective joining solution for aerospace, biomedical, and defense applications. Although FSW generally provides superior joint quality compared with conventional TIG and, in some cases, even laser welding, its widespread industrial implementation remains limited because of severe tool wear and the high cost of tool materials. FSW tools for titanium welding are typically manufactured from tungsten-based alloys, tungsten carbide, or polycrystalline cubic boron nitride (PCBN) due to the demanding processing conditions [14].

Compared with other non-ferrous metals, titanium presents unique challenges for FSW because of its high melting temperature and relatively low thermal conductivity. Consequently, lower tool rotational and

welding speeds are generally required to control heat input and minimize tool wear. In the study reported in [15], the mechanical properties and microstructure of the Ti-6Al-4V alloy were investigated using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). Microstructural analysis of specimens produced under different processing conditions revealed significant grain refinement and a homogeneous microstructure within the stir zone.

Owing to its excellent biocompatibility, titanium is one of the most important materials for biomedical implants. Consequently, various FSW-based techniques have been developed for fabrication and joining titanium components intended for medical applications.

5. MICROSTRUCTURE OF FSW JOINTS

Owing to the unique characteristics of the FSW process, which combines frictional heating with severe plastic deformation, FSW joints exhibit an asymmetric and highly heterogeneous microstructure. A typical FSW joint consists of four distinct regions: the Base Material (BM), the Heat-Affected Zone (HAZ), the Thermo-Mechanically Affected Zone (TMAZ), and the Stir Zone (SZ), also referred to as the Weld Nugget (WN) (Fig. 9).

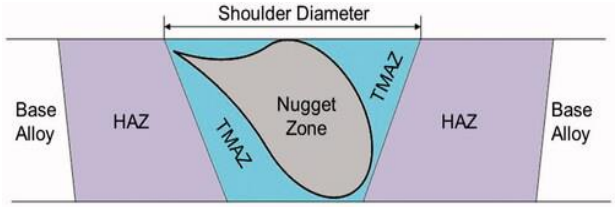


Figure 9. Schematic illustration of the microstructural regions in an FSW joint [16]

The extent of the Heat-Affected Zone (HAZ) depends primarily on the thermal cycle imposed on by the material, particularly the peak temperature and exposure time. In the Thermo-Mechanically Affected Zone (TMAZ), the material undergoes significant plastic deformation combined with elevated temperatures; however, complete recrystallization generally does not occur. The Stir Zone (SZ), located at the center of the weld, experiences the highest levels of plastic deformation and frictional heating. Consequently, extensive dynamic recrystallization occurs within this region, producing a fine equiaxed grain structure.

The boundary between the Stir Zone and the surrounding TMAZ is usually well defined in aluminum alloys because of the distinct difference in recrystallization behavior. In contrast, many other metallic materials exhibit a more gradual transition between these regions. For example, in Ti-6Al-4V and commercially pure copper, the boundaries between the HAZ, TMAZ, and SZ are often less pronounced owing to their different thermomechanical responses during welding.

The Stir Zone is characterized by a fine-grained microstructure, with grain sizes typically ranging from 2 to 10 μm, depending on the alloy system and welding conditions [17]. Figure 10 presents the microstructure of an FSW joint produced in AlMg2.5Cr0.2 aluminum alloy with a plate thickness of 2 mm, illustrating the characteristic microstructural regions.

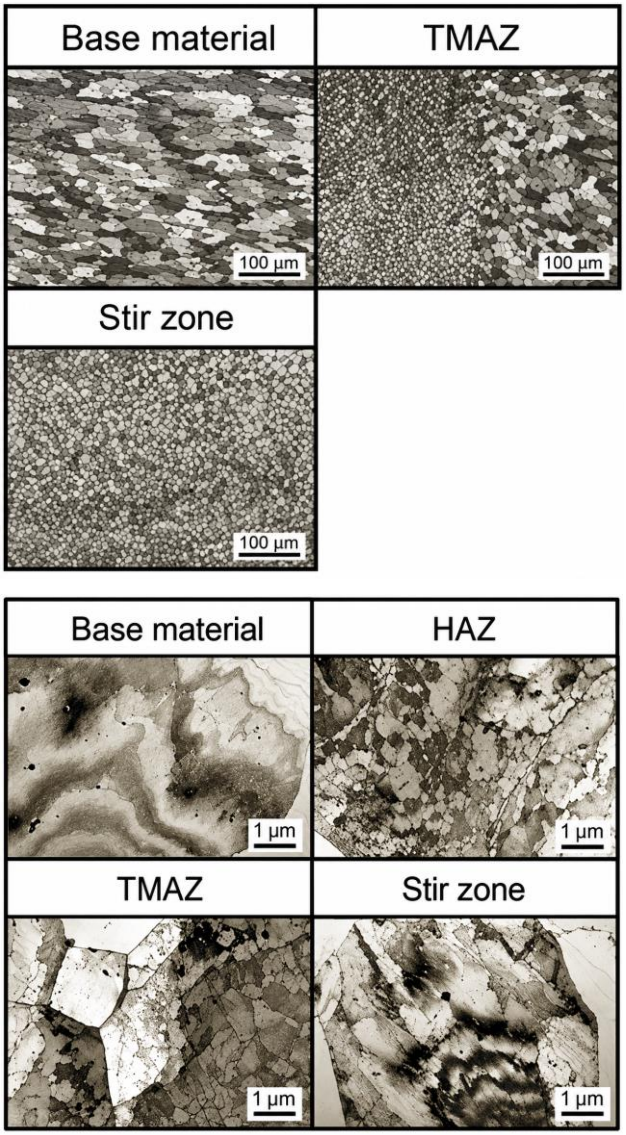


Figure 10. Microstructure of an FSW joint in AlMg2.5Cr0.2 aluminum alloy showing the characteristic microstructural regions [17]

The microstructural evolution during FSW depends strongly on the material being welded and is governed by the combined effects of severe plastic deformation and frictional heating. Dynamic recrystallization occurs within the Stir Zone, leading to the transformation of the original coarse grains into fine equiaxed grains. In aluminum alloys, this process is predominantly associated with geometric dynamic recrystallization. Outside the Stir Zone, where both the deformation and temperature are lower, the grains generally retain their elongated morphology, while dislocations rearrange to form subgrain structures.

Different strengthening mechanisms influence the microstructural evolution of aluminum alloys. In precipitation-hardened alloys, such as AA5052, AA6061, and Al-Mg-Si alloys, the thermal cycle during FSW promotes precipitate dissolution within the Stir Zone, followed by precipitate coarsening during cooling. This

phenomenon is considered one of the primary causes of the localized reduction in hardness. In magnesium alloys, which possess a hexagonal close-packed (HCP) crystal structure with a limited number of slip systems, elevated temperatures activate additional slip systems and deformation twinning. Consequently, dynamic recrystallization becomes more pronounced, often resulting in improved mechanical properties, particularly near the interface between the Stir Zone and the TMAZ [18].

During the FSW of dissimilar light-metal alloys, intense plastic deformation and material flow produce a characteristic swirl-like microstructure. The principal metallurgical challenge in such joints is interfacial diffusion, which may promote the formation of brittle intermetallic compounds. For example, Al-Mg joints typically contain a bilayer intermetallic region composed of Al_3Mg_2, formed adjacent to the aluminum side, and $Al_{12}Mg_{17}$, formed adjacent to the magnesium side. Similarly, a thin $TiAl_3$ intermetallic layer commonly develops at the interface of Al-Ti joints. Therefore, careful control of welding parameters, particularly welding speed and tool geometry, is essential for minimizing the thickness of these intermetallic layers and preserving joint integrity [18].

6. CONCLUSION

Over the past three decades, Friction Stir Welding (FSW) has evolved into one of the most advanced solid-state joining technologies owing to its ability to produce high-quality joints while offering high energy efficiency and excellent environmental sustainability. Nevertheless, further research is required to expand its application to a broader range of engineering materials, complex joint geometries, and dissimilar material combinations.

Although considerable progress has been achieved, several aspects of FSW and Friction Stir Spot Welding (FSSW) remain insufficiently understood. In particular, the joining of dissimilar materials, such as aluminum and titanium, continues to present significant scientific and technological challenges. A deeper understanding of material flow, interfacial reactions, and the formation of intermetallic compounds is essential for further improving joint quality and process reliability.

For lightweight alloys, FSW has become not only an attractive alternative to conventional fusion welding but, in many applications, the only technically feasible and economically viable joining process capable of producing high-quality solid-state joints. Future developments should therefore focus on improving tool materials and extending tool life, particularly when welding high-strength and high-melting-point alloys, where severe tool wear remains one of the primary limitations to large-scale industrial implementation.

The microstructure developed during FSW plays a decisive role in determining the final mechanical performance of the joint. Dynamic recrystallization within the Stir Zone (SZ) produces a refined equiaxed grain structure, resulting in enhanced fatigue resistance, increased hardness, and improved overall mechanical properties.

Further advances in FSW technology will rely on the integration of automation, robotics, digital manufacturing, and numerical simulation. Within the framework of smart manufacturing, virtual process simulation and digital optimization of welding parameters prior to production are becoming increasingly important for improving process efficiency, weld quality, and process repeatability. Consequently, future research should increasingly focus on the development of intelligent process monitoring and control systems to support the wider industrial adoption of FSW technologies.

Finally, one of the most significant advantages of FSW is its environmental sustainability. Since the process is performed entirely in the solid state, it does not require filler materials or shielding gases and produces no harmful fumes, spatter, or intense radiation typically associated with conventional fusion welding. These characteristics make FSW an environmentally friendly and resource-efficient manufacturing process that is widely recognized as a green technology with significant potential for future sustainable industrial applications.

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