Light metal alloys used in the aeronautical industry suitable for FSW welding/ FSP processing

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Abstract: *This study presents light metal alloys used in the aeronautical industry, specifically focusing on their suitability for Friction Stir Welding (FSW) and Friction Stir Processing (FSP). These innovative techniques play an important role in improving the mechanical properties and performance of aluminum, magnesium, and titanium alloys, which are extensively utilized in aerospace applications due to their superior strength-to-weight ratios. FSW and FSP offer significant advantages in joining and processing materials, including enhanced weld integrity, defect reduction, and refined microstructural properties. The integration of light metal alloys by these methods within the aeronautical sector fosters the production of lighter and stronger structures, contributing to reduced fuel consumption and improved overall performance in aeronautical engineering.*

Key Words: *light metal alloys, structural materials, aeronautical industry, high strength-to-weight ratio, friction stir welding, friction stir processing*

1. INTRODUCTION

The growing demand for lightweight yet high-strength materials in the aeronautical industry has led to the increased use of light metal alloys such as aluminum, magnesium and titanium alloys. These materials offer high strength-to-weight ratios, corrosion resistance and thermal stability, making them ideal for aircraft structures.

Friction Stir Welding (FSW) and Friction Stir Processing (FSP) have emerged as promising solid-state techniques for joining and modifying light metal alloys (see Figure 1).

This paper reviews the characteristics of light metal alloys, focusing on their applications in aeronautics, and explores their suitability for FSW and FSP processes. The review highlights the benefits, challenges and future potential of using FSW and FSP for enhancing the mechanical properties and weld quality of these materials.

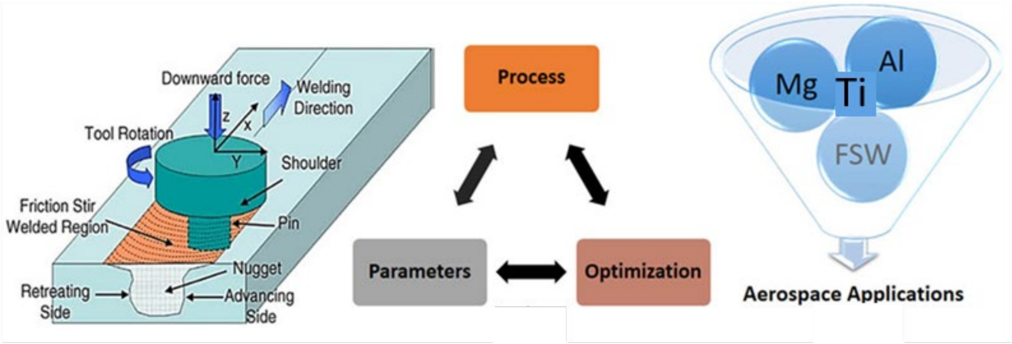

Fig. 1 The schematic representation of FSW for aerospace applications [1]

The Friction Stir Process (FSP) originated as a derivative of Friction Stir Welding (FSW), which is traditionally employed for joining plates and sheets. In contrast, FSP is performed on monolithic plates, with the primary goal of refining the microstructure of the material. A schematic illustration of the FSP on monolithic plates is presented in Fig. 2. Both FSP and FSW operate on the same fundamental principle: a specially designed tool, consisting of a pin and a shoulder, which applies thermomechanical working to the substrate material.

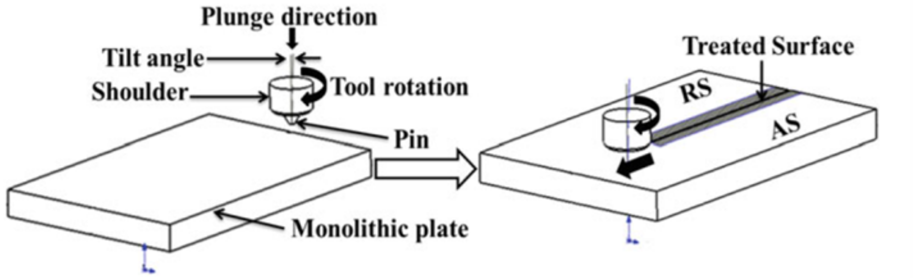

Fig. 2 Graphic representation of FSP (left: preparation for FSP, right after FSP) [15]

These methods enhance mechanical properties and enable the construction of lightweight yet durable components. Here are some key advantages:

- enhanced joint strength and fatigue resistance: FSW allows for high-quality, defect-free joints in light metal alloys, significantly improving strength and fatigue resistance over traditional fusion welding methods, which is essential for withstanding cyclic loads in aircraft structures [2];
- improved microstructure and mechanical properties: FSP refines the grain structure in alloys, leading to enhanced mechanical properties, including strength, ductility, and wear resistance. This is particularly valuable for aircraft parts that need to endure stress without compromising performance;
- high corrosion resistance: Both FSW and FSP create solid-state joints that are less prone to corrosion than those produced by fusion welding. This property is important in aerospace applications where components face harsh environmental conditions, like high humidity and saline atmospheres [3];
- weight reduction: Light metal alloys have high strength-to-weight ratios, reducing overall aircraft weight and improving fuel efficiency. FSW/FSP allows these materials to be processed with minimal added weight from weld filler materials, maximizing the weight reduction benefits of light metals;

- thermal stability: Titanium and some aluminum alloys, when processed by FSP, achieve enhanced thermal stability, which is essential for components exposed to the high temperatures of aerospace engines and other heat-sensitive areas;
- cost-effectiveness: FSW/FSP reduces production costs by eliminating filler materials and minimizing post-weld machining, while also extending the lifespan of components, leading to long-term cost savings in manufacturing and maintenance;
- These advantages make FSW and FSP invaluable in advancing the application of light metal alloys in aerospace engineering, leading to lighter, stronger and more durable aircraft [4].

The goal of ongoing research is to optimize the balance between strength and toughness in metallic glasses, expanding their utility in more extreme environments, particularly in aeronautical and military applications where failure can have severe consequences. This is important for the development of next-generation materials for aircraft components, propulsion systems, and defense equipment, where high performance and reliability are essential.

2. AEROSPACE MATERIALS

The demands of the aeronautic industry arise from intense competition to produce aircraft with enhanced technical capabilities and lower manufacturing costs, including extended service life, optimized fuel efficiency and increased payload capacity. Advanced materials are critical in meeting these requirements. Structural materials must offer reduced weight, superior fatigue and wear resistance, high damage tolerance and robust corrosion resistance. In hot engine sections, alloys with high creep resistance, superior mechanical performance at elevated temperatures, and enhanced high-temperature corrosion resistance are essential to ensure durability and reliability.

Aluminum alloys are the most widely used light metal alloys in the aerospace industry due to their low density, high strength, and excellent corrosion resistance. Key aluminum alloys used in aeronautics include AA2024, AA7075, AA6082 and AA6061, which are frequently utilized in structural components such as fuselage frames, wings, and engine parts. These alloys are typically strengthened through precipitation hardening, making them suitable for high-strength applications.

Aluminum Alloy Series 2XXX, 6XXX and 7XXX: These series are widely utilized in aerospace, particularly due to their high specific strength, stiffness, and fatigue resistance, essential for structural components like fuselage sections and wings. The application of FSP allows these alloys to achieve enhanced mechanical properties through grain refinement and improved microstructure, which are critical for fatigue-intensive components used in aircraft structures. Studies show that FSP refines the grain structure in aluminum, thus improving the alloy's damage tolerance and resistance to stress corrosion cracking, especially under extreme operational conditions in aeronautics [5].

The optimal properties of the 7XXX aluminum alloy series are achieved when the Zn/Mg and Zn/Cu ratios are approximately 3 and 4, respectively. For example, Alloy 7085, with its high yield strength, 14% elongation, and improved damage tolerance, presents a viable alternative to 7075 for aerospace applications.

Adding up to 1% zirconium (Zr) and manganese (Mn) enhances grain refinement, which in turn improves mechanical performance of the alloy [6].

An additional critical factor for aerospace applications of the 7XXX series alloys is fatigue behavior, which has been extensively studied across various parameters to optimize performance under cyclic loading conditions [7].

Magnesium (Mg) alloys: As the lightest structural engineering material, magnesium alloys hold significant potential for applications in transportation, energy, aerospace, and related sectors due to their high specific strength, specific stiffness, superior damping properties, vibration reduction, excellent liquid formability, electromagnetic shielding capability, and recyclability. However, limited high-temperature strength and poor corrosion resistance pose challenges to their broader application. Alloying is a proven approach to address these limitations. The addition of elements such as Al, Mn, Zn, Si, Ca, Li, and rare earth (RE) elements enables microstructural and structural modifications, enhancing the alloys to achieve the desired performance characteristics, making them an ideal structural material for weight reduction in aerospace applications. Alloys such as AZ91, WE41 and WE43 are commonly used in applications where weight reduction is critical, including helicopter components and aircraft interiors [9-12].

Titanium alloys: Titanium and its alloys are extensively employed across the aerospace, chemical, and biomedical sectors due to their high specific strength, corrosion resistance, and biocompatibility. In biomedical and aerospace applications, surface hardening is frequently applied to titanium alloys to enhance wear resistance, particularly in components where only the surface requires increased hardness while preserving the bulk material’s original microstructure and composition. Given that surface hardness is critical for improving wear resistance, this selective surface modification is commonly employed to fortify the softer surface layers of commercially pure titanium. Notably Ti-6Al-4V, are prized for their exceptional strength, corrosion resistance, and ability to withstand high temperatures, making them vital in jet engines and important structural components. However, titanium’s high reactivity at elevated temperatures complicates traditional fusion welding processes.

The Ti-6Al-4V alloy is highly valued in aerospace, energy, and automotive industries for its high specific strength and superior performance at elevated temperatures. Despite these advantages, challenges remain in fabricating thin-walled or complex components due to the alloy’s limited cold formability at room temperature. Superplastic forming offers an effective alternative, allowing complex sheet metal parts to be formed at elevated temperatures, typically between 850 and 950°C. Recently, advancements in ultra-grain refinement have enabled lower-temperature superplastic forming of Ti-6Al-4V, which provides benefits such as energy savings and reduced tooling costs [13].

3. FSW WELDING / FSP PROCESSING OF LIGHT METAL ALLOYS

During the processing (FSP) the rotating tool, under a controlled axial force, is plunged into the substrate such that the full-length pin and shoulder engage with the material. This interaction generates significant frictional heat at the tool-substrate interface, inducing intense plastic deformation.

As the tool moves forward, the visco-plastic material flows around the pin and is forged in the stir zone, aided by the backward tilt of the tool. The process operates at temperatures approximately 50-90% of the material's melting point (Tm), but no evidence of melting is observed, classifying it as a solid-state process [14].

Tool dimensions and pin geometry play a critical role in heat generation and material flow dynamics during Friction Stir Processing (FSP) plunging, heat is primarily generated through friction at the pin-workpiece interface, supplemented by additional heating due to material deformation.

The tool is plunged until the shoulder engages with the workpiece surface, initiating further heat generation [16].

Research indicates that the effective pin area significantly impacts frictional deformation and heat production, with larger areas intensifying heat due to increased contact surface. Pin geometry, particularly circular pins, has been shown to produce lower temperatures during the plunge phase due to reduced frictional resistance.

Studies have examined the tool size and geometry on the resulting microstructure and mechanical properties, highlighting the critical relationship between these parameters and the overall quality of processed materials [17].

3.1 Microstructural Evolution

- Aluminium

FSP enhances grain refinement in alloys like 2XXX and 7XXX, which are prominent in aircraft fuselage and structural components.

This refinement leads to superior strength and toughness, making these materials resilient under high-stress aeronautic conditions [18].

Microstructural modifications in materials processed by Friction Stir Processing (FSP) are driven by thermomechanical effects. Similar to Friction Stir Welding (FSW), the FSP-affected area comprises distinct zones: the stir zone (SZ), thermomechanical affected zone (TMAZ), heat-affected zone (HAZ), and base metal (BM) zone (Figure 3) bits an “onion ring” structure, resulting from the layered flow of plasticized material from the tool’s advancing side to the retreating side, as shown in Figure 3 for 6063 aluminum alloy.

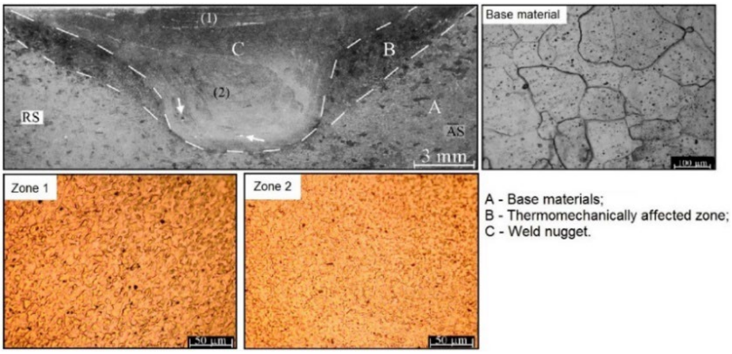

Fig. 3 Microstructure of single-pass FSP-processed 6063 aluminum alloy [18]

A review of experimental research indicates that single-pass Friction Stir Processing (FSP) at lower tool rotation speeds can achieve a substantial reduction in average grain size in aluminum alloys, decreasing it by approximately 85-96%.

This exemplifies FSP's impact on grain refinement and the enhancement of alloy strength. Key parameters, including the number of FSP passes, tool rotation speed, and traverse rate, must be carefully selected based on the specific characteristics of the aluminum alloy. Variations in these parameters can produce diverse outcomes, highlighting the need for precise control to optimize material quality [18].

- Magnesium

Grain refinement and texture modification are recognized as effective strategies to enhance the ductility of magnesium alloys, as depicted in figure 4. Friction Stir Processing (FSP) facilitates this by refining the microstructure, thereby increasing ductility without compromising tensile strength. Through dynamic recrystallization and controlled plastic deformation, FSP weakens the basal texture of the alloy and produces a fine, equiaxed grain structure, which collectively contributes to improved ductility and mechanical stability [19].

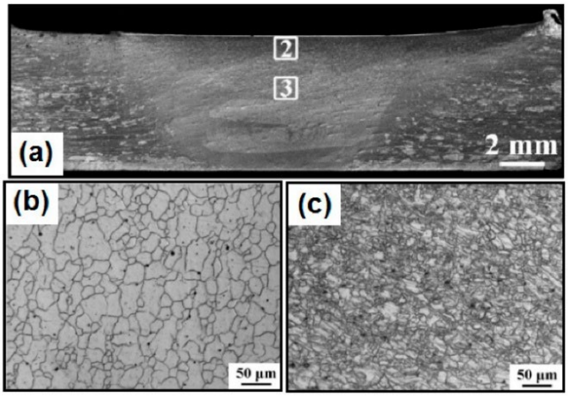

Fig. 4 The microstructure of magnesium alloy before and after FSP [20]

- Titanium

In Friction Stir Processed (FSP) pure titanium, the stress state closely resembles simple shear, with a shear plane that forms a truncated cone shape. This structure spans from the tool shoulder diameter in the upper portion of the stir zone to the pin diameter in the lower stir zone, creating a distinct macrostructural flow.

This configuration is characteristic of the processed zone, particularly evident in single-pass FSP of pure titanium, as illustrated in Figure 5. FSP introduces substantial microstructural refinement in titanium alloys.

As shown in Figure 5, the process yields an ultrafine structure in Ti-6Al-4V alloy, consisting of α-phase grains averaging about 0.51 µm, along with a minor β-phase. FSP also results in a high fraction (89.3%) of high-angle grain boundaries, which significantly enhances the microstructural refinement.

Additionally, FSP in pure titanium induces a prominent shear texture, arising from prism slip during material flow. This texture contributes to the formation of deformation-induced grain boundaries, thereby improving wear resistance and hardness by refining the surface characteristics of the alloy [19-21].

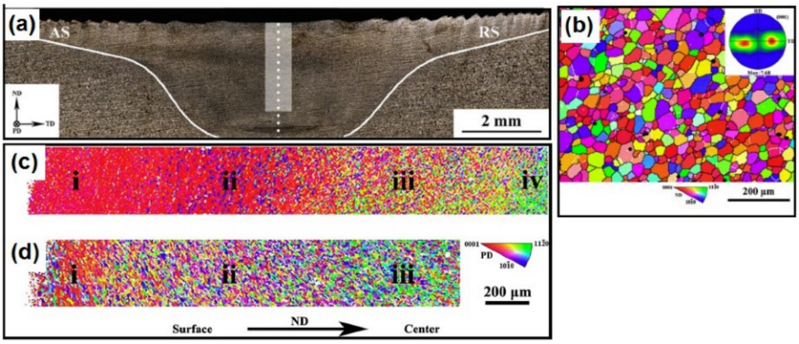

Fig. 5 Macrostructure of single-pass Friction Stir Processed (FSP) titanium: (a) region processed at a rotation speed of 180 rpm; (b) Electron Backscatter Diffraction (EBSD) map of an unprocessed pure titanium sheet; and EBSD maps of the cross-sectional areas of specimens processed at 180 rpm (c) and 270 rpm (d) [22]

3.2 Tensile test

The tensile testing of friction stir welded (FSW) joints is essential for determining the mechanical integrity of the joints under tensile loading conditions. Specimens are subjected to various loading regimes to quantitatively assess the joint strength in response to axial tensile forces. Such testing is important for comprehensively understanding the mechanical behavior of FSW joints, particularly concerning their applicability in aerospace engineering.

The experimental investigation involved performing friction stir welding (FSW) on a dissimilar joint comprising AZ91 magnesium alloy and AA 6082-T6 aluminum alloy, with a focus on various process parameters, including rotational speed, traverse speed, and axial force. A cylindrical tool with a threaded profile was employed for the welding operation.

The results of the study indicated that the tensile strength of the dissimilar joints was significantly affected by the chosen process parameters. The joints exhibited a heterogeneous distribution of intermetallic compounds (IMCs) of varying sizes, which formed during the FSW process.

Microstructural analysis demonstrated grain refinement and the formation of a partially melted zone adjacent to the joint interface. [25].

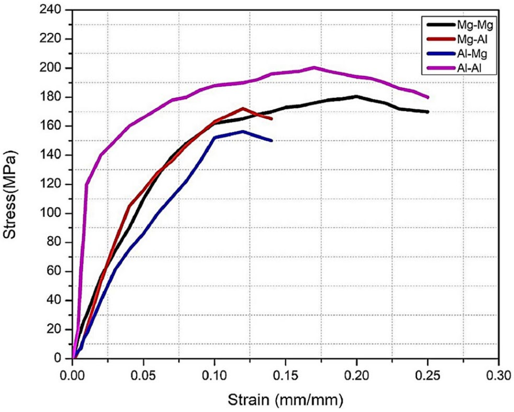

Fig. 6 The diagram from tensile tests on FSW joints of Al–Mg alloys [25]

3.3 Hardness test

Conducting a post-friction stir welding (FSW) friction stir processing (FSP) pass increased the hardness of the weld, particularly when the tool's traverse motion during the FSP pass was in the opposite direction to that of the welding pass, while maintaining the same tool rotation direction in both processes. This approach effectively enhanced the mechanical properties of the joint [26].

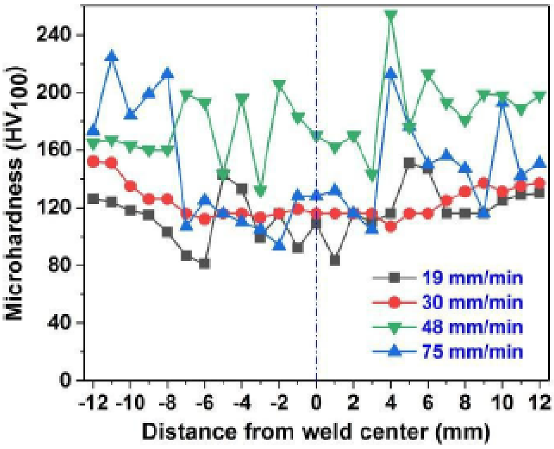

Fig. 7 Micro hardness distribution on joint interfaces

4. CONCLUSIONS

Although friction stir welding (FSW) and friction stir processing (FSP) present significant advantages for the aeronautical sector, several challenges persist. These challenges include the durability of tool materials, particularly for high-melting alloys such as titanium, as well as the need for automation techniques tailored to complex geometries. Future research should concentrate on optimizing process parameters, developing novel tool geometrics and materials as well as new methods for FSW welding and FSP processing in various mediums (water, dry ice,..) investigating the applicability of these technologies to emerging lightweight alloys. Light metal alloys, especially aluminum, magnesium and titanium alloys, are essential in modern aeronautics due to their exceptional properties, with FSW and FSP significantly enhancing their performance in aerospace applications.

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