FSP PROCESSING AN ALTERNATIVE TO IMPROVE THE PROPERTIES OF WELDED JOINTS MADE OF ALUMINUM ALLOYS

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Abstract: The paper proposes to investigate the effect of friction stir processing (FSP) on aluminum alloys before or after welding. By FSP processing, a homogenization of the alloy microstructure is achieved by a redistribution of the alloying element particles. This results in a change in the zonal hardness by improving the microstructure and reducing internal stresses [1-2]. Also, friction stir processing after welding contributes to the refinement of the microstructure, reduces porosities and the appearance of microcracks by the formation of very fine precipitates in the processed area due to the effect of intense plastic deformation and temperatures during processing [3-4].

Keywords: aluminum alloys, welded joints, friction stir processing, improve properties

1. INTRODUCTION

Aluminum alloys, similar or dissimilar, are basic materials for industrial applications due to their remarkable properties regarding low density, mechanical strength and high corrosion resistance. Wrought aluminum alloys used as basic materials in industry are grouped into 7 series of alloys with different characteristics and properties (1XXX, 2XXX, 3XXX, 4XXX, 5XXX, 6XXX, 7XXX). The 1XXX series of aluminum alloys, close to pure aluminum, is easy to weld, has low tensile strength, good corrosion resistance and very good electrical conductivity, being used as a conductor of electricity or to transport chemicals. The 2XXX series alloys have high tensile strength due to the content of Cu and other alloying elements such as nickel, titanium, manganese but are susceptible to cracking when welded. They are frequently used in aerospace applications. The 3XXX series is alloyed with manganese, easy to weld, with medium tensile strength and can be used in combination with other alloys (e.g. Al1100 and Al4043) for heat exchangers and air conditioning units. The 5XXX series aluminum alloys, rich in magnesium, have high tensile strength but cannot be welded in combination with the 4XXX series, being used in shipbuilding, bridges and civil engineering. The 6XXX series is the most used in the production of welded structures, has a high magnesium and silicon content, has high tensile strength but can be processed to improve mechanical properties. Another series that is difficult to weld due to its tendency to crack is 7XXX, rich in zinc, which gives it increased tensile strength but also reduced corrosion resistance. Current technological challenges and increasingly high-performance requirements require combinations of aluminum alloys from different series (e.g. the 2000-7000 and 5000-6000 series). Also, the large differences in thermal expansion between 5000 series aluminum alloys (aluminum-magnesium) and 6000 series alloys (aluminum-silicon-magnesium) can generate residual stresses and deformations after welding. The widespread use of aluminum alloys in applications across a variety of industrial sectors is evidenced by the ever-expanding global aluminum market, estimated to grow by over 80% between 2024 and 2034 [5]. The market growth is driven by the increasing demand for lightweight and durable materials in industries such as automotive, aerospace, and construction.

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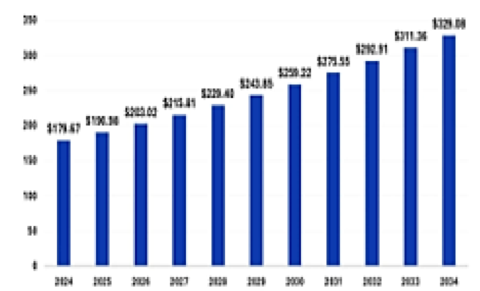

Figure 1 – Evolution of the global aluminum market [5]

The interest in the use of aluminum alloys has led to increased research activity in the field of improving their physical and mechanical properties before and after welding.

Friction Stir Processing (FSP) is an advanced technology used for the mechanical processing of aluminum alloys (as base materials), but also of their welded joints, with the aim of improving the mechanical properties and microstructure of the processed material. This solid-state processing technique can improve the physical and mechanical characteristics of the material before welding and minimize defects characteristic of conventional welds, such as porosity and intergranular cracks. Recent studies have highlighted the impact of FSP processing on the microstructure, mechanical strength and fatigue behavior of welded aluminum alloys [6-7].

2. MATERIALS AND WELDED JOINTS

Aluminum alloys are found in a wide variety of applications, in many industrial fields, both as materials themselves and as materials that require welding (as similar or dissimilar materials). Welding of similar aluminum alloys does not present difficulties due to their uniform behavior during the heating and cooling process, maintaining tensile strength and ductility in the joint area.

Some applications of Al alloys from different series are presented as examples that can be used as materials themselves or that require welding joints. Due to the malleability and very high corrosion resistance of aluminum alloy 1100 sheets, it is used for thermal insulators. From the 2XXX series, alloy 2024, due to its high fracture and fatigue resistance, is used for pistons, brake components, rotors, cylinders, wheels and gears. Alloys 3003,3004, due to their high resistance, are used for pipes, panels, etc. Alloys 3105,5005,5083,5182,5251 have high corrosion resistance and are used in the manufacture of car bodies, doors, floor panels, and other complex engine components. Silicon-alloyed alloys, 4032, which exhibit weldability and abrasion resistance is used for pistons and other engine components. Alloys in the 6XXX, 6016, 6022, 6061, 6082 series due to their high impact strength, corrosion resistance and good finishing characteristics are used for: fuel tanks, sleepers, beams. Alloys in the 7XXX and 2XXX series are used for automotive structures due to their extremely high weld strength (7003, 7046) [8]. In contrast, welding dissimilar alloys, involving materials with different chemical compositions and mechanical properties, requires strict thermal control and advanced welding technologies due to different melting points, expansion coefficients, and susceptibility to cracking.

Current technical progress and the increasingly high-performance requirements of top industrial fields (automotive, aeronautics, aerospace, industrial equipment, etc.) have led to the need to combine dissimilar materials in different combinations. In the automotive industry, for example, combinations of dissimilar alloys 6061 - 6082 are used for the manufacture of chassis and lightweight structures, and for components in the aerospace industry, where increased strength is required, similar alloys are used (e.g. 7075). In order to combine increased corrosion resistance with the structural rigidity required in the naval industry, combinations of aluminum alloys from the 5XXX and 6XXX series (e.g. 5083 and 6061) are adapted. Another combination used for industrial equipment (storage tanks, piping systems) are aluminum-manganese alloys (3XXX series) with alloys from the 5XXX series. Technological challenges require combinations of the 2XXX -7XXX and 5XXX - 6XXX series aluminum alloys. Aluminum alloys of the 2XXX series (e.g. 2024, aluminum-copper) and the 7XXX series (e.g. 7075, aluminum-zinc) are difficult to weld together due to the formation of brittle intermetallic compounds in the weld zone.

3. WELDING PROCESSES FOR ALUMINUM ALLOYS

Specialized studies analyze the welding of aluminum alloys from the point of view of the welding process and the welding procedure. Welding of aluminum is more difficult due to the fact that these alloys have a high electrical conductivity and a low melting point, which can lead to the piercing of the material during welding. Another problem in welding aluminum alloys is the oxide on the surface of the material that must be removed before welding. Porosity, loss of alloying elements, weld bead geometry and softening of the heat-affected zone are some of the problems that can occur in the welded joint.

The following table describes the characteristics of the welded joints obtained by various processes analyzed in research studies [9-20].

Table 1 – Welding processes of aluminum alloys

The welding process and characteristics of the welded joint	
MIG (Metal Inert Gas)	
1	- tensile strength is influenced by welding parameters (welding current, wire feed speed and gas shielding parameters); - hardness reduction in the HAZ is attributed to grain size increase and precipitation coagulation; - hardness reduction in the joint area due to microstructural changes; - the weld bead has a dendritic structure due to rapid solidification; - porosity and hot cracks are frequent, being influenced by welding parameters and residual gases from the alloy; - low fatigue resistance due to internal stresses; - increasing welding current intensity causes a reduction in mechanical properties; - predisposition to corrosion of the heat-affected zone (HAZ).
TIG (Tungsten Inert Gas)	
2	- tensile strength is lower than that of the base material, especially in the case of alloys from the 6XXX and 7XXX series; - hardness in the weld zone (WM) and in the heat-affected zone (HAZ) decreases significantly compared to that of the base material; - for alloys from the 5XXX series, hardness is more uniform, due to the absence of hardening phases sensitive to high temperatures; - reduction of the general mechanical properties of the joint due to the dentic structure with large grains; - in the HAZ the grains increase due to prolonged exposure to high temperatures; - fatigue strength is lower compared to that of the base material; - crack propagation occurs due to the concentrations of internal stresses and microcracks in the heat-affected zone (HAZ); - welding parameters (current and voltage) significantly influence the quality of the weld; - high welding current affects the microstructure and reduces mechanical properties; - the use of appropriate filler materials can improve the mechanical properties and corrosion resistance of the joint; - 7XXX series alloys show a high sensitivity to corrosion in the heat affected zone (HAZ); - superior quality of the weld bead appearance compared to MIG welding.
FSW (Friction Stir Welding)	
3	- high mechanical strength, comparable to that of the base material, especially for alloys in the 6XXX and 5XXX series; - absence of defects caused by the melting of the material, such as porosity or cracks; - the stirring zone (SZ) has a high hardness due to fine grain size and dynamic recrystallization; - for heat treatable alloys, such as 6061-T6, the hardness may decrease in the heat affected zone (HAZ);

	- for non-heat treatable alloys (e.g. 5XXX), the hardness remains more uniform throughout the welded section, due to the higher resistance to thermal effects; - Stir Zone (SZ) is characterized by a fine, equiaxial grain size, due to dynamic recrystallization; - in the heat affected zone (TMAZ) the grains are deformed and elongated under the influence of mechanical and thermal forces; - the heat affected zone (HAZ) is characterized by increased grain size and reduced hardness for heat treatable alloys; - fatigue resistance is superior compared to joints obtained by conventional welding (MIG/TIG); - high corrosion resistance, especially for alloys in the 5XXX series; - for heat treatable alloys (6XXX or 7XXX), the HAZ may become susceptible to intergranular corrosion due to microstructural changes; - joints are uniform, without spatter or cracks, which ensures superior aesthetic quality; - welding parameters (rotation speed of the welding tool, feed speed and geometry of the welding tool pin) significantly influence the quality of the joint; - residual stresses are reduced and deformations are minimal compared to fusion welding.
RSW (Resistance Spot Welding)	
4	- spot welding has a good resistance close to that of the base material; - the process is effective for small material thicknesses; - copper-free aluminum alloys from the 7XXX series have a good corrosion resistance compared to the 3XXX, 5XX and 6XXX alloys - to prevent electrode wear, it is recommended to clean the surface of the material with chemicals to reduce the oxide layer; - porosity and oxide inclusions reduce tensile strength, fatigue and corrosion resistance; - it is a fast and energy-efficient joining process, without the use of filler material.
GMAW (Gas Metal Arc Welding)	
5	- it is an improvement of the MIG method by using a pulsed current; - the weld bead is more uniform than MIG welding, with fewer defects due to the thermal process generated.
CMT (Cold Metal Transfer Welding)	
6	- reduced heat input minimizes thermal deformations and the size of the heat affected zone HAZ; - being a controlled process, the electric arc is stable and the transition of the filler material drops is uniform, resulting in a reduction of spatter during welding; - thermal control during the process limits the risk of porosity and cracks; - the weld zone has a fine grain, with a uniform distribution of intermetallic phases; - mechanical strength and ductility are improved compared to joints obtained by MIG or TIG processes; - good fatigue performance (e.g. for alloy 5083); - the method is applicable to both welding similar and dissimilar materials; - reduced consumption of energy and filler materials.
Collision Welding	
7	- being a solid-state joining process, it prevents the formation of solid intermetallic phases and reduces the risk of cracks appearing through solidification; - the lack of the HAZ heat-affected zone determines mechanical properties comparable to those of the base material; - the strength of the joint is influenced by the process parameters: discharge energy, collision angle and impact velocity; - the process completely eliminates oxide layers and surface contamination through the jetting phenomenon, which improves the quality of the joint; - similar and dissimilar aluminum alloys can be joined, difficult to weld by conventional methods; - the process is used to make linear and tubular joints;
MPW (Magnetic Pulse Welding)	

8	- the lack of a heat-affected zone (HAZ) contributes to preserving the mechanical properties of the base materials, making the process ideal for aluminum alloys sensitive to high temperatures; - no microstructural changes occur during the joining process, reducing the risk of cracks and embrittlement; - the jetting phenomenon completely eliminates oxide layers and surface contamination, which improves the quality of the joint; - the weld quality is influenced by the process parameters (discharge energy, collision angle and impact velocity) - the weld interface has a fine grain and increased hardness, due to microstructural refinement and dynamic recrystallization; - linear and tubular joints can be made for materials that are difficult to weld using conventional methods; - it is a clean process without consumables, limiting the environmental impact.
Laser Welding	
9	- reduced heat affected zone (HAZ) and minimal deformation; - high welding speeds, which improves productivity compared to traditional methods; - is ideal for heat sensitive alloys such as those in the 2xxx and 7xxx series in combination with post-weld processing; - joints with increased tensile strength and high ductility can be obtained by optimizing the process parameters (laser power, feed speed, beam diameter).

4. FSP PROCESSING

4.1 General aspects of FSP processing

Friction Stir Processing (FSP) is a relatively new technique, derived from friction welding, used to modify the internal structure of metallic materials in a controlled manner, without melting them. Basically, a special rotating tool penetrates a material (e.g. aluminum) and moves along a predetermined trajectory, generating heat through friction and locally deforming the material. Figure 2 schematically shows the working sequences of friction stir processing [21].

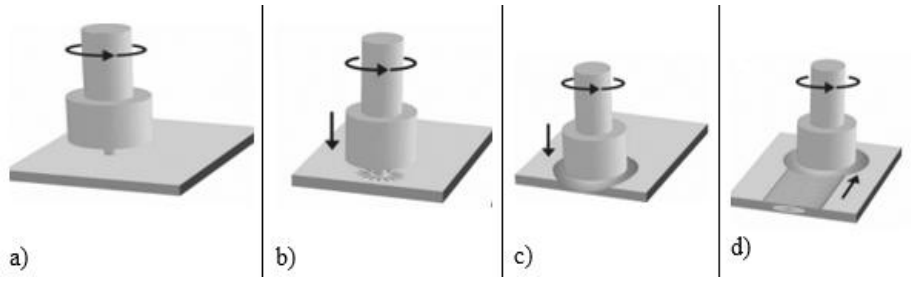

Figure 2 – Schematic illustration of friction processing

In the case of welded joints, the application of processing in the weld zone causes a rearrangement of the microstructure and a significant reduction of typical weld defects, such as porosity, residual stresses or fine cracks. In recent years, the applications of FSP processing have diversified greatly, especially due to its flexibility. It is not only used to treat welded areas, but also to improve metal surfaces or to make composite materials by incorporating ceramic particles into the metal mass.

4.2 Application methods

• FSP processing of the actual materials is a technique for improving the microstructure and mechanical properties of the processed materials;

• FSP processing after welding of the actual materials: For example, in the case of aluminum alloy 5083 - H111, the application of FSP after welding by conventional methods led to a clear decrease in grain size and an increase in hardness and tensile strength. The material thus becomes more uniform, stronger and more reliable in operation. It is also worth noting that the processing takes place at temperatures below the melting point, which preserves the overall integrity of the part. In addition, the structural refinement obtained by this method contributes to superior behavior under repeated stress conditions, such as vibrations or thermal variations - essential aspects in applications in the naval, aerospace or automotive industries [22-25].

• Pre-weld processing: In the case of alloy 6061-T6, for example, which is notorious for its cracking problems during welding, it has been found that the prior application of FSP helps to reduce these problems. This is due to the formation of a more homogeneous microstructure, with smaller grains, which limits the appearance of cracks during subsequent solidification. Thus, the material becomes easier to weld and acquires a more predictable behavior under working conditions.

• Processing on materials/parts obtained through additive technologies: Another interesting example is the use of FSP to uniformize parts produced through additive technologies, such as Selective Laser Melting. These are often affected by internal porosities, but friction processing allows the elimination of these imperfections and the achievement of a denser and more resistant material.

FSP is more than a simple mechanical treatment – it is a versatile technique that allows the adaptation of material properties to the requirements of increasingly varied and demanding applications.

4.3. Process parameters in Friction Stir Processing (FSP)

The FSP process involves a series of parameters that must be carefully adjusted for the final result to be efficient and uniform. Two of the most important are the tool rotation speed and the feed rate.

• The rotation speed influences the amount of heat generated during friction, and a value that is too low does not generate enough energy to plasticize the material, while an excessive speed can lead to overheating and damage to the metal structure.

• The feed rate, that is, the speed at which the tool moves along the part, regulates the time in which the material is subjected to plastic deformation and influences the degree of mixing. As a rule, an optimal ratio, often called the “heat ratio”, must be maintained between these two speeds, which varies depending on the type of alloy. For example, in the case of alloy 6082-T6, it was found that a rotation speed of 1000 rpm and a feed rate of 50 mm/min generated very good results in terms of microstructural homogenization and increased tensile strength [26-27].

• The depth of penetration of the tool into the material to be processed. This must be well calibrated, so that the affected area is processed completely, but without damaging the substrate or producing uncontrolled material outflows. In general, the depth is set depending on the thickness of the part, but also on the geometry of the tool pin. For example, for a 6 mm thick aluminum sheet, the pin penetration should be approximately 5.7–5.8 mm, with a slight shoulder pressure on the surface.

• The angle of inclination of the tool, which is usually set between 1° and 3°. Too small an angle can reduce the mixing capacity, and too large an angle can lead to the appearance of defects such as non-homogenization channels or even discontinuities on the surface. The importance of these fine adjustments cannot be underestimated, as any deviation from the optimal values can compromise the entire process, especially when working with sensitive aluminum alloys or with parts that will bear high loads in service [28].

• The geometry and characteristics of the tool, which is in direct interaction with the material during the process, is another essential parameter. The shape of the pin (e.g. cylindrical, conical, threaded or pyramidal), the size of the shoulder and the presence of special grooves or profiles on its surface have a major impact on the flow of plasticized material, on the tool and on the heat distribution. Studies show that tools with a threaded conical pin, combined with a grooved shoulder, provide more intense mixing and a more homogeneous distribution of alloy particles. Also, the choice of the material from which the tool is made influences not only its durability, but also the thermal efficiency of the process. H11 and H13 steels are usable for materials with lower melting temperatures, and tungsten carbides are preferred for high-temperature processing, and in special applications, such as processing under water or in cryogenic environments, tools with ceramic protective layers can be used. All these details, although they may seem technical, are actually essential for the quality control of the final product and for the industrial repeatability of the FSP process [29].

4.4. Factors influencing processing

FSP processing is a process sensitive to a number of factors that can significantly influence the quality of the treated area and the final properties of the material.

• the base material, namely its chemical composition and initial state, is one of the most important factors. For example, 5000 series aluminum alloys (magnesium-based) respond differently to deformation compared to 6000 series (magnesium and silicon-based), having a distinct behavior in terms of material flow and recrystallization rate during processing. The pre-existing structure – whether rolled, cast or extruded – influences the way in which grains refine under the effect of friction and plastic deformation. Furthermore, the presence of initial defects, such as inclusions or pores, can negatively affect the uniformity of the processed area, leading to the formation of inhomogeneities or the appearance of microcracks if the parameters are not carefully controlled.

• The working conditions in which the processing is carried out are another very important factor. Ambient temperature, humidity, the method of fixing the part and the rigidity of the assembly significantly influence the stability of the process. For example, in working conditions at low temperatures, such as FSP carried out in a liquid environment (under water or with an active cooling jet), a finer microstructure is obtained, due to the rapid cooling that reduces diffusion and keeps the grains at a small size. However, too sudden cooling can produce internal stresses or even cracks, if it is not correctly correlated with the rest of the parameters. Also, an unstable fixing of the part or the vibrations transmitted from the machine tool can lead to the appearance of defects such as incomplete channels, unmixed areas or even damage to the tool. A balance between the applied mechanical forces, thermal conditions and the geometry of the part is therefore necessary to obtain an optimal result. In addition, accidental contamination of the work area – for example by oils, dust or aluminum oxide – affects the effective contact between the tool and the material, generating non-uniformities and structural defects. Therefore, in industrial FSP processes, rigorous surface cleaning, frequent equipment maintenance and continuous monitoring of critical parameters are recommended.

• Tool wear is an often underestimated but extremely important aspect in terms of its impact on process consistency in repeated industrial applications. As the tool is used repeatedly, its profile changes, directly influencing the mixing capacity and heat generation. Even a small difference in pin or shoulder size can significantly change the material dynamics during deformation.

Controlling these factors not only improves the performance of the processed parts, but also reduces the risk of batch-to-batch variations, ensuring essential reproducibility for critical applications [30-31].

4.5. Equipment and tools used in processing (geometries and materials)

FSP processing is derived from FSW welding, has the same working principles and uses the same type of equipment. This equipment can have low, medium or high configuration and complexity, depending on the areas of use and the type of applications in which they are used.

They can be equipment with which joints or processing of materials can be made in a linear direction, respectively with which complex welding/processing paths can be made. The equipment is robust to ensure the smooth running of welding/processing processes. Considering that at ISIM Timisoara FSW/FSP welding and processing is a direction of interest, figure 3 shows the FSW equipment from the institute's equipment.

Figure 3 – FSP processing equipment [31]

The tool used in friction stir processing (FSP) plays a central role in the efficiency and results of the process. Being in direct contact with the material being processed, it must be designed to generate the optimal amount of frictional heat, ensure efficient mixing of the material, and withstand wear and intense mechanical stress. In general, the tool is made up of two main components: the shoulder, which comes into contact with the surface of the part, and the pin (probe), which penetrates the material. The shoulder has the role of generating heat and plasticizing the upper layer, while the pin induces movement of the material in the volume, favoring homogenization. The geometry of these components varies depending on the application, material, and thickness of the part. For example, for the processing of thin aluminum sheets, short cylindrical pins are usually used, while for thicker components or hard alloys, conical or threaded shapes are preferred, which favor stronger mixing.

The geometry of the pin has a major impact on the flow of material during processing. Cylindrical pins are effective in simple processes and on materials with good plastic behavior, but have limitations in terms of deep mixing. Tapered or threaded pins create a more intense vertical flow and facilitate the movement of material both laterally and in depth. Sometimes pins with a pyramidal, triangular or helical profile are also used, for special applications that require a specific directional distribution of the material. The shoulder can be flat, convex, conical or profiled with concentric or spiral grooves. The grooves help to capture the plasticized material and direct it back to the processing area, preventing the appearance of voids or incomplete channels. The tools can also be provided with holes for the circulation of the coolant in applications where more precise thermal control is desired. Choosing the ideal combination of geometries depends not only on the type of material, but also on the shape of the part and the purpose of the processing – whether it is improving the structure of a weld, treating a surface or manufacturing a metal composite.

The material from which the tool is made directly influences its durability and the quality of the machining. Since FSP processing involves high temperatures (in the case of aluminum, often above 450°C) and constant mechanical stresses, the tools must be made of materials that are resistant to wear, thermal stability and oxidation. High-speed steels (such as H13 or AISI M2) are most often used for light alloys, as they offer a good compromise between cost, mechanical strength and temperature behavior. For more demanding applications, such as the machining of titanium alloys or composite materials, tools made of tungsten carbide or even ceramic materials are used, which withstand higher temperatures and have a longer service life. In recent research, tools made of composites based on cubic boron nitride (cBN) have also been tested, which offer outstanding performance, but are significantly more expensive. The choice of tool material must, therefore, be made taking into account the balance between performance, durability and cost, especially in the context of industrial applications where repeatability and reliability are essential [33].

For example, figure 5 shows several tools with different geometries, made of steels and W-sintered carbides, used at ISIM for aluminum alloys, respectively steels and copper.

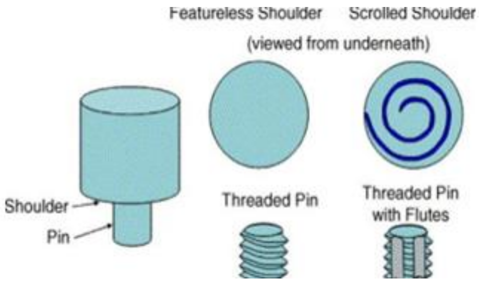

Figure 4 – Types of FSP tools [34]

Figure 5 – Types of geometries for FSP processing tools

4.6. Beneficial effects of processing

The microstructure and mechanical performance of aluminum alloys as well as welded joints made of aluminum alloys are positively influenced by FSP processing. FSP helps to eliminate possible stress concentrators by promoting homogeneous dispersion of intermetallic phases and reducing local segregation of alloying elements [35-36]. The improvement of fatigue strength after applying FSP processing is an important result that has been reported in the literature [37]. The reduction of the hardness gradient and dislocation density in the HAZ (Heat Affected Zone), as well as the uniform morphology of the treatment zone are both responsible for this improvement.

Last but not least, FSP offers the possibility to functionalize the treated zone by adding ceramic particles or adjusting the phase orientation, which opens new avenues for composite research and essential applications where mechanical performance is essential.

5. CONCLUSIONS

Friction Stir Processing (FSP) generates significant structural changes, contributing to the homogenization of the distribution of intermetallic phases in the treated area and to the refinement of the microstructure. Compared to the initial state, the FSP treatment causes a considerable reduction in grain size and a uniform dispersion of strengthening precipitates, which leads to a local increase in hardness and yield strength. Due to the dynamic recrystallization that occurs during FSP processing, significant mechanical improvements are observed, including increased tensile strength and ductility of welded joints. In addition, uniform hardness profiles, together with the elimination of stress concentrations in the heat-affected zone (HAZ), optimize the fatigue behavior, which contributes to the extension of the service life of functional components. The microstructural quality and mechanical properties obtained are significantly influenced by the FSP process parameters, such as rotation speed, thermal ratio, tool geometry and number of passes. Optimizing these parameters represents a balance between avoiding local overheating, which could generate excessive grain coalescence, and ensuring adequate plastic deformation for homogenization.

Thus, FSP processing can be used before or after welding of different metallic materials, proving to be effective in improving the mechanical properties and microstructure of aluminum alloys. The processing contributes to modifying the hardness, tensile strength and fatigue resistance of the joints, by uniformizing the distribution of intermetallic phases and granular refinement. From an industrial perspective, FSP applications extend considerably for alloys sensitive to diffusion and thermal corrosion, through controlled cooling and multi-pass techniques. These features offer significant advantages especially in the automotive, naval and aerospace sectors.

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