

STUDY ON INCREASING THE CORROSION RESISTANCE OF ALUMINUM ALLOYS BY FSP/SFSP PROCESSING

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ABSTRACT: The work considers an analysis of some studies and researches carried out internationally regarding the improvement of the corrosion resistance of aluminium alloys through FSP/SFSP processing. The study investigates the increase in corrosion resistance of aluminium processed by friction stir processing in various working environments. The paper aims to identify the parameters of the technological process that influence the increase in corrosion resistance and the improvement of the metallic properties of aluminium alloys. The obtained findings will contribute to the expansion of the use of aluminium alloy processing technology in various industrial applications exposed to corrosive environments.
KEYWORDS: friction stir processing, in various cooling media, corrosion resistance, aluminium alloys

1. INTRODUCTION

Aluminium alloys mainly contain aluminium (85%), to which other elements are added in the proportion of 15%, such as: iron, copper, magnesium, silicon and zinc. The addition of these elements gives the alloy improved mechanical properties compared to pure aluminium. Due to its low weight, high mechanical strength, chemical stability and thermal conductivity, aluminium alloys are used in a wide variety of industrial applications, especially in the aeronautical industry. A major disadvantage of these metallic materials is their susceptibility to corrosion. The most common corrosive environments for aluminium alloys in industrial applications are: salt water, acidic environments (sulfuric acid, hydrochloric acid, etc.), basic environments (strong alkalis such as: sodium hydroxide), humid environments and warm, and industrial environments (aluminium alloys exposed to various chemicals). Depending on the quality of the alloy and the corrosiveness of the environment in which it is operated, corrosion resistance can be improved by methods such as plating, painting or rotary active friction processing.

2. PROCESS DESCRIPTION

Friction stir processing is a solid state process used to modify the microstructure and mechanical properties of sheet metal and cast materials. FSP is a friction processing technology of the surface of metallic materials and the layers below their surface, using a processing tool with or without pin, aiming to change the microstructure and properties of the processed surface. At the contact between the shoulder of the processing tool, which is in rotation, and the surface of the material to be processed, a quantity of heat is generated by friction which causes an intense plastic deformation of the material which generates a dynamic recrystallization in the processing area. The samples processed by friction stir processing showed higher corrosion resistance compared to the base metal [1]. A significant amount of material is permanently deformed, mixed and exposed to heat in the processing area. By cooling the processed surface, in various environments, a significantly modified microstructure of the material results. Cooling of the processed material can be done in air (FSP), water (SFSP) or dry ice (solid CO_2). The treated area is distinguished by a recrystallized fine-grained structure [2]. The principle scheme for friction stir processing is shown in figure 1.

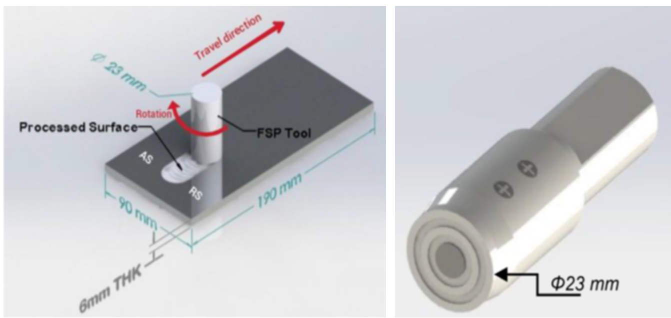


Figure 1. Scheme of the FSP process, [3]

FSP (Friction Stir Processing) and SFSP (Submerged Friction Stir Processing) significantly improves aluminium alloys at the microstructural level by:

- refining the crystal structure by reducing grain sizes, porosity and eliminating defects, especially in cast materials;
- improvement of mechanical properties (tensile strength, deformability and plasticity, ductility, etc.);

- microstructure homogenization, redistribution of alloying elements (e.g. magnesium, copper, silicon, etc.);
- improved corrosion resistance through a finer and more homogeneous heat affected zone (HAZ) structure.

When applying FSP processing, the base material (BM) is subjected to a process of heating and local plastic deformation. As a result, under the action of the processing tool, the stir zone (SZ) of the processed material, the thermomechanical affected zone (TMAZ) in its immediate vicinity and the heat affected zone (HAZ) can be observed. The advancing side is the one in which the horizontal movement (processing direction) and the direction of rotation of the tool coincide, and the retreating side is the one for which they are opposite (figure 2).

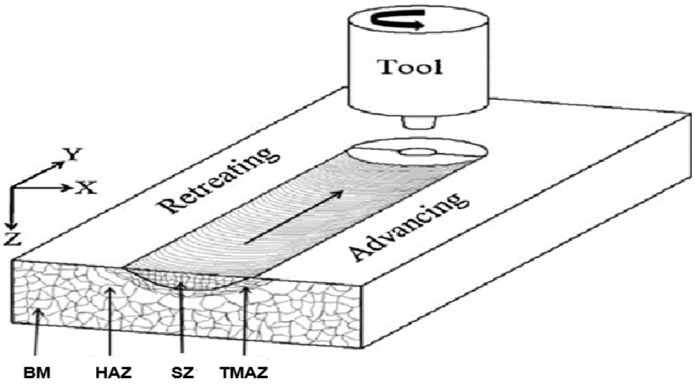


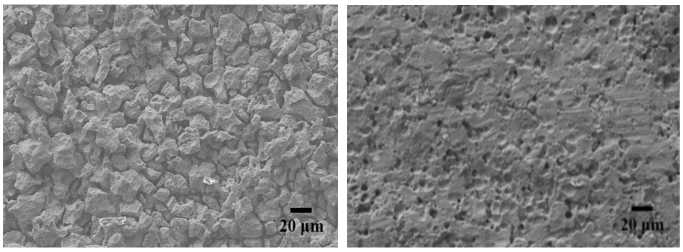
Figure 2. Specific zones of the friction stir processing, [4]

FSP/SFSP Aluminium Alloy Processing Technology to Increase Corrosion Resistance

Rotary Active Element Friction Processing Technology is an aluminium alloy processing technique that has the ability to locally modify the microstructures in the surface layers of the material in the processed area. Through the rotating action of the processing tool a significant amount of material is fragmented, mixed and exposed to heat in the processing area. The processed zone is distinguished by a recrystallized fine-grained structure [5]

For example, figure 3 shows the images of microstructure for one unprocessed material (BM) and for one processed material.

The cooling medium during processing can be air, water or dry ice. Studies have shown that following FSP processing, recrystallized fine grains developed in the mixing area (stir zone) due to severe plastic deformation and dynamic recrystallization. In the case of using water as a working/cooling medium, finer and even ultrafine UFG granular structures can be obtained in the processed material in comparison with air-cooled FSP, respectively with dry ice [7].



(a) *(b)*

Figure 3. SEM images for the microstructure of the base material and for the processed material, [6]

a) SEM image of the base specimen after the IGC test;

b) FSP processed sample after IGC test

Examining the FSP/SFSP processed samples by comparison, it was found, by intergranular analysis, that by using water processing (SFSP) a higher refinement of the grains and a homogenization of the alloying elements were obtained. From the experimental point of view, the studies show that 4 types of tests were carried out: the immersion test, the open circuit potential test, the Tafel polarization test and the electrical impedance spectroscopy test to analyse the electrochemical behaviour of the FSPed specimens [8]. All corrosion findings confirmed that samples processed in water led to higher corrosion resistance than those cooled in dry ice or air due to the formation of fine/ultrafine UFG structures and very fine precipitates [9].

3. CORROSIVE ENVIRONMENTS FOR ALUMINIUM ALLOYS

The FSP and SFSP methods bring significant improvements in the corrosion resistance of aluminium alloys compared to untreated (unprocessed) alloys, due to microstructural transformations and redistribution of alloying elements that generate a finer and more homogeneous microstructure through dynamic recrystallization induced by severe plastic deformation. Corrosive environments are: salty, acidic and basic environments.

Corrosion resistance in salty environment increases by processing aluminium alloys by FSP or SFSP methods due to the dense and homogeneous microstructure created, which limits the penetrability of chlorine ions from salt water [10].

Protection against acidic and basic environments is due to the homogeneous microstructure and lack of internal defects.

These characteristics improve the overall behaviour of the material in corrosive environments. The uniform redistribution of alloying elements (e.g. magnesium, copper and silicon) reduces the formation of anodic and cathodic zones that can accelerate galvanic corrosion processes [11].

4. INFLUENCE OF ALLOYING ELEMENTS OF FSP/SFSP PROCESSED ALUMINUM ALLOYS ON CORROSION RESISTANCE

Alloying elements for aluminium alloys are generally 15% with the remaining 85% being aluminium. The main alloying elements are: iron, copper, magnesium, silicon and zinc. Through FSP/SFSP processing, a redistribution of alloying elements takes place, resulting in a homogeneous, fine-grained microstructure, which can have a positive impact on the corrosion resistance of aluminium alloys.

The effects on corrosion resistance depend on the optimization of the processing parameters and are manifested by:

- homogeneous and uniform distribution of alloying elements;
- refining the grains of the alloying elements and increasing the density of the material, which reduces the diffusion of corrosive agents;
- the elimination or significant reduction of defects such as: pores, cracks and other microstructural defects that can be corrosion initiators.

The alloying elements that influence the corrosion of aluminium alloys are: copper, silicon and magnesium.

Copper is the alloying element used to improve the mechanical strength and hardness of aluminium alloys. In a humid-salty operating environment, the susceptibility to intragranular corrosion and exfoliation increases. FSP/SFSP processing contributes to a uniform distribution of copper forming, through solidification, fine intermetallic structures that increase tensile strength and reduce negative effects from the corrosive environment [10].

Silicon is the alloying element that has little impact on corrosion, but can indirectly influence the behaviour by changing the microstructure. The uniform distribution of silicon following FSP/SFSP processing can help achieve more stable intermetallic phases that are less susceptible to corrosion. In general, alloying with silicon contributes to the reduction of the coefficient of thermal expansion, improving the wear resistance and the castability of the aluminium alloy [12].

Magnesium, in high concentration, increases the susceptibility to galvanic corrosion, being the alloying element used to improve the mechanical strength and hardness of aluminium alloys. Through FSP/SFSP processing the negative impact on aluminium alloy corrosion can be minimized by uniform intergranular distribution [5].

5. INFLUENCE OF FSP/SFSP PROCESSING PARAMETERS ON CORROSION RESISTANCE ENHANCEMENT

Previous studies have investigated the effect of FSP/SFSP processing parameters on the microstructural evolution, mechanical properties and corrosion behaviour of aluminium alloys. The balance between these parameters ensures adequate plastic deformation, complete recrystallization and uniform distribution of alloying elements, all of which contribute to improving the mechanical properties and corrosion resistance of aluminium alloys [13].

The processing of the material can be done in a single pass or may require multiple successive passes (Fig. 4) to obtain the desired characteristics and mechanical properties.

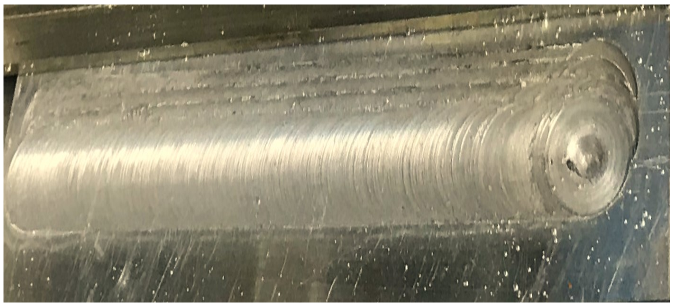


Figure 4. FSP processing in multiple passes, [14]

FSP and SFSP processing parameters that can improve the corrosion resistance of aluminium alloys include:

- the rotational speed of the processing tool is one of the most important parameters of FSP processing. This influences the amount of heat generated in contact with the processed material and the degree of mixing of the material in the processing area, which increases in proportion to the rotation speed. An appropriate, well-managed process temperature leads to a finer and more homogeneous microstructure, reducing porosity and internal defects in the processed material. If the tool rotation speed is too high, defects such as excessive porosity or microcracks due to overheating may occur [15]. A low rotation speed of the processing tool causes a lower temperature and insufficient plastic deformation of the material to be processed. The material not being sufficiently mixed and homogenized results, in the processing area, in an incomplete recrystallization with a coarse microstructure resulting in areas of material with unequal properties [16].
- the processing speed (feed rate of the tool in the processing direction), the diameter of the shoulder of the processing tool, the number of successive passes, all these can influence the corrosion

resistance. The processing speed in the FSP/SFSP process is a parameter that influences the microstructure of the materials and, implicitly, the corrosion resistance. A low processing speed generates enough heat for complete recrystallization and removal of internal defects increasing the corrosion resistance of the processed material area. Too high processing speed causes a coarser microstructure and internal defects that can compromise the corrosion resistance of the processed material zone [17].

- increasing the number of FSP/SFSP processing passes results in a reduction in the degree of corrosion in the processed zone due to the reduction of intermetallic particle sizes in the mixing zone in multi-pass FSP/SFSP processing. The shoulder diameter of the processing tool influences, directly proportionally, the contact surface between the tool and the material, the level of mixing of the material to be processed. The force with which the processing tool acts on the material to be processed influences the degree of deformation of the material. Thus, at a high pressure force, the plastic deformation of the material to be processed is more intense, reducing the porosity and resulting in a denser and more homogeneous microstructure, without internal defects. However, excessive compressive force can cause defects such as cracks or uncontrolled deformation if the material cannot withstand the applied compressive force. A small pressing force causes insufficient plastic deformation resulting in an uneven microstructure, affecting the overall properties of the processed material [13].
- the processing temperature influences the recrystallization and redistribution of alloying elements, resulting in finer and more homogeneous structures. This is determined by the rotational speed and pressing force applied by the processing tool. An appropriate, well-managed process temperature determines a fine and homogeneous microstructure in the processed material area. If the process temperature is too high, for a longer period of time, then the microstructure and appearance of the processed surface will be affected, causing burning or deformation and thermal imprinting of the material to be processed. If the temperature is too low, the material will not reach the plasticity required for effective mixing, maintaining a coarse and uneven microstructure of the material [9] and implicitly the resistance to corrosion is affected [18].

Influence of the cooling medium during FSP processing:

- In the case of FSP processing, the cooling medium as air, water or dry ice were mentioned in studies and research. Corrosion research has shown that following FSP processing, recrystallized fine grains developed in the mixing zone due to severe plastic deformation and dynamic recrystallization. Also, due to the effect of faster cooling in water, ultrafine UFG granular structures of approximately 0.7 μm resulted compared to dry ice cooling and air cooling, for which the grains size of 0.8 μm and of 0.92 μm were obtained [7].

6. USE OF ALUMINUM ALLOYS WITH IMPROVED CORROSION RESISTANCE THROUGH FSP/SFSP PROCESSING

FSP/SFSP improves not only corrosion resistance but also mechanical properties such as hardness and wear resistance. Friction Stir Processing (FSP) alloys that have increased corrosion resistance are used in several industrial applications due to their improved durability and performance.

The fields in which these processed alloys are used are:

- in the aerospace industry, in the manufacture of structural components (aircraft and satellite parts), where corrosion resistance is essential to cope with extreme atmospheric conditions and exposure to corrosive environments;
- in the automotive industry in the manufacture of body parts and structural components to improve the durability and the service life of parts exposed to varied weather conditions and corrosive agents;
- in the marine industry, in the manufacture of naval structures and marine equipment operating in wet and saline environments, where corrosiveness is a major problem;
- in constructions and infrastructure (bridges and buildings) where corrosion protection is important for the safety and durability of the constructions;
- in the manufacture of industrial equipment (machine components and processing equipment) that are exposed to harsh conditions or corrosive environments during operation;
- for renewable energy (equipment for wind turbines and solar panels) to increase durability and resistance in the type of operation.

7. CONCLUSIONS

Research on the corrosion of aluminium alloys demonstrated that the corrosion resistance was improved after FSP processing due to the formation of a refined and homogeneous grain structure. From the analysis of studies and research, regarding the corrosion resistance of aluminium alloys processed by friction stir processing, it follows that the processing parameters and the cooling environment are of particular importance. With respect to the cooling medium, a greater increase in corrosion resistance resulted for the SFSP processed alloys due to the formation of the UFG structure and very fine precipitates. Basically, corrosion is inversely proportional to the cooling rate.

Regarding the processing parameters, the following conclusions were drawn from studies and research:

- the low rotation speed of the processing tool causes a lower temperature in the processed area and insufficient plastic deformation resulting in areas of material with an uneven, coarse appearance, with very high surface roughness. If the tool rotation speed is too high, defects such as excessive porosity or microcracks due to overheating may occur.
- a suitable processing speed of the processing tool (processing speed), correlated with the rotation speed of the tool, allows the generation of a sufficient amount of heat in the processed area resulting in a structure resistant to corrosion.
- the number of passes and the diameter of the processing tool influence the corrosion resistance.

In the case of Cu and Zn alloying elements, studies have shown that FSP processing leads to an increase in the surface concentration of the alloying elements, the Cu content increasing especially in the case of water cooling. This fact is explainable due to the high cooling rate that prevents the dissolution of the alloying elements (Cu, Zn) back into the Al matrix. In the aggressive environment of NaCl the corrosion rate of water processed alloys (SFSP) is inversely proportional to the size of the resulting grains because it reduces the distance between the particles of the Al matrix causing increased intragranular corrosion [18]. Thus, in the case of aluminium alloys, which have Cu and Zn as alloying elements, slower cooling with air is indicated, because the corrosion rate decreases and the pitting potential increases. The increase in the corrosion rate is due to the coverage of a larger area of the Cu-rich regions [10].

8. ACKNOWLEDGEMENTS

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