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ASPECTS REGARDING THE INFLUENCE OF WORKING CONDITIONS ON THE FRICTION STIR PROCESSING OF EN AW 6061 ALUMINUM ALLOY

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Abstract: Friction stir processing is an environmentally friendly solid-state processing process applied to well-defined areas of metallic materials, with the aim of locally modifying the microstructure and mechanical properties. Studies and research in the field of FSP processing of metallic materials show increased interest of researchers and specialists regarding the possibilities of application to a wide range of materials. The use of different working conditions and cooling media during the process can influence the microstructure and mechanical characteristics of the processed material. The paper analyzes friction stir processing in different working/cooling media of the aluminum alloy EN AW 6061, based on an analysis of the specialized literature. The studies show the possibility of applying FSP processing for this alloy, as well as changes in the microstructure and mechanical properties of the material after processing, obtaining different results depending on the working/cooling media used.

Key words: friction stir processing FSP, working conditions, cooling medium, EN AW 6061 aluminum alloy, structural analysis, mechanical properties.

1. INTRODUCTION

Friction stir processing is a solid-state machining process for metallic materials, derived from the friction stir welding (FSW) process. A rotating processing tool with a shoulder and pin (Figure 1a) penetrates the material to be processed until the shoulder and the upper surface of the material to be processed come into firm contact, generating heat through their friction, which plasticizes the material in the tool's area of action. Under the action of the pin of the processing tool, the plasticized material is mixed and by moving the tool in rotational motion in the processing direction at the prescribed feed rate, the processed material bead is formed (Figure 1b). Different working media or cooling media (air, water, dry-ice, etc.) can be used during processing, with the aim of achieving a refinement and homogenization of the microstructure compared to that of the base material, as well as to locally modify the hardness and improve the mechanical properties of the processed area [1]-[4], [6]-[10].

The entire work process is carried out at a temperature lower than the melting temperature of the material to be processed [1]-[10], using specialized equipment/machines that allow friction stir processing, equipped with specialized modules for processing in different working mediums or to be able to use different methods for cooling the processing tool and the processed material (Figure 1c).

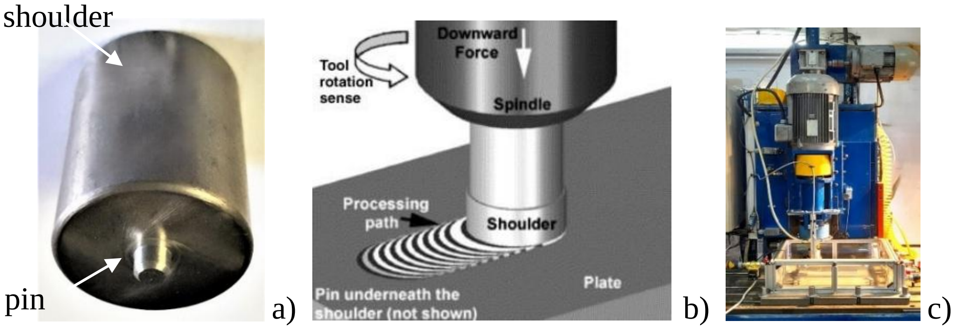

Figure 1 – a) Processing tool [10]; b) Schematic presentation of FSP processing [3]; c) Processing equipment ,equipped with a liquid processing module [10]

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The process is environmentally friendly, without emissions of pollutants or radiation, does not require filler materials and has great versatility for processing a wide variety of metallic materials, with the largest share being aluminum alloys [1], [2], [4], [6]-[9].

The EN AW 6061 aluminum alloy is one of the materials frequently used in structural engineering applications due to its good mechanical characteristics and properties. It is a lightweight and strong material used to make structural components in the aerospace industry (e.g. spars, panels, fasteners, etc.), in the automotive industry (engine mounts, chassis elements, suspension arms, etc.), in shipbuilding (e.g. components that are in contact with salt water, beams, panels, etc.), as well as in other fields (e.g. decorative panels for architectural structures, for civil construction, etc.).

Being a material widely used in industrial applications, it is topical and of interest to research the possibilities and effects of applying friction stir processing FSP to this alloy with the aim to improve its performance (tensile strength, increased corrosion resistance, microstructure refinement in the processed area, etc.) [11]-[27].

2. EXPERIMENTAL RESEARCH

2.1. Material to be processed

For the studies, EN AW 6061-O (thickness <2mm, [11]) and EN AW 6061-T6 (thickness 4mm [12] and thickness 3.2mm [13]) aluminum alloy sheet was used, with the chemical composition presented in Tables 1 and 2 [11] and [12], the melting point of the 6061-O alloy being 617°C.

Table 1 - Chemical composition - EN AW 6061-O [11]

Mg (%)	Si (%)	Fe (%)	Mn (%)	Cu (%)	Al (%)
1.16	0.66	0.4	0.2	0.22	balance

Table 2 - Chemical composition - EN AW 6061-T6 [12]

Mg (%)	Si (%)	Fe (%)	Cu (%)	Cr (%)	Zn (%)	Mn (%)	Ti (%)	Al (%)
1.1	0.6	0.6	0.2	0.18	0.18	0.1	0.1	balance

EN AW 6061 aluminum alloy is a low-strength alloy, from the precipitation/age hardening Al alloys category, with magnesium and silicon as the main alloying elements [13]. It has better corrosion resistance compared to other aluminium alloys [14]. The grain size of Al 6061-T6 (base material) was about 50µm [4]. The EN AW 6061 aluminum alloy has applicability in structural engineering given its high mechanical strength, corrosion resistance and machinability.

2.2. Processing experiments. Results

Studies on the possibilities of applying processing in different process conditions or cooling media were conducted For the aluminum alloy Al 6061, analyzing the effect produced on the microstructure and mechanical properties of the processed material [4], [11], [12].

2.2.1. Type of processing

Studies and research have considered the use of several process conditions and cooling media when processing the EN AW 6061 aluminum alloy, presented in Table 3.

Table 3 - Data on processing conditions and cooling media

Material, thickness	Processing conditions	Working/cooling medium	Study
EN AW 6061-O, 2.5 mm thickness	friction stir processing in liquid medium and processing using different cooling media, respectively	Cold water	1
EN AW 6061-T6, 4.0 mm thickness		Air cooling (AC) Cryogenic cooling (CC) Submerged (underwater) processing (UW)	2
EN AW 6061-T6, 3.2 mm thickness		water	3

In the first study, 2.5 mm thick EN AW 6061-O aluminum alloy was subjected to a single pass of submerged friction stir processing and the entire process was performed in cold water [11].

In the second study, FSP processing was performed on 4 mm thick EN AW 6061-T6 aluminum alloy, by using different cooling media: air, cryogenic and water [12]. Cooling media and FSP process parameters exert a considerable influence on grain refinement in the stir zone (SZ), with effect on the microstructure and mechanical properties. The idea of using different cooling media when processing EN AW 6061-T6 aluminum alloy was based on studies where cooling media to friction stir processing of other materials were used. For example, using a dry ice medium to cool the processed area immediately after processing influences the achievement of additional grain refinement and better mechanical properties of the processed material than in other cooling media [12].

The processing of 4 mm thick EN AW 6061-T6 aluminum alloy was performed under ambient conditions, but also under assisted cooling conditions, in order to compare the results obtained. In the case of cryogenic cooling, a mixture of dry ice and ethanol was applied to the processing area immediately after processing. In the case of water cooling, the material to be processed was in an enclosure where the water is changed to maintain a constant temperature throughout the process.

In the third study, the processing of 3.2 mm thick EN AW 6061-T6 aluminum alloy was performed underwater in multiple passes (Figure 2). Underwater processing reduces the amount of heat introduced into the process, avoiding overheating of the processing tool and the material to be processed [4].

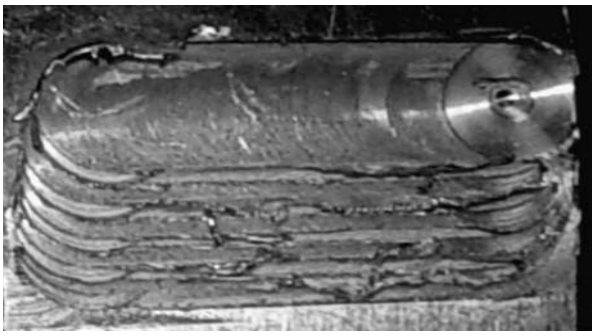
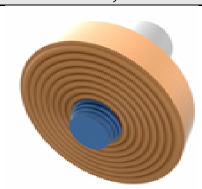


Figure 2 – Processing in multiple passes of Al 6061 [4]

2.2.2. Processing tools and process parameters

The geometry and dimensions of the processing tools, made of tool steels, used in studies on the processing of the EN AW 6061 aluminum alloy are presented in Table 4.

Table 4 – Processing tools used in experiments

Study 1 EN AW 6061-O, 2.5 mm thickness		Study 2 EN AW 6061-T6, 4.0 mm thickness		Study 3 EN AW 6061-T6, 3.2 mm thickness	
 [11]		 [12]		 [4]	
Shoulder diameter	10 mm	Shoulder diameter	24 mm	Shoulder diameter	19.1 mm; 12.7 mm
Pin length	2.0 mm	Pin length	3.7 mm	Pin length	2.79 mm
Pin base diameter	3.5 mm	Pin base diameter	8 mm	Pin base diameter	3.19 mm
Pin tip diameter	2.5 mm	Pin tip diameter	6 mm		

For each study, the processing parameters are presented in Table 5.

Table 5 –Process parameters

Process parameters	Study 1, EN AW 6061-O, 2.5 mm thickness [11]	Study 2, EN AW 6061-T6, 4 mm thickness [12]	Study 3, EN AW 6061-T6, 3.2 mm thickness [4]
Tool rotation speed (rpm)	1800; 3600; 5400	800	1000
Processing speed (mm/min)	60	40	0.42-1.69

2.2.3. Evaluation of processed materials

To evaluate the processed materials, it is necessary to take samples for structural analysis and hardness measurements, respectively specimens for mechanical testing. The samples for structural analysis require preparation by grinding and polishing, followed by etching with appropriate metallographic reagents.

Structural analyses for EN AW 6061 aluminum alloy related to studies 1 and 3 (thickness 2.5 mm in O condition and thickness 3.2 mm in T6 condition), show that processing in liquid working medium - water [4, 11], leads to the obtaining of refined microstructures compared to the microstructure of the base material (Figure 3).

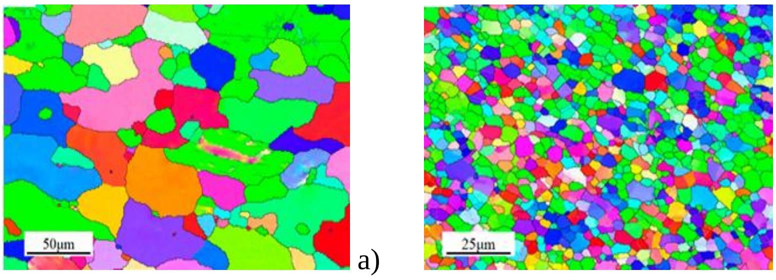


Figure 3 - Microstructures for base material (a) and processed material (b) [11]

In the case of the 4 mm thick EN AW 6061-T6 aluminum alloy (study 2), the use of different working/cooling media (air, cryogenic, and water) leads to refined microstructures. The resulting microstructure after processing and cooling in ambient conditions is refined (Figure 4a) compared to the base material, but processing in cryogenic working/cooling media and underwater, leads to even more refined microstructures, with even smaller grain sizes (Figure 4 b, c).

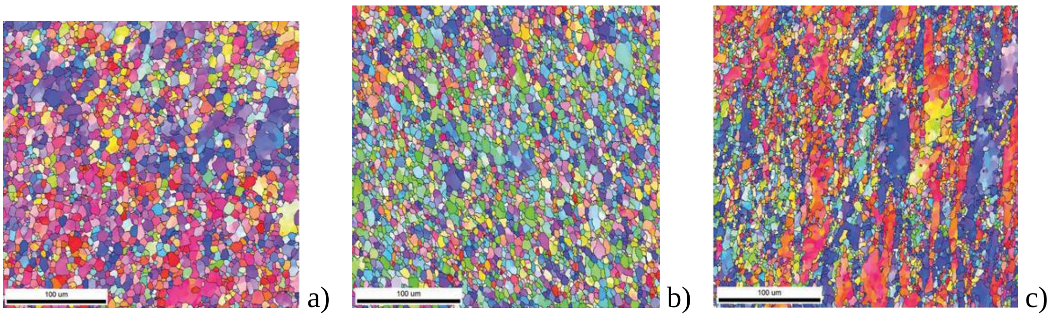


Figure 4 - Microstructures of processed material, with cooling in: a) air; b) dry ice; c) water [12]

Regarding the influence of the working medium on the microstructure, cryogenic cooling and water cooling ensure a rapid decrease in temperature of the processed material, prevent grain growth and contribute to the refinement of the microstructure. Comparing cryogenic cooling with water cooling, it is observed that when using dry ice on the surface of the processed material, the cooling effect consists mainly in reducing the heat in the area bordering the processing area, while when cooling with water the cooling effect is more consistent in the processed area. Studies have shown that the average grain size in the analyzed samples is influenced by the medium in which the cooling of the processed materials was carried out. Thus, in the sample taken from the processed material where the cooling was carried out in ambient conditions (Air Cooling FSP), the average grain size was 4.8 µm. In the case of cooling the processed material in a cryogenic medium (Cryogenic Cooling FSP) the grain size was 3.9 µm, and in the case of using water cooling (Water Cooling FSP) their size was 2.8 µm. It was observed that in the water-cooled samples the grain sizes were smaller compared to the other cooling media [12].

Hardness measurements for samples taken from processed materials (studies 1 and 3), show that the hardness in the processed zone (stir zone SZ) is higher than in the thermo-mechanically affected zones TMAZ (Figure 5).

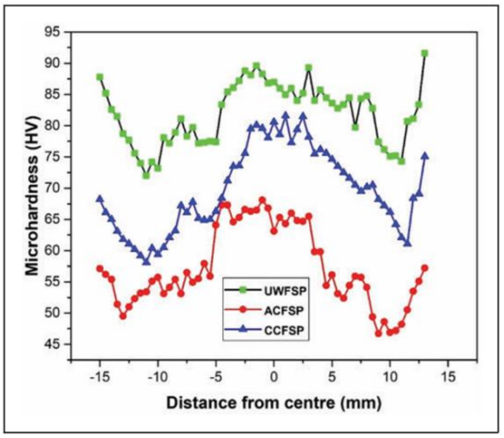


Figure 5 - Hardness variation in processed material, using different cooling media in FSP processing (air cooling - AC, cryogenic cooling CC, underwater processing UW) [12].

When cooling in the ambient conditions (AC-FSP air cooling), the cooling process of the processed material is slower, the temperature in the processed material decreases slowly, allowing the dimensional growth of the grains in the microstructure. Cryogenic cooling (CC-FSP) is applied to the surface of the processed material, contributing to the reduction of its cooling time, as well as the possibility of grain growth, contributing to an increase in hardness in the processed area compared to processing with cooling in ambient conditions (air). Underwater FSP processing (UW-FSP) leads to a rapid cooling of the processed material by the fact that it is immersed in water, cooling occurs on all surfaces of the processed material, avoiding grain growth (Figure 5). This results in a more refined microstructure, with very small grains, as well as a higher hardness of the processed area compared to the cases where cryogenic cooling and cooling in ambient conditions were used. In all cases it is observed that the hardness in the stir zone (SZ) is higher compared to the hardness of the thermo-mechanically affected zone (TMAZ), respectively compared to the hardness of the heat affected zone (HAZ), which is the lowest considering that the material in that zone is only exposed to a certain temperature level, without any mechanical action of mixing the material during the actual processing. Thus, a very good correlation is observed between the variation of hardness and the microstructures in the processed areas.

The tensile tests of the specimens taken from the processed materials addressed in the paper show that for different processing parameters, as well as for different processing conditions, stress-strain curves are obtained and from their analysis it can be seen which are the most favorable conditions for obtaining the best possible processing results (in terms of process parameters and cooling conditions). The stress-strain curves in Figure 6a show that the best results were obtained when using a tool speed of 3600 rpm. The use of different cooling/working mediums influences both the microstructure and the mechanical properties of the processed materials. The tensile strengths of the specimens taken from the materials processed in different working/cooling media (Figure 6b) follow a similar evolution to the variation of the hardnesses depending on the working/cooling media, being lower for air cooling (224 N/mm^2), higher for cryogenic cooling (240 N/mm^2) and highest for underwater processing (261 N/mm^2). The tensile strength for the base material is approx. 285 N/mm^2 (Figure 6b).

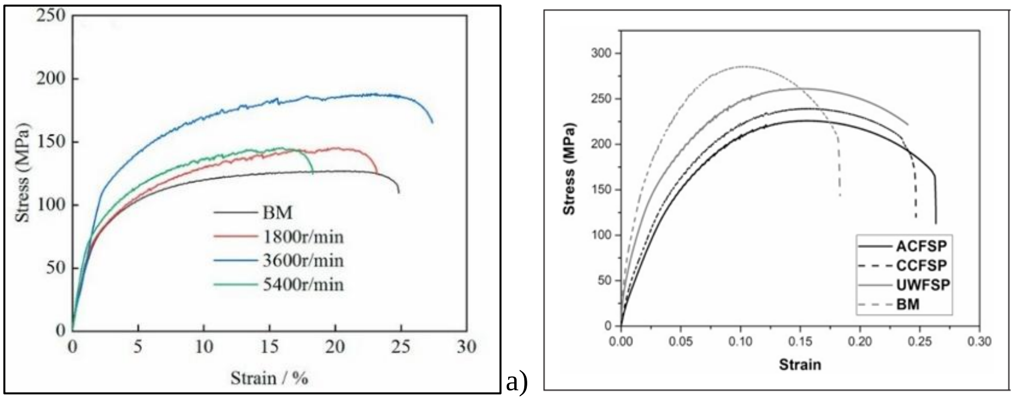


Figure 6 - Stress-strain curves for processed material, using different tool rotation speeds (a) and different cooling media (b) in FSP processing (air cooling AC, cryogenic cooling CC, underwater processing UW) [11].

Comparing the results of several researches on the processing of aluminum alloy 6061 [4], [10]-[17] it was observed that processing in liquid medium SFSP using a high rotation speed of the processing tool leads to obtaining better processed materials in terms of microstructure, hardness and tensile strength. A faster cooling of the processed material led to decrease of the elongation at break and ductility of the material decrease, the tendency being towards brittle fracture (Table 6).

Table 6 Tensile strength and elongation values for the processed material, under different working/cooling conditions [12]

	FSP processed material, air cooling (AC)	FSP processed material, cryogenic cooling (CC)	FSP processed material, underwater (UWFSP)
Tensile strength Rm (N/mm^2)	224	240	261
Elongation at break A (%)	26,2	24,6	24,0

A comparative analyze of the values in the table above shows that the highest value of breaking strength but also the lowest value of elongation at break has been achieved for material underwater processed.

3. CONCLUSION

Studies on the processing of EN AW 6061 aluminum alloy in the O and T6 conditions show that [11]-[13], [15], [16], [19]-[27]:

- If a high rotation speed is used when processing EN AW 6061-O, good mechanical properties can be achieved.
- If a processing tool with a small shoulder diameter is used, the amount of heat generated by friction can be increased by increasing its rotation speed, in correlation with the processing speed.
- Increasing of the rotation speed above certain values can lead to an excessive increase in the heat generated by friction and to the growth of grains, simultaneously with a decrease in the strength of the processed material.
- For the materials addressed in the paper (EN AW 6061-O and EN AW 6061-T6), the application of friction stir processing leads to the refinement of the microstructure in the processed area, through dynamic recrystallization, obtaining grains with small dimensions.
- The different cooling media used in processing contribute to the additional grains refinement, for underwater processing resulting smaller grain sizes compared to the other cooling media used.
- A microstructure with refined and recrystallized grains contributes to increasing the mechanical strength of the processed material, including salt water corrosion of the 6061-aluminum alloy.
- The analyzed studies show that the corrosion resistance of the FSP and SFSP processed areas is better than that of the base material, in the case of EN AW 6061-T6 this being better in the case of FSP processing compared to SFSP processing.

- When FSP processing in multiple passes of EN AW 6061-T6 with a tool rotation speed of 800 rpm and a processing speed of 40 mm/min, better corrosion resistance is achieved compared to single pass processing, due to the fine and homogeneous grains in the microstructure.
- The hardness variation in the processed area has a similar profile for all three media used (air cooling, cryogenic cooling and underwater processing), with lower values observed for air cooling under ambient conditions and higher values for underwater friction stir processing.
- In multiple-pass processing, the efficiency of water-cooling or in other conditions is also influenced by the temperature of the processed material between processing passes, before starting a new processing row.
- For the materials addressed, the tensile strength of the material underwater processed is higher compared to cases where cryogenic cooling or cooling in ambient conditions (air) is used. At the same time, for the materials addressed in these studies, the elongation at break has the lowest value for underwater friction stir processing and the highest value for cooling of the processed material in ambient conditions.
- Friction stir processing is useful for local modification of the characteristics and mechanical properties of metallic materials, without affecting the entire material and without melting it, the processing taking place in the solid state.

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