SUBMERGED FRICTION STIR PROCESSING OF EN AW 7075 ALUMINUM ALLOY

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ABSTRACT: Friction stir processing is a process for processing metallic materials that aims to locally modify the microstructure and mechanical properties. Submerged friction stir processing aims to limit the process temperature by using a liquid working medium, so as to avoid thermal overloading of the processing tool and the materials to be processed. The paper presents experimental research carried out at ISIM Timisoara on submerged friction stir processing for the 5mm thick EN AW 7075 aluminum alloy. Processing experiments were carried out in single pass and in multiple passes, with positive results. The evaluation program of samples/test pieces taken from the processed materials included visual examination and penetrating radiation, macro- and microscopic structural analyses, as well as mechanical tensile and bending tests.
KEYWORDS: submerged friction stir processing SFSP, EN AW 7075 aluminum alloy, single and multiple passes, structural analysis, mechanical properties.

1. INTRODUCTION

Friction stir processing is an ecological, modern and versatile method of processing metallic materials. It is an area of interest for scientific research, as well as for specialists from leading industries, in order to know the process and its particularities, to analyze the possibilities and limits of application to a wide range of metallic materials and of specific applications [1-14].

Derived from friction stir welding (FSW), friction stir processing (FSP) has the same process principle and uses the same working equipment. The difference is that the process does not join materials, but is applied only to a material with the aim of locally modifying its microstructure and mechanical properties on limited areas.

In both FSW welding and FSP processing, the process takes place in the solid-state, below the melting temperature of the processing materials [5], [7-9], [13, 15, 16]. The processing tool is positioned along the processing line, rotates around its axis at a preset speed, the tool pin penetrates the material to be processed until firm contact is made between the tool shoulder and the upper surface of the material to be processed, at which point the tool begins to move along the processing line at the set processing speed.

The tool speed, processing speed, number of processing passes and the working medium are factors that influence the amount of heat released in the process and the plasticization of the material to be processed, with effects on the microstructure and mechanical properties of the material in the processed area [2, 3, 6, 7, 9, 12], [16-18].

Over time, research in the field of friction stir welding and friction stir processing have evolved, with variants being developed to help improve processes and results [5, 7, 9, 11, 16, 19].

Submerged friction processing (SFSP) is a processing variant that aims to limit the process temperature to avoid excessive heating of the tool and the material to be processed in the processing area. This can increase the service life of the processing tools and minimize/avoid material deformation during processing [4-10], [13, 15, 16], [19- 22].

The possibilities of applying friction stir processing in different working mediums are analyzed through experimental research carried out for various categories of materials, aluminum alloys being the most used [1-37].

The EN AW 7075 (AlZn5.5MgCu) aluminum alloy is a heat-treatable alloy, known for its excellent tensile strength and frequently used in aeronautical and automotive applications, where strength and durability are critical.

The aluminum alloy EN AW 7075 (Al-Zn-Mg-Cu) is widely used in the aerospace and nuclear industries, due to its high strength and low weight. It is used for structural elements that are designed under the influence of severe requirements regarding their weight and strength, components in the aircraft structures and application in the military field subjected to high loads, ball bearings, tools, highly demanded sports equipment, assembly elements, components for various industrial equipment, etc. [4, 6, 8, 9], [17-37].

Being areas of interest for the joining and processing of metallic materials, friction stir processes represent a research direction for ISIM Timișoara, experimental research being carried out on the submerged friction stir processing SFSP of the 5 mm thick EN AW 7075 aluminum alloy.

2. PROCESSING EXPERIMENTS AND PROCESSED MATERIAL EVALUATION

2.1 Material to be processed

For the SFSP processing of the rolled aluminum alloy EN AW 7075, sheets of size 200x200x5mm were used, with the same experimental conditions in terms of the material to be processed, the liquid working medium and the geometry of the processing tool. The SFSP processing was performed in a single pass, as well as in multiple passes. Table 1 presents the chemical composition of the EN AW 7075 aluminum alloy determined using an optical emission spectrometer (OES, Hitachi OE720 type).

Table 1. Chemical composition of EN AW 7075 aluminum alloy

Al (%)	Zn (%)	Mg (%)	Cu (%)	Cr (%)	Fe (%)	Si (%)	Others, total (%)
90.15	5.55	2.20	1.44	0.24	0.17	0.08	0.17

Table 2 shows values of hardness, tensile strength and bending angle for the EN AW 7075 aluminum alloy as a base material (unprocessed), determined using new and high-performance equipment from ISIM Timișoara.

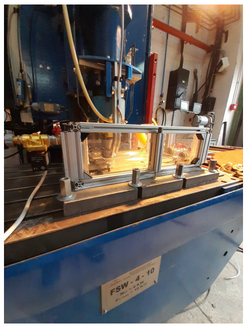
Table 2. Mechanical properties for EN AW 7075 aluminum alloy, 5mm thick

Material	Average hardness value HV1	Tensile strength R_m (N/mm^2)	Static bending test α [°], for 2 specimens
EN AW 7075	171	539	48°and 57°

2.2 Equipment and processing tool

For the experimental research program of SFSP (Submerged Friction Stir Processing), the FSW 4-10 welding machine (figure 1a) from ISIM Timișoara was used, on which appropriate modules and elements were mounted to allow the use of the liquid working medium in processing. The processing tools used in the experimental program were made of C45 steel, the pin having conical shape with four flat chamfers (figure 1b).

To carry out the experimental processing program and evaluate the processed materials compared to the base material, several high-performance equipment from ISIM's endowment was used, which were purchased to develop the research infrastructure:
- OMAX Maxiem 1530, waterjet and abrasive cutting equipment, for dimensional preparation of materials to be processed, extraction of samples (from processed and unprocessed material) for structural analysis and specimens for mechanical testing,
- Qpol 250A2-ECO, machine for grinding and polishing samples for structural analysis,
- OES Hitachi OE720, optical emission spectrometer for chemical analysis,
- Nikon SMZ745 with MshOt camera, optical microscope for macroscopic analysis,
- XJP-6A with Dino-lite camera, microscope for microscopic analysis,
- LabTest 6.100, 100kN universal machine for mechanical testing.



a)


b)

Figure 1. FSW 4-10 welding machine (a) and tool geometry used for processing (b)

2.3 Experiments. Evaluation of the processed material

The experimental research program aimed at the submerged (underwater) processing, in single pass and in multiple passes, of the EN AW 7075 aluminum alloy, in the form of a sheet of 5mm thickness and dimensions 200 mm x 200 mm. The SFSP processing experiments were carried out under the same conditions in terms of working equipment, tool and processing parameters, according to the data in Table 3.

Table 3. Tool data and SFSP processing parameters of EN AW 7075 aluminum alloy, 5mm thickness

Processing tool		
	Tool material	C45 steel
	Tool shoulder	Flat, 22 mm diameter
	Pin geometry	Conical with 4 flat chamfers
	Pin length L_{pin}	3.86 mm
Processing parameters		
	Tool rotation speed, n	2400 rpm
	Processing speed, v	100 mm/min
	Rotation direction	counterclockwise

The processing was performed in two variants: in a single pass (Exp.20AC), but also in five passes (Exp.11AC), the step between passes being 3mm, in correlation with the dimensions of the pin of the processing tool. The step value between multiple passes directly influences the quality of the processed material. Too large step between passes leads to the alternation of processed areas with unprocessed areas, affecting the homogeneity of the microstructure and the mechanical properties of the processed area.

After processing, the plates of processed material were visually analyzed and examination with penetrating radiation (according to SR EN ISO 17636-1:2022) was performed using an X-ray examination device with an ERESCO 42MF2 radiation source.

Figures 2 and 3 show the surface appearance of the material processed in one pass and in multiple passes, as well as the X-ray images related to these submerged (underwater) processing experiments, for the EN AW 7075 aluminum alloy. Analyzing figures 2a and 3a, the uniform appearance of the processed areas is observed, without defects and with constant width. On the X-ray images (figures 2b and 3b) it is observed that in both processing variants (in a single pass and in multiple passes), the processed material is homogeneous, without defects, variations in appearance or width of the processed rows.

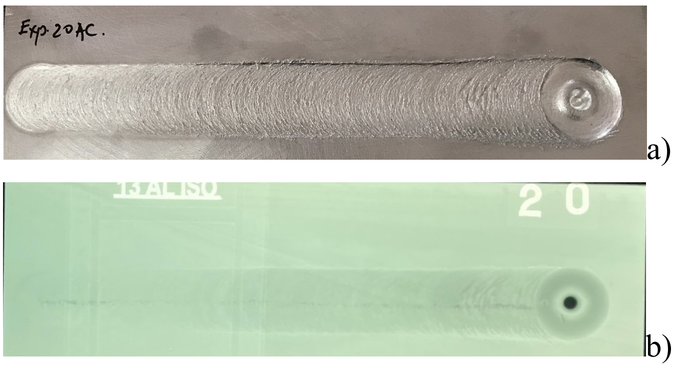


Figure 2. Processed surface appearance (a) and X-ray image (b), EN AW 7075 alloy SFSP processed in a single pass

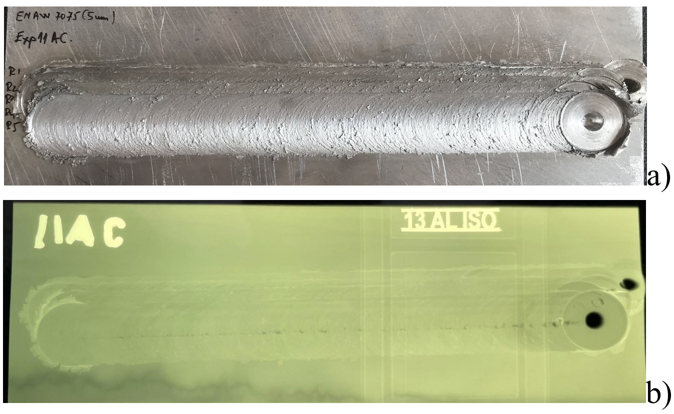


Figure 3. Processed surface appearance (a) and X-ray image (b), EN AW 7075 alloy SFSP processed in multiple passes

The monitoring of the working process was carried out through the temperature of the liquid working medium (water), following the initial temperature of the water introduced into the enclosure before the start of processing, respectively the value of the water temperature after processing. The values of the water temperature in the enclosure, before and after processing are presented in table 4.

Table 4. Liquid medium temperature values before/after each processing row

Experiment No.	Water temperature, ^{0}C		Row no.
	initial	final	
Exp. 20AC, 1 pass	16	26	R1
Exp. 11AC, 5 passes	16	24; 25; 25; 27; 29	R1, R2, R3, R4, R5

During multiple-pass processing, minor increases in the temperature of the working environment are observed, related to the processed rows R1-R5, without producing significant thermal fluctuations or affecting the quality of the surface of the processed material. An average water temperature of approx. 26°C is obtained in the SFSP processing chamber, as in single-pass processing, which shows that the material was not subjected to a more intense thermal regime in the case of multiple-pass processing.

To evaluate the SFSP processed material in multiple passes, samples necessary for structural analyses, as well as specimens for mechanical tests, were taken (by water jet cutting). The samples were prepared by grinding and polishing, for structural analyses and hardness measurements. The results of the macroscopic analysis (in accordance with SR EN ISO 17639:2022, respectively SR EN ISO 6520-1:2007) for samples taken from materials processed in one pass, as well as in multiple passes, are presented in Figure 4.

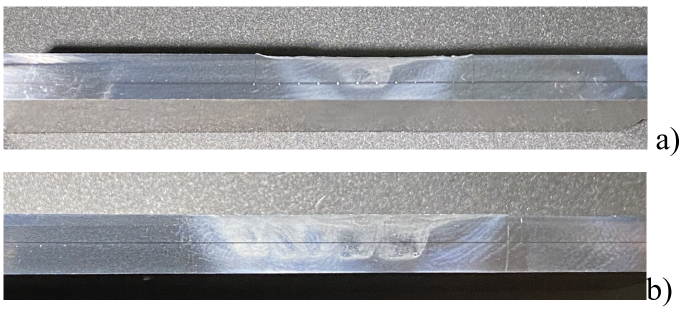


Figure 4. Macroscopic analysis of SFSP processed material samples: a) single pass; b) five passes

The macroscopic analysis for the material processed in a single pass (figure 4a) shows that the processed material area is compact and without defects, consistent with the X-ray image (figure 3a). In the case of the material processed in multiple passes (figure 4b), the macroscopic analysis shows a good processed material, with a compact appearance, with well-consolidated rows/passes, without defects in the area related to the processed rows, consistent with the image on the radiographic film (figure 3b). The step between passes was chosen appropriately so that no discontinuities of processed material (alternations of processed and unprocessed material) appear.

Microscopic analysis (in accordance with SR EN ISO 17639:2022 and SR EN ISO 6520-1:2007) of samples extracted from the processed materials shows the change in the appearance of the microstructure and the refinement of the grain size in the processed material (figure 5 b, d) compared to the microstructure of the base material (figure 5 a, c), both in the case of single-pass processing (figure 5b) and in the case of multiple-pass processing (figure 5d).

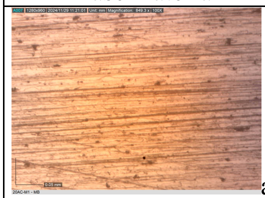
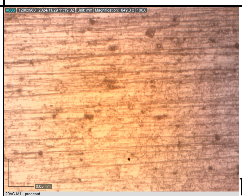
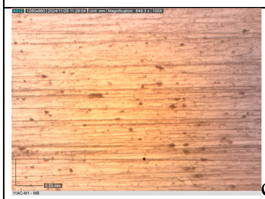
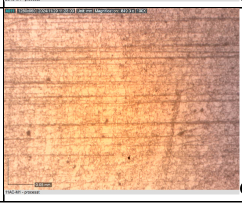
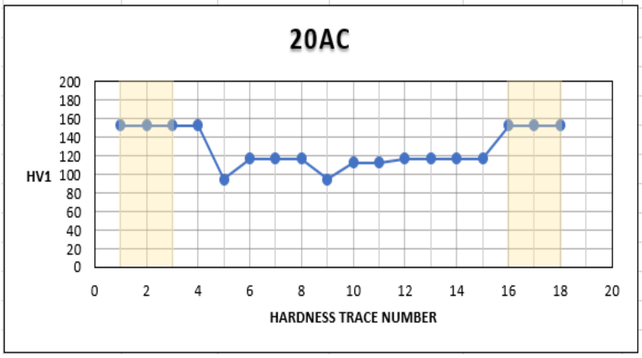
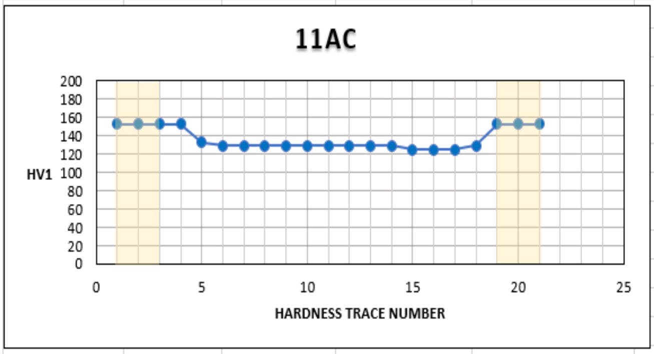
Base material	Processed material	Exp. No.
 a)	 b)	Exp. 20AC Single-pass processing
 c)	 d)	Exp. 11AC Five passes processing

Figura 5. Microscopic analysis aspect for samples taken from base material and processed material (100x)

The evaluation of the processed materials included HV1 hardness measurements in the cross-section of their processed area (in accordance with SR EN ISO 6507-1:2023 and SR EN ISO 9015-1:2011), on the midline of the material thickness. The step between the hardness measurements was 2 mm, targeting both the processed area and the base material area. The hardness values for samples taken from the materials processed in a single-pass (Exp.20AC) and in five passes from (Exp.11AC) are presented in figure 6. The marked areas at the ends of the hardness variation graphs represent 3 measured values for the hardness of the base material. For the base material, hardness values of 153 HV1 were measured. It is observed that the hardness in the processed material area decreases compared to the base material, for both analyzed samples. The average hardness values of the processed material are presented in Table 5. The average hardness of the material processed in a single-pass (116 HV1) and that of the material processed in 5 passes (130 HV1) represent approximately 76% and 85% of the hardness of the base material, respectively.



a)



b)

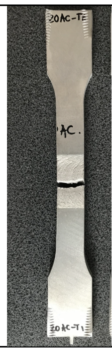
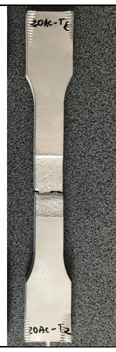
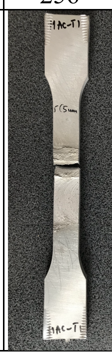
Figure 6. Graphs of hardness variation, processed materials

Table 5. Average hardness values in the processed areas

Sample No.	Exp 20AC 1-pass processing	Exp.11AC 5-passes processing
Average hardness	116 HV1	130 HV1

Mechanical tensile tests were performed on specimens taken from the processed materials, but also from the base material, the results being presented in Table 6.

Table 6. Tensile test results, SFSP processing

Tensile test, SR EN ISO 6892-1:2020 EN AW 7075, 5 mm thick, SFSP processed				
Equipment: Universal Machine 100 KN, LabTest 6.100; Digital caliper, KS Tools; CEM digital thermohygrometer				
Test temperature: 23^0C, ambient environment				
Specimen no.	20AC-T1	20AC-T2	11AC-T1	11AC-T2
Tensile strength R_m (N/mm^2)	230	283	256	266
				

The average value of the tensile strength for specimens taken from the material processed in one pass (Exp. 20AC) is Rm = 257 N/mm^2 and Rm = 261N/mm^2 for specimens from the material processed in multiple passes (Exp.11AC).

For both processing experiments, static bending tests (according to SR EN ISO 5173:2023 and SR EN ISO 7438:2020) were performed with both the stretched upper surface (of the processed material) and the stretched lower surface (root), on specimens taken from the SFSP processed areas and from the base material. The result of these tests is presented in Figure 7.

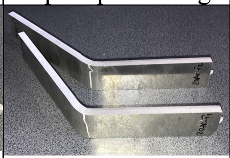
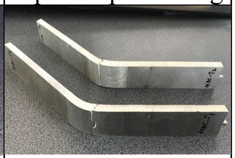
Base material	1-pass processing	5-passes processing
		
a)	b)	c)
BM-I1, 48^0 BM-I2, 57^0	20AC-I1,54^0, TRBB 20AC-I2,34^0, TRBB	11AC-I1,49^0, TRBB 11AC-I2,43^0, TFBB

Figure 7. Bending tested specimens: a) base material; b) 1 pass processing; c) 5 passes processing

For the specimens taken from the base material, it is observed that during the bending test, they cracked at bending angles of 48^0 and 57^0 (figure 7a). During the bending test (with the TRBB stretched root) of the samples taken from the material processed in one pass, they cracked at angles of 54^0 and 34^0, respectively (figure 7b). During the bending test (with the TRBB stretched root and the TFBB stretched surface) of the specimens taken from the material processed in multiple passes, the results show that they cracked at bending angles of 49^0 and 43^0, respectively (figure 7c), observing that the bending behavior being similar to that of the base material (figure 7a).

3. CONCLUSIONS

- Visual analysis of materials processed in one pass and in multiple passes shows the uniform appearance of the processed areas, without defects and with constant width.
- X-ray images highlight a homogeneous processed material, without defects, no variations in appearance or width of the processed rows, in both processing variants (in one pass and in multiple passes).
- Macroscopic analysis shows that the processed material area is compact and without defects for the material processed in a single pass. In multiple pass processing, the correct choice of the step between passes led to the obtaining of a compact processed material, with well-consolidated rows, without discontinuities or alternations between processed and unprocessed material, respectively without defects in the area related to the processed rows.
- At the microstructural level, refined grains are observed compared to the microstructure of the base material, both in single-pass and multiple passes processing.
- The temperature of the liquid medium after the completion of each processed row in multi-pass processing has minor increases that do not produce significant thermal fluctuations and do not affect the quality of the surface of the processed material. The water temperature values in the working enclosure after each processed row show that the processed material was not subjected to a more intense thermal regime in the case of multiple passes processing, compared to single-pass processing.
- The hardness values in the processed area, measured on the median line of the material thickness, show decreases compared to the base material, for both analyzed samples (single-pass and multiple passes processing). In the case of multiple passes processing, an increase of approx. 12% of the average hardness value is observed compared to single-pass processing.
- In the tensile test, the average values of the tensile strength for the specimens taken from the materials processed in one pass (Rm = 257 N/mm^2) and in multiple passes (Rm = 261 N/mm^2) were close.
- The results of the static bending tests show that in both processing cases (1 pass and 5 passes) the bending behavior (with the stretched root and with the stretched surface) of the specimens taken from the processed materials was similar to that of the base material.
- Friction stir processes are current and require studies and complex research to investigate the possibilities of use in a wide range of metallic materials, in order to identify and develop applications of these processes in various industrial fields.

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