©2026 Romanian Association of Nonconventional Technologies

ASPECTS REGARDING FRICTION STIR PROCESSING IN TWO WORKING MEDIUMS OF EN AC 5083 CAST ALUMINUM ALLOY

Lia-Nicoleta Boțilă[1], Ion-Aurel Perianu[2], Iuliana Duma[3] and Gabriela-Victoria Mnerie[4]
[1] National R&D Institute for Welding and Material Testing - ISIM Timisoara, 30 Mihai Viteazu Blv., *Corresponding author*, ORCID No. 0000-0003-4680-0559, lbotila@isim.ro
[2] National R&D Institute for Welding and Material Testing - ISIM Timisoara, 30 Mihai Viteazu Blv., ORCID No. 0000-0002-0684-0372, aperianu@isim.ro
[3] National R&D Institute for Welding and Material Testing - ISIM Timisoara, 30 Mihai Viteazu Blv., ORCID No. 0000-0002-1366-4776, iduma@isim.ro
[4] National R&D Institute for Welding and Material Testing - ISIM Timisoara, 30 Mihai Viteazu Blv., ORCID No. 0000-0001-7799-5307, gmnerie@isim.ro

ABSTRACT: One of the materials processing processes, currently in use by researchers and at an international industrial level, is Friction Stir Processing (FSP), an innovative solid-state processing process for the surfaces of metallic materials, developed from the friction stir welding process FSW. The FSP process is environmentally friendly and versatile, used for local processing, on well-defined areas, of the surfaces of metallic materials used in various applications. An interesting FSP processing method is the one in which the process takes place in a liquid working medium. Due to the water used as a working medium, the process temperature can be better controlled, avoiding excessive heating of the processing tool and the material to be processed, thus increasing the service life of the processing tool. Cast aluminum alloys are found in various industrial applications. The cast aluminum alloy EN AC 5083 has good mechanical properties, corrosion and chemical resistance, with applicability in the shipbuilding, aeronautics, automotive, chemical industries, etc. The paper presents results of experimental research carried out at ISIM Timișoara on friction stir processing in two different working mediums (underwater - SFSP and in ambient environment - FSP), in one pass and in multiple passes, of the cast aluminum alloy EN AC 5083 of 5 mm thickness. A comparison of the results obtained after evaluating the processed material by visual examination, with penetrating radiation, structural analysis, mechanical tensile and static bending tests is also presented, these being more favorable in underwater processing conditions.

KEYWORDS: friction stir processing FSP, submerged friction stir processing SFSP, EN AC 5083 cast aluminum alloy, experiments, structural analysis, mechanical properties.

1. INTRODUCTION

Friction stir processing (FSP) is along with other modern techniques, an advanced solid-state machining method for metallic materials, derived from friction stir welding, which is based on the generation of heat by friction between a non-consumable tool and the material surface. This heat causes localized plasticization and plastic deformation, with the aim of modifying the microstructure and improving the material properties in well-defined areas [1-20].

The FSP technique is intensively studied for its applicability to aluminum alloys and other metallic materials, the impact of processing on the microstructure and post-processing mechanical characteristics being analyzed. The aim is to obtain homogeneous, fine-grained microstructures, leading to superior mechanical properties [1-20].

An important advantage of this method lies in its environmental friendliness: it does not involve the use of consumables and does not generate harmful emissions or radiation. FSP can also be applied in a liquid medium, by immersing the material in water, which contributes to the thermal control of the process and prevents overheating of the tool [1, 3, 5, 7, 10, 12, 15].

Cast aluminum alloys are found in applications in various industrial fields. The EN AC 5083 cast aluminum alloy has good mechanical properties, corrosion resistance and chemical resistance, with applicability in the shipbuilding, aeronautics, automotive, chemical industries etc. [3, 5, 7, 12].

Within ISIM is underway a research project that addresses the processing of FSP under ambient conditions and liquid medium for aluminum alloys. In this context, experimental processing research was carried out on EN AC 5083 cast aluminum alloy sheets, in order to evaluate the behavior of the material under different processing conditions.

2. EXPERIMENTAL PROGRAM. EVALUATION OF THE PROCESSED MATERIAL

2.1 Material to be processed

The experimental research of processing was carried out on 5 mm thick EN AC 5083 cast aluminum alloy sheets with the chemical composition presented in

Table 1. Table 2 show the average values of tensile strength and static bending test results for this aluminum alloy, as base material, experimentally determined at ISIM Timisoara.

Table 1. Chemical composition - EN AC 5083 aluminum alloy

Al (%)	Mg (%)	Mn (%)	Fe (%)	Si (%)	Cr (%)	Cu (%)	Zn (%)	Others, total (%)
94.10	4.53	0.48	0.38	0.27	0.07	0.05	0.04	0.08

Table 2. Mechanical properties (average values) of base material EN AC 5083 cast aluminum alloy, 5 mm thickness

Material	Average hardness value HV1	Tensile strength R_m (N/mm^2)	Bending angle α [°]
EN AC 5083	73	220	51-53

2.2 Equipment and processing tool

For the experimental research program of submerged (underwater) friction stir processing, equipment from ISIM were used (Figure 1):

- FSW 4-10 welding machine (Figure 1a) for FSP processing (under ambient conditions), equipped with specific modules for SFSP processing in a liquid medium (Figure 1b);
- processing tool with square pin (Figure 1c);
- X-ray control equipment with ERESCO 42MF2 radiation source;
- OMAX Maxiem 1530 water jet and abrasive cutting equipment (Figure 1d) for cutting to size the materials to be processed and for taking samples and specimens necessary for the evaluation program of the processed materials;
- OES optical emission spectrometer, Hitachi OE720 C type for determining the chemical composition of the base material used in the experiments (Figure 1e);
- Qpol 250A2-ECO type grinding and polishing machine (Figure 1f) to prepare metallographic samples for structural analysis;
- XJP-6A microscope with Dino-lite camera (Figure 1g) for microscopic examination;
- Nikon SMZ745T optical microscope with MshOt camera (Figure 1h) for macroscopic analysis;
- Zwick 3212 equipment for hardness measurement in the base and processed material;
- 100 kN universal machine type LabTest 6.100 (Figure 1i), for tensile and bending tests of the EN AC 5083 aluminum alloy, as base material and as processed material.

The processing tools used in the experimental research program for SFSP and FSP processing of 5 mm thick EN AC 5083 cast aluminum alloy were made of X38CrMoV5 (H11) steel and C45 steel.

All processing tools used for experiments have smooth shoulder of 22 mm diameter, square pin (Figure 1c) and pin length (L_{pin}) of 3.7-3.8 mm, in correlation with the thickness of the materials to be processed.

Figure 1. Equipment used in processing and evaluating processed material

2.3 Experimental program and evaluation of the processed material

Table 3 shows the proposed structure and the range of processing parameters for the experimental research program of processing in two different working mediums (underwater-SFSP and under ambient conditions-FSP, respectively) of the 5 mm thick EN AC 5083 cast aluminum alloy.

Table 3. Proposed range for SFSP/FSP processing parameters

Processing tool pin geometry	Tool rotation speed (rpm)	Processing speed (mm/min)	Tool rotation direction	No. of processing passes, pitch (mm)
Square	2400-3000	50-100	counter-clockwise	1 pass / multiple passes, pitch 4

In order to analyze the changes that occur after processing, the results for SFSP and FSP processing will be compared, also taking into account the data on the microstructure and mechanical properties of the base material (unprocessed). The evaluation and characterization plan for SFSP and FSP processed materials includes visual examination and X-ray control of the processed materials, micro and macroscopic analyses, hardness measurements, mechanical tensile and static bending tests.

For the experimental research program of SFSP and FSP processing of cast aluminum alloy EN AC 5083, 5 mm thick sheets with dimensions of 200 mm x 200 mm were used. The processing was performed, as appropriate, in a single pass, as well as in multiple passes with partial overlap of the processing rows, the pitch between passes being 4 mm in correlation with the processing tool pin dimensions, as to ensure compact rows of processed material, without discontinuities between them, across the thickness of the material. Data regarding tool material and tool geometry used for experiments are presented in Table 4. The SFSP and FSP processing parameters used for each experiment are presented in Table 5.

Table 4. Tool material and tool geometry used in SFSP/FSP experiments of EN AW 7075 aluminum alloy, 5mm thickness

Exp. No., processing type	Tool			
	Material	Pin type	Pin length L_{pin} (mm)	Type/shoulder diameter $Ø_{shoulder}$ (mm)
Exp. 1 (SFSP)	Steel H11 (X38CrMoV5)	square	3.8	smooth, 22
Exp. 2 (SFSP)				
Exp. 3 (SFSP)	Steel C45		3.73	
Exp. 4 (FSP)				

Table 5. Technological process parameters for Exp.1-Exp 4

Exp. No., processing type	Process parameters			
	Tool rotation speed n (rpm)	Processing speed v (mm/min)	Tool rotation direction	Row No.
Exp. 1 (SFSP)	2400	70	counter-clockwise	R1
Exp. 2 (SFSP)	3000	100		R1
	2400	70		R2-R5
Exp. 3 (SFSP)	2500	50		R1
Exp. 4 (FSP)	2400	70		R1

The surface appearance of the processed samples, for the experiments in Table 5, is shown in Figure 2.

Figure 2. Surface appearance of processed EN AC 5083 aluminum alloy

The images in Figures 2a and 2b shows the uniform appearance of the processed surfaces, with a constant width imprint of the tool shoulder on the surface of the processed material, without visible defects, which indicates the stability of the work process, without variations during processing. The images in Figures 2c and 2d shows a relatively uniform appearance of the processed material area, but also an inconsistent operation of the equipment in terms of tool pressure/depth of penetration of the tool into the material to be processed.

The images from the radiographic films related to the evaluation by X-ray control of the processed materials are shown in Figure 3.

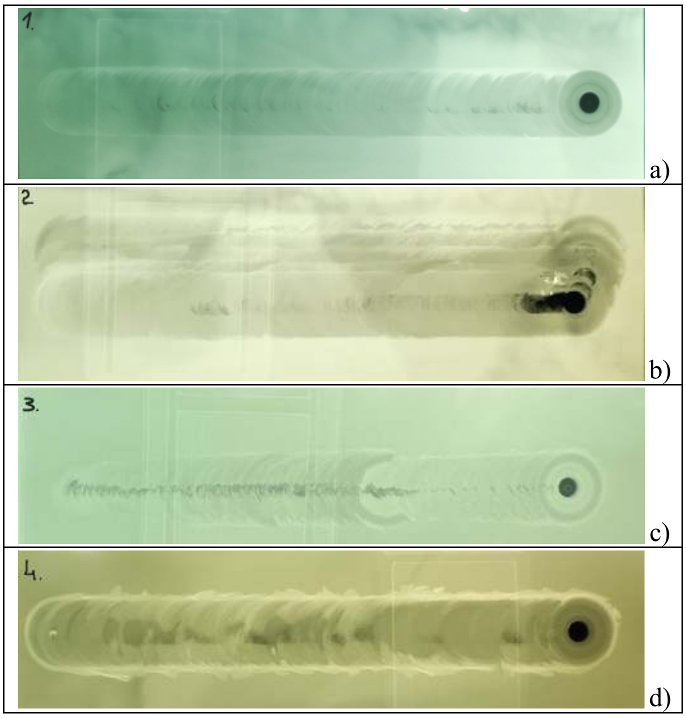


Figure 3. Radiographic film image for processed EN AC 5083 aluminum alloy

The analysis of the radiographic films presented in Figure 3 highlights the correlation with those presented regarding the appearance of the joint. Thus, it is observed that for Exp. 1 (Figure 3a), the processed material does not present defects, has no variations in appearance or width of the area where the tool shoulder interacts with the surface of the material to be processed. For Exp. 2 (Figure 3b), at the end of the last row of the processed material, a defect is observed in the area near the keyhole. The inconsistent functioning of the work equipment during processing is also reflected in the X-ray images related to the last two processing experiments (Figure 3c and Figure 3d), in correlation with the corresponding images in Figure 2.

The monitoring of the SFSP working process was carried out from the point of view of the temperature of the liquid working medium (water), considering the initial temperature of the water introduced into the enclosure before the start of processing and the value of the water temperature after processing, respectively. These water temperature values are presented in Table 6.

Table 6. Water temperature before/after SFSP processing

Exp. No	Processing parameters			Water temperature °C		Row No.
	Tool rotation speed n (rpm)	Processing speed v (mm/min)	Rotation speed / processing speed ratio n/v	initial	final	
Exp.1	2400	70	34	24	35	R1
Exp.2	3000	100	30	24	39	R1
	2400	70	34	24	35	R2-R5
Exp.3	2500	50	50	11	31	R1

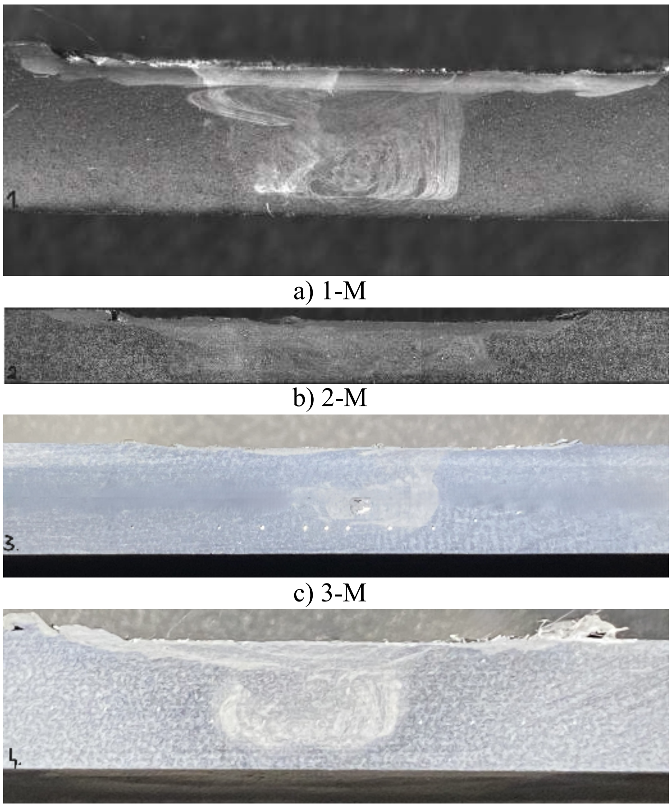
For experiments Exp.1 and Exp. 2, the initial temperature of the water, used as the liquid working medium, was 24°C. In Table 6 it can be seen that for Exp. 1 the value of the water temperature in the enclosure increased by 11°C, from 24°C at the beginning of the process, to 35°C, at the completion of the processing. In Exp. 2 the value of the water temperature in the enclosure reached 39°C, at the completion of the processing of row R1. The surface appearance of the first processed row R1 showed a too high processing speed and improperly plasticized material, which has determined to change the process parameters. Thus, the tool rotation speed was modified from 3000 rpm to 2400 rpm and the processing speed was reduced from 100 mm/min to 70 mm/min, the ratio between speed and processing speed changing from 30 to 34. Using these parameters, the water temperature at the end of each processed row R2-R5 had the same value of 35°C, which shows the process stability and repeatability.

The initial water temperature for Exp. 3 was 11°C at the beginning of the process, reaching 31°C at the end of the processing. Increasing the tool rotation speed from 2400 rpm to 2500 rpm and reducing the processing speed from 70 mm/min to 50 mm/min (Exp.3, compared to Exp.1) means a ratio between rotation speed and processing speed of 34 (in Exp.1) and 50 (in Exp.3). These ratios influence the process and the mechanical properties of the processed materials. From the point of view of the process temperature, a higher ratio between tool rotation speed and processing speed means a higher amount of heat generated in the process. As a result, the process temperature in the case of Exp. 3 is higher compared to Exp.1, which is highlighted by the range of increase in the temperature of the water used as the working medium. According to the data in Table 6, in Exp. 1 the water temperature increased by 11°C at the end of the process, and in Exp. 3 this range was 20°C.

For Exp.4, the FSP processing was carried out at an ambient temperature of about 18°C.

The evaluation plan for the samples and specimens taken from the processed SFSP and FSP materials (related to Exp. 1, Exp. 2, Exp. 3 and Exp. 4) included structural analyses (micro and macroscopic), hardness measurements, tensile tests and static bending tests. The samples and specimens for evaluation were taken by the modern water jet cutting method, being subsequently ground/polished for structural analysis, respectively prepared for mechanical tests [17, 18].

The macroscopic appearance of the samples taken from the SFSP and FSP processed material plates, related to Exp. 1- Exp. 4 are presented in Figure 4.



a) 1-M

b) 2-M

c) 3-M

d) 4-M

Figure 4. Analysis of the macroscopic sample of the SFSP and FSP processed material (Exp. 1-4)

Macroscopic analysis for samples 1-M (Figure 4a, Exp.1) and 3-M (Figure 4c, Exp.3) taken from SFSP processed materials in one pass and 4-M (Figure 4d, Exp.4) taken from FSP processed material, highlights the well-consolidated processed material area on the material thickness, no defects, which indicates good plasticization and mixing of the material to be processed. Macroscopic analysis for sample 2-M (Figure 4b, Exp.2) taken from SFSP processed material in 5 passes shows that the processed area is compact, without discontinuities between the rows of the processed material, being in correlation with the related X-ray image.

The microscopic appearance of the EN AC 5083 cast aluminum alloy samples of 5 mm and 6 mm thickness, SFSP processed (Exp. 1, Exp. 2, Exp. 3) and FSP processed (Exp. 4) is presented in Figure 5. For each analyzed sample, the microstructure in the area of the base material as well as in the area of the processed material can be observed. The images related to the processed material areas show differences compared to the base material, the refinement of the casting structure is observed, the microstructure of the processed material being more homogeneous, with fine grains and flow lines of the plasticized material during processing are visible.

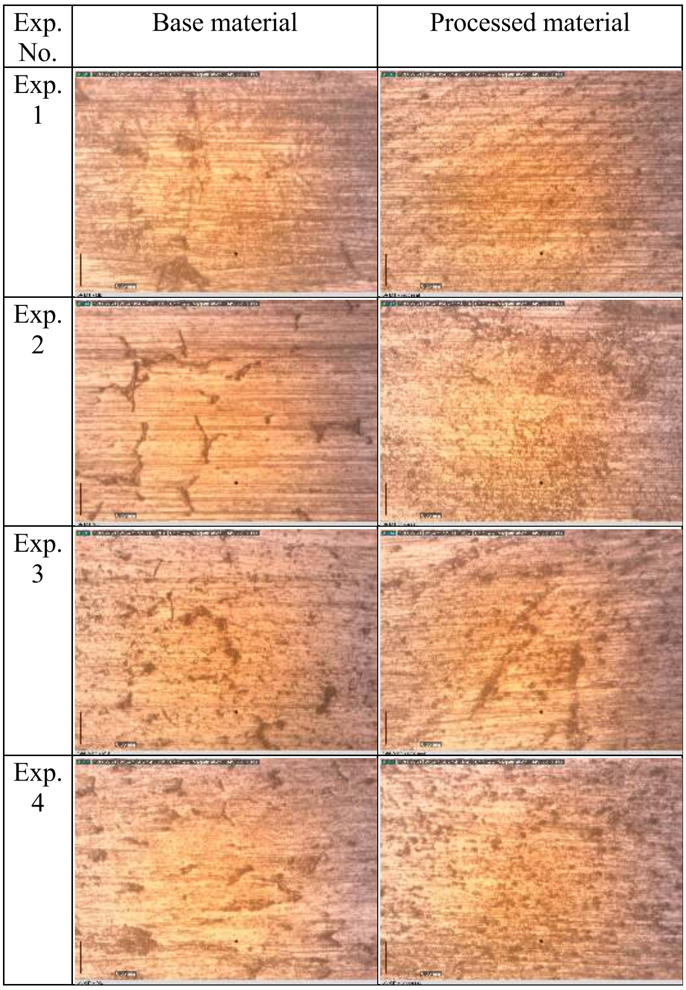


Figure 5. Microscopic analysis appearance, samples taken from Exp. 1-Exp. 4 (100x)

The HV1 hardness measurements for the base material and the processed area were performed in the section of the samples taken, on the midline with a step of 2 mm between measurements. The hardness variation graphs are presented in Figure 6. For each sample, the hardness of the base material was determined in 3 points, in the marginal areas marked on the graphs. For the analyzed samples, the hardness in the base material area was 72 HV1 and 64 HV1, the differences being probably caused by non-uniformities and inhomogeneities in the structure of the base material. In the processed area, the hardness is between 72-79 HV1 (Exp.1), 71-82 HV1 (Exp.2), 64-72 HV1 (Exp.3) and 69-82 HV1 (Exp.4).

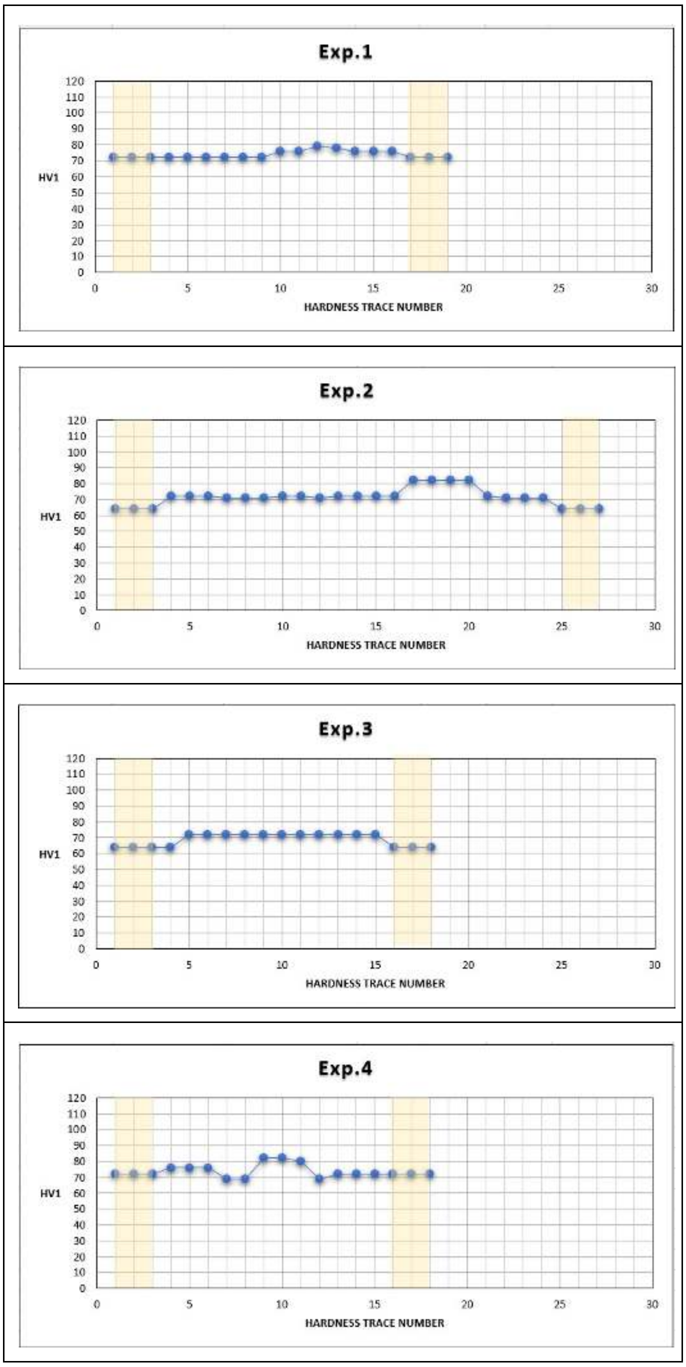


Figure 6. Graphs of hardness variation of processed materials, Exp.1-Exp.4

The average hardness values of the processed material for each analyzed sample are presented in Table 7.

Table 7. Average hardness values in processed areas

Experiment No.	Exp.1	Exp.2	Exp.3	Exp.4
Average hardness in the base material area	72 HV1	64 HV1	64 HV1	72 HV1
Average hardness in the processed material area	75 HV1	74 HV1	72 HV1	75 HV1

Analyzing the hardness variation graphs for samples extracted from the processed sheets of the materials (Figure 6), a minor increase in hardness was observed in the processed areas compared to the hardness of the base material. Also, the data in Table 7 show for each experiment, an increase in the average hardness values in the processed areas compared to the base material area (of approx. 4% in Exp.1, 16% in Exp.2, 13% in Exp.3 and 4% in Exp.4). For Exp.1 (underwater processing) and Exp.4 (processing under ambient conditions), in which the same process parameters are used, the same average hardness values are obtained in the area of the base material and in the area of the processed material. Also, a greater increase in hardness in the processed area is observed in the case of SFSP processing in multiple passes, compared to processing in a single pass.

For samples taken from the processed materials from Exp.1, Exp.2, Exp.3 and Exp.4, tensile tests were performed, the results of which are presented in Table 8 and Figure 7.

Table 8. Tensile test results, SFSP/FSP processing, Exp. 1-4

<table>
<tr><td colspan="7">Test: Tensile test processed material SR EN ISO 6892-1:2020.</td></tr>
<tr><td colspan="7">Equipment type:
Universal Machine 100 KN, type LabTest 6.100;
Digital caliper, brand KS Tools;
Digital thermohygrometer CEM</td></tr>
<tr><td rowspan="2">Exp. No.</td><td colspan="3">Specimen dimensions</td><td rowspan="2">Maximum force F_{max} (N)</td><td rowspan="2">Tensile strength R_m (N/mm^2)</td><td rowspan="2">Breaking zone</td></tr>
<tr><td>thickness a (mm)</td><td>width b (mm)</td><td>section a x b (mm^2)</td></tr>
<tr><td>1</td><td>5.02</td><td>12.43</td><td>62.40</td><td>13777</td><td>221</td><td>heat affected zone</td></tr>
<tr><td>2</td><td>4.71</td><td>12.31</td><td>57.98</td><td>10091</td><td>174</td><td rowspan="3">processed area</td></tr>
<tr><td>3</td><td>5.74</td><td>12.74</td><td>73.13</td><td>6434</td><td>88</td></tr>
<tr><td>4</td><td>5.90</td><td>12.67</td><td>74.75</td><td>7460</td><td>100</td></tr>
</table>

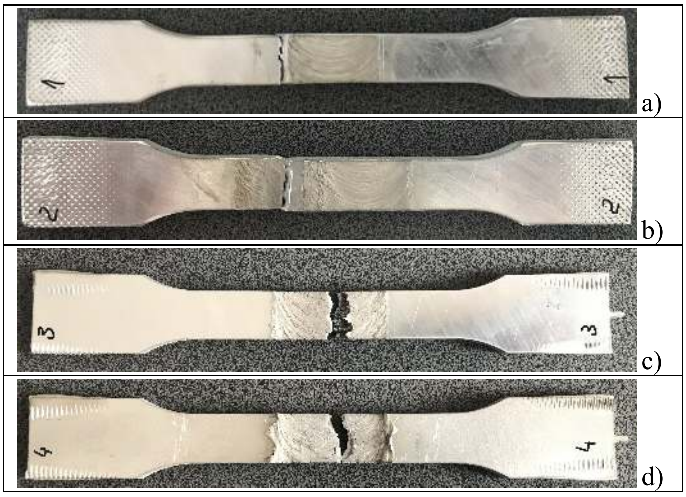
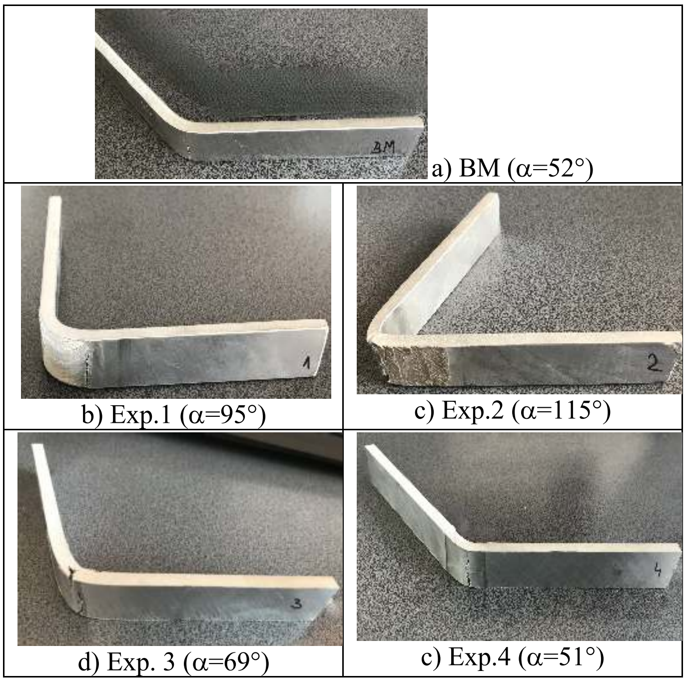


Figure 7. Tensile tested specimens (Exp.1 - Exp.4)

In Exp. 1 (SFSP processing) can be observed that the tensile test specimen broke at the edge of the processed row, in the heat affected zone, at the limit of the contact area of the tool shoulder surface with the surface of the material to be processed, at a value comparable to that of the base material (Figure7a). The tensile test specimens from Exp. 2, Exp.3 and Exp.4 broke in the processed area. Analyzing the data in Table 8 and the images in Figure7, can be observed that the highest tensile strength was obtained in the case of Exp.1 (SFSP processing), and the lowest in the case of Exp. 3, in which the tool rotation speed was higher and the processing speed was lower compared to the other experiments. The ratio between the processing tool speed and the processing speed is approx. 34 in Exp. 1, and 50 in Exp.3. In this case, when the tool rotation speed is about 50 times higher than the processing speed and the tensile strength is reduced, a thermal degradation caused by the generation of an excessive amount of heat through friction can be considered, which leads to a decrease in grain refinement. A tool rotation speed that is too high can have effects on the processed material but also on the processing tool. Thus, in the plasticized material can be caused turbulence, with the possibility to occur porosities or even microcracks. At too high tool rotation speeds, the processing tool can wear out faster and intense vibrations may occur, which can affect the uniformity of processing. Also, processing at high tool rotation speeds and high rotation speed-to-processing speed ratio (e.g. 50) can be considered intense, as the thermal and mechanical action can lead to internal stresses that can counteract the benefits of structure refinement and can lead to faster failure of tensile tested specimens. The presence of residual stresses can reduce tensile strength especially in the transition areas between the processed and unprocessed material.

The static bending test for the base material specimens shows that they broke at α bending angle of approx. 52° (Figure 8 a). Specimens were taken from the SFSP/FSP processed materials and were tested for bending.

The bending angle α of the specimen was ca. 95° for Exp.1 (Figure 8b), 115° for Exp. 2 (Figure 8c), 69° for Exp. 3 (Figure 8d) and 51° for Exp. 4 (Figure 8e). If we compare the bending angle of the material processed in multiple passes (Figure 8c) with that of the base material (Figure 8a), it is found that after processing it was at least 2 times higher, which shows the effect of processing in multiple passes on the increase in the plasticity of the processed material. The bending angle of ca. 69° (Exp. 3, Figure 8d) shows a slight improvement in the plasticity of the processed material compared to the base material. For Exp.4 (Figure 8e), the bending angle of ca. 51° (close to that of the base material) shows that in this case the plasticity of the material did not change after processing.



a) BM (α=52°)

b) Exp.1 (α=95°)

c) Exp.2 (α=115°)

d) Exp. 3 (α=69°)

c) Exp.4 (α=51°)

Figure 8. Bending tested specimens: a) base material, b-e) processed materials

The bending angle of the specimen was ca. 95° for Exp.1 (Figure 8b), 115° for Exp. 2 (Figure 8c), 69° for Exp. 3 (Figure 8d) and 51° for Exp. 4 (Figure 8e). If we compare the bending angle of the material processed in multiple passes (Figure 8c) with that of the base material (Figure 8a), it is found that after processing it was at least 2 times higher, which shows the effect of processing in multiple passes on the increase in the plasticity of the processed material. The bending angle of ca. 69° (Exp. 3, Figure 8d) shows a slight improvement in the plasticity of the processed material compared to the base material. For Exp.4 (Figure 8e), the bending angle of ca. 51° (close to that of the base material) shows that in this case the plasticity of the material did not change after processing. Compared to the bending angle for the base material, the SFSP processed materials had better plasticity after processing.

3. CONCLUSIONS

- Experimental research on friction stir processing in two working environments (air and water) shows that the results obtained are influenced by processing parameters, working conditions and the number of successive passes.
- In the first two experiments, a generally stable working process is observed, with a fairly uniform appearance of the processed surfaces and a constant width imprint of the tool shoulder on the surface of the processed material, without visible defects. An inconsistent operation of the equipment is reflected in the appearance on the processed surfaces from experiments 3 and 4.
- Macroscopic analysis shows areas of processed material (in one pass and in multiple passes) well consolidated across the thickness of the material, without defects, which indicates that the process parameters used ensured good plasticization and mixing of the material in the processing area.
- Microscopic analysis of the processed samples shows differences compared to the base material, observing the refinement of the casting structure, the microstructure of the processed material being more homogeneous, with fine grains, and flow lines of the plasticized material during processing being visible.
- A high ratio of 50 between tool rotation speed and processing speed in FSP processing leads to a refined microstructure, characterized by fine grains and an increase in local hardness by about 13% compared to the base material. However, the tensile strength is lower compared to processing at a ratio of 34, indicating that excessive heat input and possible residual stresses can negatively affect the mechanical properties of the material.
- Although microstructure refinement and hardness increase are achieved, a good correlation between rotation speed and processing speed is important to achieve a balance between microstructure refinement, hardness and tensile strength.
- Compared to the bending angle for the base material, SFSP processed materials had better plasticity after processing.
- Compared to ambient processing, underwater processing contributes to the active cooling of the work area, reducing the risk of overheating of the processing tool and the materials to be processed.

4. ACKNOWLEDGEMENTS

The paper was developed within the project PN 23 37 01 02 "Research on the modification of metallic materials properties using the innovative and environmentally friendly method of friction stir processing in liquid environment" (financed by the Ministry of Education and Research, within the Nucleu Program of ISIM Timisoara, contract 16N/2023 - Nucleu Program PN ISIM 2023-2026).

To carry out the experimental research, new and high-performance equipment was also used, purchased within the INFRATECH project ”Infrastructure for excellence research in welding” (Code SMIS 2014+126084, funded by the Ministry of Research, Innovation and Digitization, as Intermediary Body for the Competitiveness Operational Program 2014-2020, contract 360/390036/27.09.2021).

5. REFERENCES

1. El-Zathry, N.E., Akinlabi, S. et al., Friction Stir-Based Techniques: An Overview, *Welding in the World* Vol.69, pp.327–361 (2025), https://doi.org/10.1007/s40194-024-01847-w;
2. Ma, Z.Y., Feng A.H. et al., Recent Advances in Friction Stir Welding/processing of aluminum Alloys, Microstructural Evolution and Mechanical Properties, *Crit. Rev. Solid State Mater. Sci.* Vol. 43, No. 4, pp. 269-333 (2017), https://doi.org/10.1080/10408436.2017.1358145
3. El-Sayed, M.M., Shash, A.Y., Abd-Rabou, M. et al., Welding and processing of metallic materials by using friction stir technique: A review, *J. Adv. Join. Process*., Vol. 3, 100059, (2021), https://doi.org/10.1016/j.jajp.2021.100059;
4. Kumar, R.A. et al., Review of friction stir processing of aluminium alloys, M*ater. Today Proc.*, Vol.16, pp. 1048–1054, (2019), https://doi.org/10.1016/j.matpr.2019.05.194;
5. Li, K., Liu, X. and Zhao, Y., Research status and prospect of friction stir processing technology, *Coatings*, Vol. 9, pp. 129, (2019), doi:10.3390/coatings9020129;
6. Maurya, M. et al., Variants of friction stir based processes: review on process fundamentals, material attributes and mechanical properties, *Materials Testing*, Vol.66, No. 2, pp. 271-287, (2024), https://doi.org/10.1515/mt-2023-0196;
7. Heidarzadeh, A., Mironov, S., Kaibyshev, R. et al., Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution, *Prog. Mater. Sci*., Vol. 117, 100752, (2021), https://doi.org/10.1016/j.pmatsci.2020.100752;
8. Patel, V., Li, W., Vairis, A. et al., Recent Development in Friction Stir Processing as a Solid-State Grain Refinement Technique: Microstructural Evolution and Property Enhancement, *Crit. Rev. Solid State Mater. Sci.* Vol. 44, pp. 378–426, (2019), https://doi.org/10.1080/10408436.2018.1490251
9. Srivastava, A.K. et al., 20th Century Uninterrupted Growth in Friction Stir Processing of Lightweight Composites and Alloys, *Mater. Chem. Phys.,* Vol. 266, 124572, (2021), https://doi.org/10.1016/j.matchemphys.2021.124572
10. Msomi, V., Fabrication of Metal Matrix Composites using the Submerged Friction Stir Processing Technique: A Recent Progress Review, *Eng. Technol. Appl. Sci. Res.,* Vol.14, No.5, pp. 17256-17260 (2024), https://doi.org/10.48084/etasr.8255;
11. Silvestri, A.T, El Hassanin, A., De Alteriis, G., Astarita, A., Energy Consumption and Tool Condition in Friction Stir processing of Aluminum Alloys, *Int. J. Precis. Eng. Manuf. – Green Technol.,* Vol.12, pp.1-18, (2025), https://doi.org/10.1007/s40684-024-00633-9;
12. Patel, M.S., Immanuel, R.J., Rahaman, A. et. al., Critical Review of Advanced Cooling Strategies in Friction Stir Processing for Microstructural Control, *Crystals*, Vol.14, pp. 655, (2024), https://doi.org/10.3390/cryst14070655;
13. Datta, A. et al., Application of Friction Stir Processing for Generating Novel Engineering Parts—A Review. In: Sahoo, P., Barman, T.K. (eds) *Advances in Materials, Manufacturing and Design.* INCOM 2024, *Lect. Notes Mech. Eng*., https://doi.org/10.1007/978-981-97-6667-3_38;
14. Marazani, T. et al., Mass flash reduction strategies in friction stir processing of aluminum alloys: A review. *Engineering Reports*, Vol. 6, No. 10, (2024), https://doi.org/10.1002/eng2.12981;
15. Iwaszko, J., New Trends in Friction Stir Processing: Rapid Cooling – a Review, *Trans. Indian Inst. Met.,* Vol. 75, pp.1681-1693, (2022), https://doi.org/10.1007/s12666-022-02552-2;
16. Oancă, O., Sîrbu, N.A., Binchiciu, E.F., Mnerie, G.V., Perianu I.A., Method and technologies Functional Constructive Configuration Concept of a Flexible Unconventional Hybrid FSW-US Welding Process, *Adv. Mater. Res*., Vol.1153, pp.85-91, (2019), https://doi.org/10.4028/www.scientific.net/AMR.1153.85
17. Perianu, I.A., Murariu, A.C. et al., Advancements in abrasive waterjet cutting technologies: A comprehensive overview and future prospects in the manufacturing technology, *KEM*, Vol.996, pp.77-86, (2024), https://doi.org/10.4028/p-Zr0osO;
18. Murariu, A.C., Non-destructive and mechanical tests for quality evaluation of friction stir welding joints, *Welding & Materials Testing*, Vol.1, pp11-15, (2020), https://www.bid-isim.ro/bid_arhiva/bid2020/bid1_2020_11-15.pdf;
19. El-Attara, T. et al., Friction Stir Processing: A Novel Approach for Strengthening and Surface Engineering, *Benha Journal of Engineering Science and Technology, BJES*T, Vol. 2, Issue 1, pp: 9-24, (2025),DOI:10.21608/bjest.2025.445848;
20. Akbari, M., DebRoy, T., Asadi, P., Sadowski, T., Recent advances in friction stir welding/processing tools, *J. Manuf. Process*., Vol.142, pp. 99-156, (2025), https://doi.org/10.1016/j.jmapro.2025.03.089;