RESEARCH ON SUBMERGED FRICTION STIR PROCESSING OF EN AW 6082 ALUMINUM ALLOY

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ABSTRACT: Submerged friction stir processing (SFSP) is a variant of processing the surfaces of metallic materials that uses the liquid medium to ensure a process temperature that does not thermally overload the materials to be processed or the processing tool. SFSP processing aims at local modification of the properties of the materials to be processed. The paper presents results of experimental research carried out at ISIM Timisoara on submerged friction stir processing (SFSP) of the 5mm thick EN AW 6082 aluminum alloy. In the SFSP processing experiments, multiple processing rows were performed with their partial overlap. The evaluation of the processed material consisted of visual examination and with penetrating radiation, structural analysis, mechanical tensile tests and bending tests, positive results the results being achieved.

KEYWORDS: *submerged friction stir processing, EN AW 6082 aluminum alloy, experiments, structural analysis, mechanical properties, SFSP.*

1. INTRODUCTION

Submerged Friction Stir Processing (SFSP) is an eco-friendly and versatile solid-state processing method designed for metallic materials. It is a variant of Friction Stir Processing (FSP), specifically developed to enable precise control over the processing temperature within the working zone [1-16]. This approach aims to prevent excessive overheating of both the processing tool and the material being treated. Consequently, SFSP operates at reduced temperatures, thereby minimizing or entirely mitigating any deformation of the material under processing [7, 8, 10, 14, 15].

During the procedure, the processing tool, rotating at a predetermined speed, penetrates the material until the tool shoulder establishes contact with the upper surface of the material. Subsequently, the tool advances along a designated processing trajectory at a controlled feed rate. The friction generated between the tool shoulder and the material, as well as between the tool pin and the material, produces sufficient heat to facilitate plasticization, mixing, and homogenization of the material. Notably, this process is conducted below the melting temperature of the material, ensuring the preservation of its solid-state characteristics [2, 3, 5, 7, 9, 10, 14-16].

Material processing can be performed in a single pass or in multiple passes, the number of passes influencing the plasticization and deformation of the material, thus contributing to the modification of the microstructure, as well as the mechanical properties of the processed material [2, 6-12].

Research on friction stir processing in different working medium are current and target various categories of metallic materials, the approach of aluminum alloys having an important role [1-16].

The aluminum alloy EN AW 6082 (AlSi1MgMn) is renowned for its exceptional combination of high strength, durability, superior machinability, and remarkable corrosion resistance in a variety of operational environments.

It is extensively employed in the manufacturing of components and structures for a wide range of structural applications, spanning the automotive, aeronautical, aerospace, naval, and maritime industries [1, 6, 10, 11, 14, 15].

Given that submerged friction stir processing (SFSP) is recognized as a modern and advanced technique for the treatment of metallic materials, it has emerged as a subject of significant interest for ISIM Timisoara.

The institute has conducted experimental investigations to explore the application of SFSP to EN AW 6082 aluminum alloy with a thickness of 5 mm.

2. SFSP EXPERIMENTAL PROGRAM. PROCESSED MATERIAL EVALUATION

2.1 Material

For the experimental research on SFSP, a 5 mm thick sheet of EN AW 6082 aluminum alloy was utilized. The chemical composition of the alloy, determined at

ISIM Timisoara using an optical emission spectrometer (OES, Hitachi OE720 model), is provided in Table 1.

Table 1. Chemical composition -EN AW 6082 aluminum alloy

Al (%)	Si (%)	Mg (%)	Fe (%)	Mn (%)	Cu (%)	Zn (%)	Others, total (%)
97.01	1.0040	0.6743	0.5368	0.4570	0.0878	0.0595	0.1706

The tensile strength and static bending angle of the EN AW 6082 aluminum alloy, in its unprocessed (base material) state, were experimentally determined through mechanical testing conducted at ISIM Timisoara. The results of these tests are documented in Table 2.

Table 2. Mechanical properties of EN AW 6082, 5mm thick

Material	Tensile strength R_m (N/mm^2)	Average hardness HV1	Bending angle α[°]
EN AW 6082	290	110	100

2.2 Equipment and processing tool

The experimental research on SFSP processing have been performed on the FSW 4-10 welding machine from ISIM Timisoara, equipped with modules/elements necessary for using water as a working medium for processing (Figure 1a), as well as with a processing tool (Figure 1b).

The sheets were cut to the required dimensions for the processing experiments, and samples/specimens were extracted from both the base material and the processed material for evaluation using the OMAX Maxiem 1530 water jet and abrasive cutting equipment (Figure 1c). The preparation of samples for structural analysis was carried out using the Qpol 250A2-ECO grinding and polishing machine (Figure 1d).

Chemical analysis of the base material has been performed with a OE720 Hitachi OE720 optical emission spectrometer (Figure 1e), macroscopic analysis has been performed with a Nikon SMZ745 optical microscope with MshOt camera (Figure 1f), microscopic analysis with an XJP-6A microscope with a Dino-lite camera (Figure 1g), and for mechanical testing a 100kN universal machine type LabTest 6.100 has been used (Figure 1h).

The equipment in Figures 1c-f and Figure 1h are new and high-performance, having been purchased by ISIM within a project to develop its own research infrastructure.

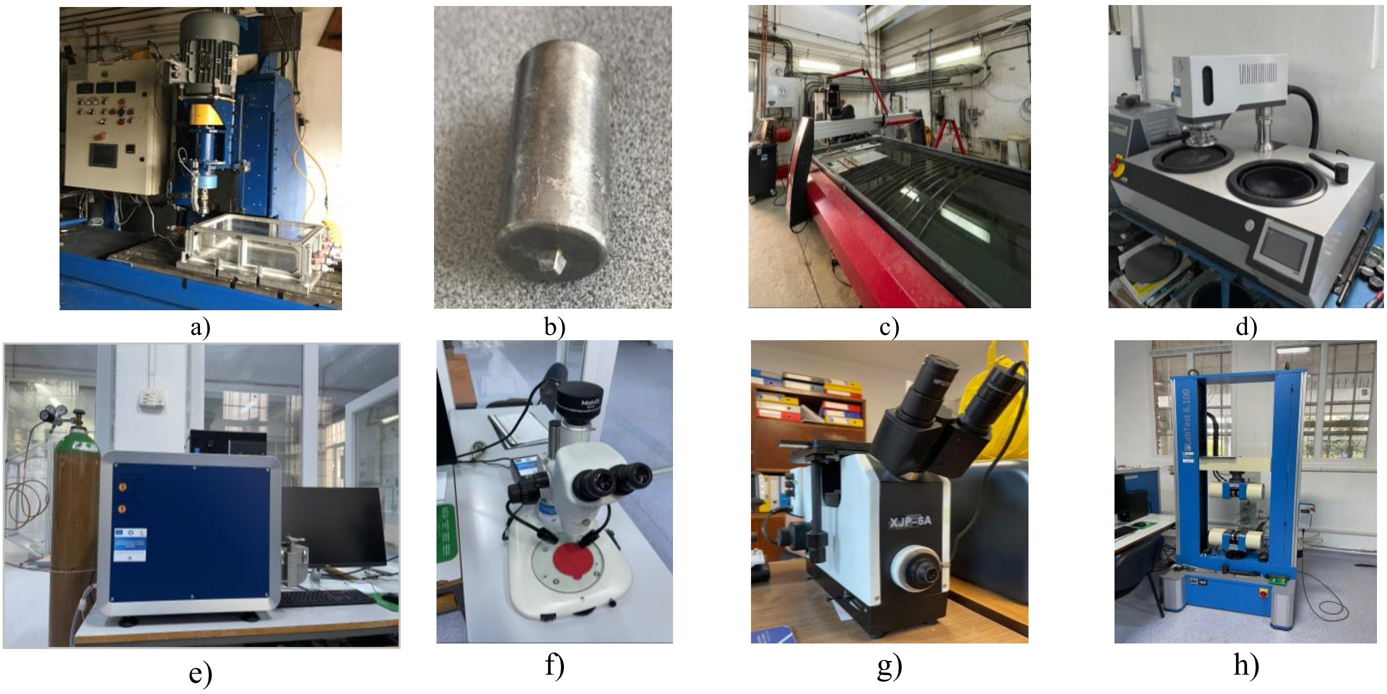


Figure 1. Equipment used in processing, preparing materials and samples for evaluation

2.3 SFSP experimental program and evaluation of the processed material

Experimental processing research on the 5 mm thick EN AW 6082 aluminum alloy aimed to analyze the possibilities of applying submerged friction stir processing to this alloy.

For the SFSP processing of the EN AW 6082 rolled aluminum alloy, a sheet with dimensions of 200 × 200 × 5 mm was utilized. The SFSP was conducted in multiple passes using the FSW welding machine (Figure 1a) and a processing tool with a conical shape featuring four flat chamfers (Figure 1b). The processing parameters are detailed in Table 3.

The processing was performed in five passes (R1-R5) made in the same direction, with a processing tool made of H11 steel (X38CrMoV5) with a conical pin having 4 flat chamfers, the pitch between passes being 3 mm. The pitch was correlated with the dimensions of the processing tool pin to ensure partial overlap of the passes and to prevent the occurrence of discontinuities in the thickness of the processed material. Sampling and specimen extraction from both the base material and the processed material were performed using water jet cutting, with the equipment shown in Figure 1c.

Table 3. Technological processing parameters SFSP - aluminum alloy EN AW 6082, 5mm thickness

Processing tool	Material	H11 (X38CrMoV5) steel
	Pin type	Conical shape, 4 chamfers
	Pin length L_{pin}	3.82 mm
	Type/shoulder diameter $Ø_{shoulder}$	smooth 22 mm
Process parameters	Tool rotation speed, n	2400 rpm
	Processing speed, v	70 mm/min (row R1) 1000 mm/min (rows R2-R5)
	Rotation sense	counterclockwise

The evaluation program of the processed material began with visual analysis, followed by examination with penetrating radiation (according to SR EN ISO 17636-1:2022) using an X-ray examination device with an ERESCO 42MF2 radiation source.

Figure 2 shows the surface appearance of the EN AW 6082 aluminum alloy SFSP processed in multiple passes using parameters mentioned in Table 3, as well as the image of the radiographic film for the processed material. A uniform appearance and a constant width of the processed rows, which shows the stability of the working process and a constant pressing of the shoulder on the surface of the material to be processed, are observed in Figure 2a. The resulting burrs, if any, on the surface of the processed material have been mechanically removed after the completion of the processing row, before the next pass.

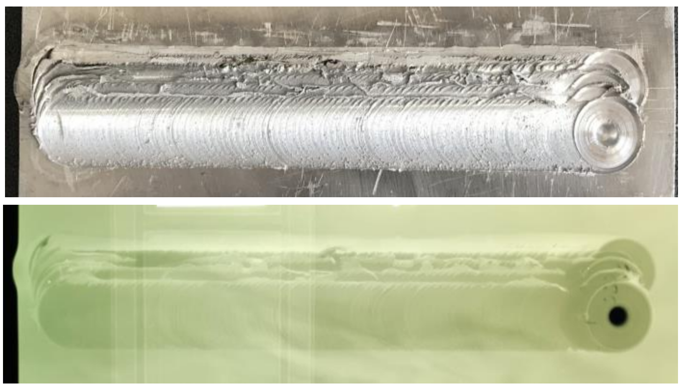


Figure 2. Top surface appearance and Rx image - SFSP processed material - EN AW 6082 (5mm)

On the X-ray film (Figure 2b) it is observed that the processed material does not present defects, there are no variations in appearance or width of the processed rows.

The working process was monitored in terms of the temperature of the liquid working medium (water). The initial temperature values of the water introduced into the enclosure before the start of each processing row, as well as the water temperature value after each row of processed material have been monitored. In order to perform the processing in multiple passes, it was necessary to evacuate the water from the enclosure after the completion of each row, to extract the processed material plate from the machine and remove the burrs from the processing (if any), repositioning and fixing the EN AW 6082 aluminum alloy plate in order to be able to perform a new processing row. A new amount of water has been introduced into the enclosure after ending of these operations. The values of the water temperature in the enclosure, before and after each processing row, are presented in Table 4.

Table 4. Water temperature values in the enclosure, before and after each processing row

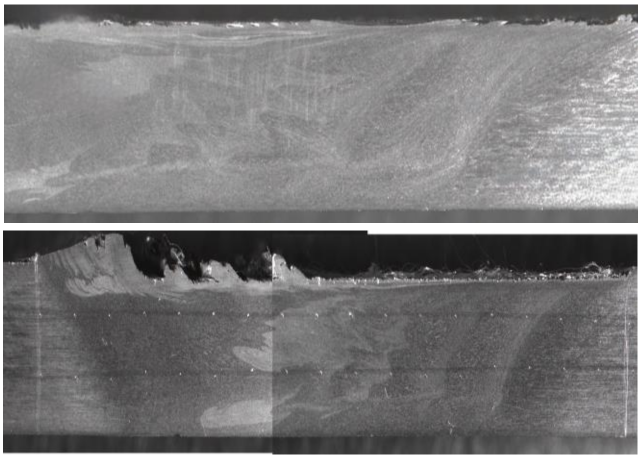
Process parameters		Water temperature,		Row no.
Tool rotation speed n (rpm)	Processing speed v (mm/min)	initial, ˚C	final, ˚C	
2400	70	24	31	R1
2400	1000	24	27	R2 -R5

The data presented in Table 4 indicate that the temperature of the liquid working medium reached 31°C at the end of the processed row R1, while it measured 27°C at the end of rows R2-R5. The initial water temperature at the start of processing was 24°C. The 31°C temperature observed at the end of row R1 is directly correlated with the process parameters, specifically resulting from the use of a processing speed of 70 mm/min. Increasing the processing speed to 1000 mm/min at the same rotation speed of 2400 rpm, led to a lower liquid medium temperature (27°C), compared to the use of the first set of process parameters. The constant temperatures of the working medium, related to the processing of rows R2-R5, show the stability, uniformity and repeatability of the processing, no thermal fluctuations, ensuring the same quality for each processed row.

The evaluation of the SFSP-processed material in multiple passes required the extraction of samples for macro- / microscopic structural analysis and hardness measurements, as well as specimens for tensile and static bending tests. The preparation of the samples for structural analysis was performed with a grinding and polishing machine (Figure 1d).

The macroscopic analysis was performed with the microscope in Figure 1f (and in accordance with SR EN ISO 17639:2022 and SR EN ISO 6520-1:2007 respectively). The images related to the macroscopic analysis of samples taken from the processed material are presented in Figure 3.

The macroscopic analysis for M1 and M2 samples shows a processed material without defects, compact and with well-consolidated rows of processed material (Figure 3). The pitch between passes has been chosen, so that no discontinuities of processed material (alternations of processed and unprocessed material) appeared. It was observed that the increase in processing speed from 70mm/min to 1000 mm/min did not negatively affect the macroscopic appearance of the processed material.

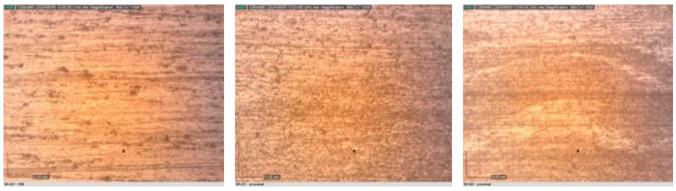


M1

M2

Figure 3. Macroscopic analysis of processed material samples

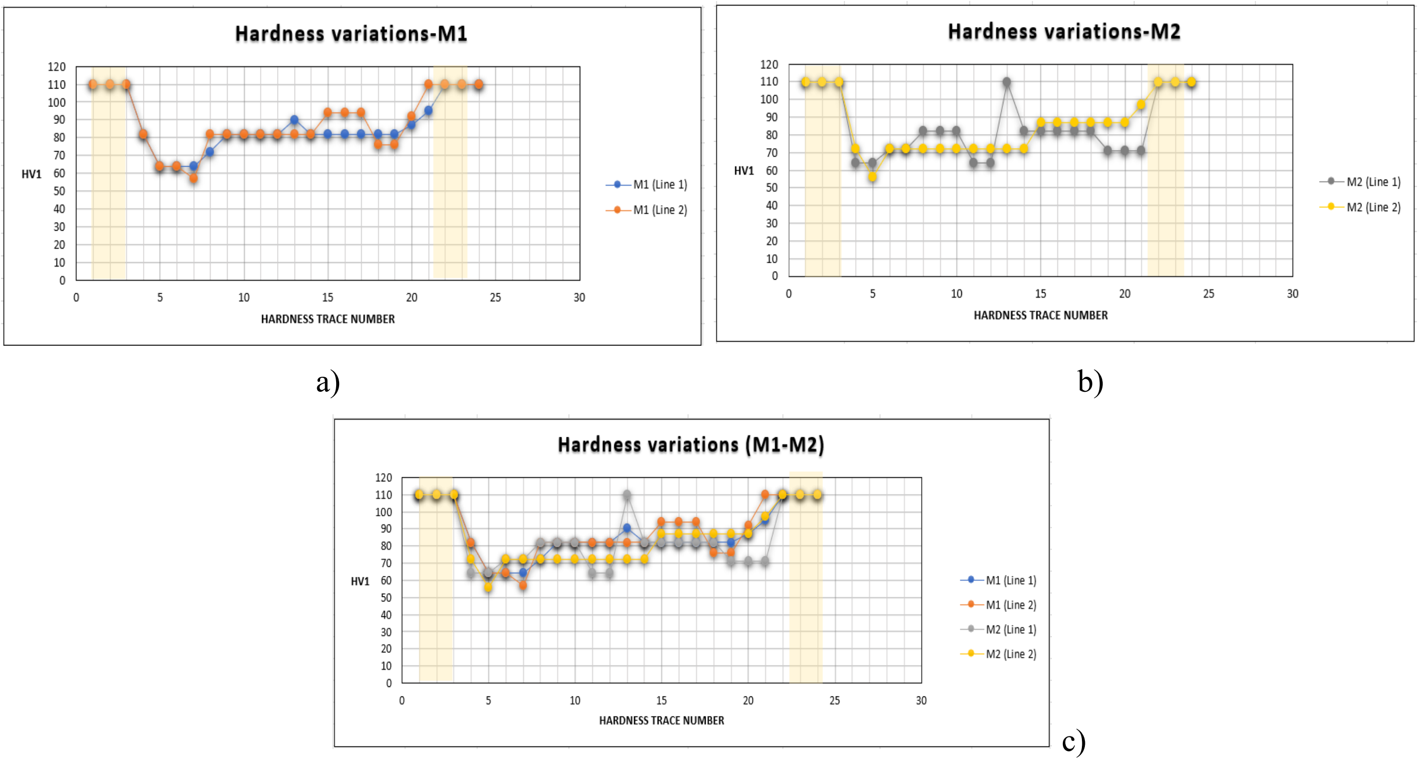
The microscopic analysis for M1 and M2 samples, performed with the microscope in Figure 1g (according to SR EN ISO 17639:2022 and SR EN ISO 6520-1:2007), shows the microstructure of the base material (Figure 4a) and of the processed material (Figures 4b-c). A microstructure with refined grains compared to the microstructure of the base material (Figure 4b) can be observed, as well as areas where flow lines of the processed material and its mixing zone are visible (Figure 4c).



a) BM b) M1 c) M2

Figure 4. Microscopic analysis appearance for samples taken from base material and processed material (100x)

The evaluation process of the processed material also included measurements of the HV1 hardness (in accordance with SR EN ISO 6507-1:2023 and SR EN ISO 9015-1:2011) in the cross-section of the processed samples, using a Zwick 3212 equipment. The measurements were performed on two levels, 1 mm (measurement line 1) and 4 mm (measurement line 2) away from the top surface of the processed material, with 2 mm pitch between measurements points and included the base material area and the processed area. Figure 5 shows the hardness variation graphs.



a) b) c)

Figure 5. Graphs of hardness variation of processed materials

The hardness of the base material was determined by 3 measurements, the values being visible in the marked areas at the ends of the graphs. Hardness values of 110 HV1 have been measured for the base material. In the processed material area of samples M1 and M2 has been observed that the hardness values decrease compared to the base material, the values being between 64 HV1 and 97 HV1, but punctually reaching 110 HV1 (Figure 5 a, b). The hardness graphs of samples M1 and M2 show that on both hardness measurement lines, the lowest values may correspond to the first processing row R1, when the processing speed 70 mm/min was used. The hardness values (on both measurement lines) have been on different levels (e.g. 72 HV1, 82 HV1 and 87 HV1) for the rows R2-R5 where the processing speed of 1000 mm/min was used.

By overlapping the hardness variation graphs (related to samples M1 and M2) has been observed that the hardness variation profile has similarities, generally following the same variation pattern, for both samples extracted from the processed material (Figure 5c). Table 5 presents the average hardness values of the processed material (samples M1 and M2) for the two measurement lines.

Table 5. Average hardness values of processed areas

Measurement level	M1 sample	M2 sample
Line 1	80 HV1	77 HV1
Line 2	82 HV1	78 HV1

The analysis of the hardness values shows that for each sample of processed material, the average hardness values on the two measurement levels/lines are close, indicating that there are no significant changes on the thickness of the material. Due to the processing in multiple passes (5 rows) and the plasticization of the material during processing, a decrease of hardness in the processed area compared to the base material has been observed.

The evaluation program of the processed material also included mechanical tensile tests and bending tests, performed using the machine in Figure 1h. The tensile tests were performed on specimens taken from the processed SFSP area, but also from the base material, in accordance with SR EN ISO 6892-1:2020, the results being presented in Table 6 and Figure 6.

Table 6. Tensile test results, SFSP processing

Mechanical test	Tensile test - processed material, SR EN ISO 6892-1:2020		
Equipment type	Universal machine 100 KN, LabTest 6.100; Digital caliper, KS Tools; Digital thermohygrometer CEM		
Testing temperature	23^0C, ambient conditions		
Material	EN AW 6082, 5 mm thick		
Specimen No.	MB - T	T1	T2
Specimen thick a (mm)	5.00	4.33	4.64
Specimen width b (mm)	12.53	12.27	12.42
Section a x b (mm^2)	62.65	53.13	57.63
Maximum force F_{max} (N)	18191	10400	10993
Tensile strength R_m (N/mm^2)	290	196	191
Breaking area	-	processed area	


T1

T2

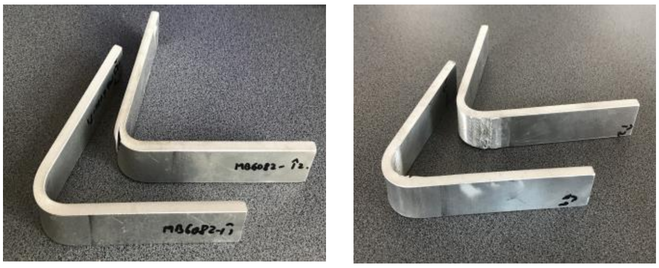
Figure 6. Processed material specimens, tensile tested

It has been observed that when applying submerged friction stir processing SFSP, both specimens broke in a similar way at about 45^0 at the edge of the first row of processed material. The processing speed for the first row R1 of the processed material has been 70 mm/min, being much lower than in the case of the R2-R5 rows where processing has been performed at a speed of 1000 mm/min. Considering the fact that the break did not occur in the area of the R2-R5 rows of the processed material using a speed of 1000 mm/min, it can be seen that this very higher processing speed had a positive effect on the processed material. The average value of the tensile strength for the samples taken from the processed material is Rm = 194 N/mm^2, representing about 67% compared to the tensile strength of the base material Rm_{BM} = 290 N/mm^2.

The evaluation program of the processed material also included static bending tests, performed on specimens taken from the SFSP processed area and from the base material BM. The bending test of the processed material was performed (according to SR EN ISO 5173:2023 and SR EN ISO 7438:2020) with both the stretched surface (of the processed material) and the stretched root. The result of these tests is presented in Table 7 and Figure 7.

Table 7. Bending test results of processed material SFSP

Specimen marking	MB-I1	MB-I2	Î1	Î2
Specimen thickness a[mm]	5.00	5.00	4.33	4.64
Specimen width b[mm]	20.00	20.00	20.20	20.10
Bending angle α[°]	Max.	100	Max.	Max.
Bending position	-	-	TRBB - stretched root	TFBB - stretched surface
Observations	No imperfections	cracked	No imperfections	No imperfections



Base material EN AW 6082 SFSP processed material

Figure 7. Bending tested specimens, processed EN AW 6082

From Figure 7 it can be seen that during the bending test, one of the samples taken from the base material cracked. In comparison, the samples taken from the SFSP processed material bent without cracking, in both bending cases (with the stretched root and with the stretched surface).

3. CONCLUSIONS

- The macroscopic appearance shows a processed material without defects, with compact and well-consolidated rows of processed material, a fact also highlighted by the image of the radiographic film. The pitch between passes was chosen appropriately so that no discontinuities of processed material appear (alternations of processed and unprocessed material). The EN AW 6082 aluminum alloy allowed the processing speed to be increased from 70 mm/min to 1000 mm/min with no negative influence on the macroscopic appearance of the processed material.
- The microstructure of the processed material exhibits refined grains in comparison to the base material, with visible flow lines and a distinct mixing zone in the processed region.
- The temperature of the liquid working medium (water) is closely correlated with the applied process parameters, showing higher values at lower processing speeds. Modifying the process parameters is essential for effectively controlling the temperature of the liquid working medium. Constant processing parameters (rows R2-R5) determined a stable, uniform working process, as well as a constant temperature of the liquid working medium at the end of processing.
- The analysis of the hardness values shows that for both samples of processed material, the average hardness values on the two levels/measurement lines are close, showing that no significant changes occur in this respect on the material thickness. As a result of the multiple-pass processing (5 rows) of the EN AW 6082 aluminum alloy and its plasticization during processing, a decrease in hardness is observed in the processed area compared to the base material area.
- The average value of the tensile strength Rm=194 N/mm^2 for the SFSP processed EN AW 6082 aluminum alloy represents approximately 67% of the tensile strength of the base material Rm_{BM} = 290 N/mm^2.
- In bending tests, both with the stretched root and the stretched surface, the results were better compared to the base material BM, the specimens from the processed material bent without cracking.

Experimental research will continue to compare SFSP and FSP processing of EN AW 6082 aluminum alloy, under the same working conditions regarding equipment, tools and process parameters.

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