WATER JET CUTTING INFLUENCE ON LIGNIN-BASED POLYMER SAMPLES

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Abstract: Arbofill Fichte material combine a series of properties focus directly with its chemical composition. The material is biodegradable one and as constituent's can be counted from biopolymers such as lignin, polylactic acid (PLA), starch, natural resins and waxes, etc. So far, there are no experimental results on this lignin-based material on machinability by abrasive water jet cutting, a technological process very often used in industrial practice. The article aims to establish theoretically solutions for optimizing the working regime for processing with water jet with abrasive in order to obtain a higher quality surface compared with the currently existing ones for biodegradable polymeric materials. The main aspects of water jet abrasive processing are surface roughness and dimensional accuracy. Also, the article performs an systemic analysis of the technological parameters regarding the quality surface and dimensional accuracy of the parts. The main technological parameters of the process taken into account were as follows: pressure, feed rate and abrasive material flow.

Key words: abrasive water jet cutting, lignin-based polymer, roughness.

1. INTRODUCTION

Abrasive Water Jet (AWJ) technology has proven to be a useful manufacturing process for the space, aircraft, boat and automotive sectors due to its specific advantages in the processing of composite materials. However, the AWJ cutting of composite laminates presents several challenges. It is necessary to develop a methodology for adapting the process parameters for each type of Fibre-reinforced plastic (FRP) and Carbon fiber reinforced polymer (CFRP) material, which allows easy AWJ cutting operations on composite materials, as machine manufacturers still do not provide good databases for composite cutting. Water jet cutting is a method based on the erosion phenomenon obtained by pressure and small diameter of the water jet (acceleration medium), with or without abrasive powder, depending on the qualitative needs of the application concerned but also power of the pump used by the equipment. Other advantages of this process also refer to: flexibility both in terms of dimensions and materials (including composites); environmentally friendly process (toxic gases, harmful substances, steam, ultraviolet radiation) and human health; thermal influence; dimensional stability and accuracy; surface quality; efficiency and profitability, etc. But, like any other technology / process, it also has some limitations and especially when it comes to the quality of the lower surface of the cut part. In this sense, the researchers investigate aspects related to the quality of the exit area of the water jet, considering mainly the roughness of the resulting surface. The width of the cut will depend on the diameter of the nozzle as well as the amount of abrasive used during processing. The volume of material removed during cutting can be determined by using calculation relationships related to the density and initial volume of the sample (MRR-Material Removal Rate method) subject to cutting but its value will be much lower than that obtained by using conventional procedures. Also, contamination with various impurities (chemical elements - metals, gases, etc.) is zero as the part comes into contact on the processed area only with water and abrasive, without other lubricants or processing tools, [1].

A number of scientific papers refer to the abrasive water jet cutting of conventional polymeric materials such as polyamides 6 - PA6 (SIPAS 60), polypropylene green composites, polymer matrix composites, [2-7] etc., mainly to determine the quality of the surface by determining the roughness and the dimensional and geometric accuracy but also for determining the amount of material removed during the cutting process. The machinability index for various composite materials with different thicknesses was found experimentally, which showed very different results for different materials. A study of the effect of abrasive process parameters of water jet on cutting quality (taper and surface roughness) was performed, [8].

In order to obtain the targeted answers, a series of parameters involved in the water jet abrasive processing process are taken into account. In this sense, a brief systemic analysis will be performed in the following, which follows the influence of the variable factors on the output parameters, Figure 1.

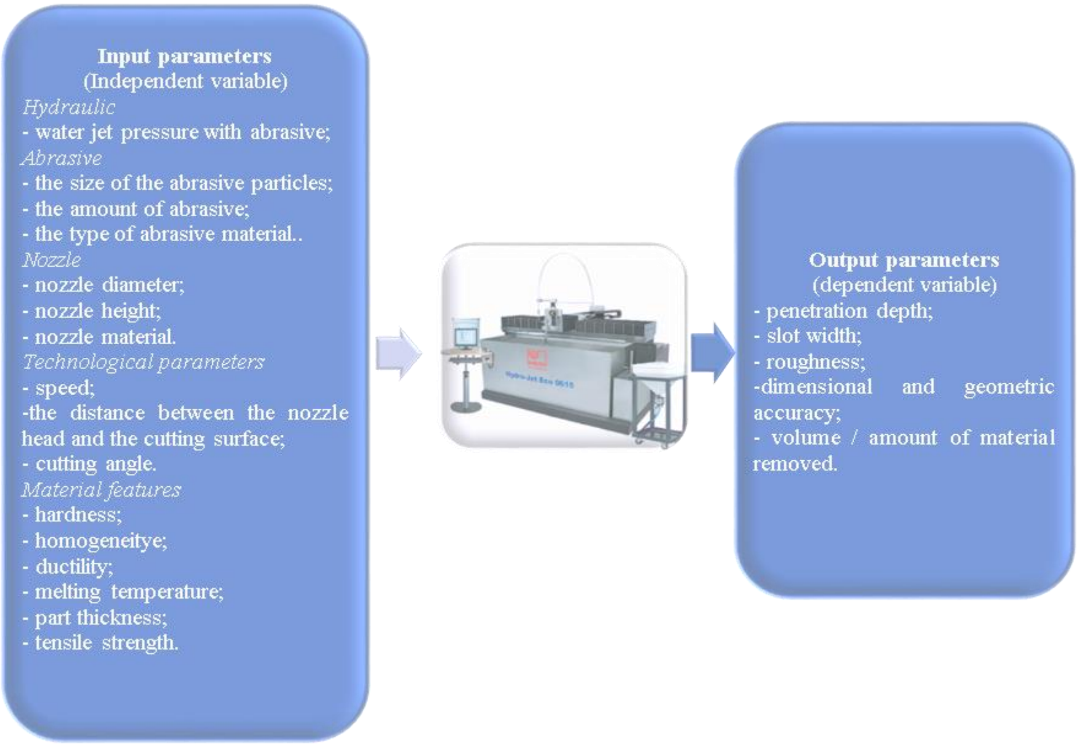


Fig. 1. The relationship between the variable parameters and the dependent ones, [1, 7]

Material thickness: The larger this size, the higher the surface roughness because in the lower part of the part, the area where the water flow with abrasive comes out does not have enough energy to properly cut the material. To eliminate this low surface quality, the abrasive water jet pressure is usually increased, a larger amount of abrasive is incorporated into the water flow and the speed of the cutting head is reduced.

Melting temperature of the material to be processed: Biodegradable polymeric materials have a much lower melting temperature than conventional polymeric materials, so their cutting using a "cold" cutting process is more than necessary because a cutting using conventional methods (laser, plasma, oxygen) involving thermal sources that destroy the characteristics of the material (structure, properties) on the portion in which it comes into direct contact with the heat source (edges of cut parts) should be avoided in industrial applications and beyond.

The amount of abrasive: The higher it is, the finer the surfaces are obtained and with its decrease or even lack of it, rough, unsightly surfaces appear [9]. In the process of water jet cutting with abrasive, the abrasive is the actual cutting, the water being the environment in which the abrasive particles are accelerated to a speed appropriate to the application and also through it are directed particles to the predetermined cutting point, [10, 11].

Abrasive water jet pressure: This is a very important input parameter because with its increase smooth surfaces are obtained. However, processing with a jet pressure exceeding a certain limit of 400MPa together with the use of a small width of the working slot leads to severe damage to the material by delamination [12], shearing, splitting, cavitation, disintegration, and so on.

Processing speed: By increasing the cutting speed the resulting parts will have rougher surfaces and inaccurate size, but if you reduce the speed then you will see a tendency to improve surface quality, the cut being even more accurate.

Standoff distance: has a significant influence because as this distance increases the surface quality decreases and the cutting becomes less accurate. The width of the water jet increases as it moves away from the nozzle, leading to the formation of the taper effect on the cutting line. The parameters - cutting speed and material thickness - also significantly influence the taper effect, be it V-shaped - the cutting tip is wide on the nozzle side and narrower on the reverse side of the part, Figure 2(a), with reverse effect - narrower on the nozzle side and wider on the opposite side, Figure 2(b) with barrel conical effect - narrow on both sides but in the middle of the slot with a wide round shape, Figure 2(c) and trapezoidal or rhomboidal conical shape, it derives from the conical shape in V but it is slightly inclined, hardly visible to the naked eye, Figure 2(d), [10, 13].

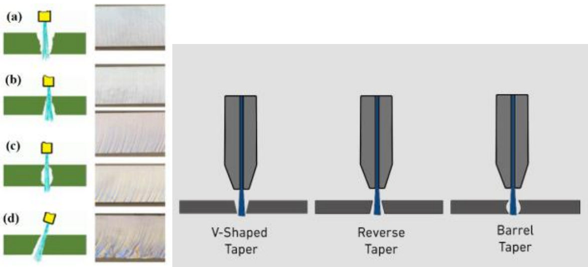


Fig. 2. Types of erosion during cutting with water jet with abrasive, [10, 13]

Nozzle composition: This equipment uses nozzles made of composite material - tungsten carbide or sintered boron, withstanding water pressures up to 620MPa.
Abrasive material: Abrasive particles can be of several types depending on the application concerned. Among the most used particles can be those of silicon carbide, garnet, glass granules, alumina, etc., [14]. The finer granulation of the abrasive influences the quality of the surface resulting from the cutting by reducing the width of the cut, the striations on the walls that came in contact with the water jet with the abrasive and the cutting speed.

2. MATERIALS AND METHODS

The material used in this paper is Arbofill Fichte, which is part of the category of biodegradable materials based on biodegradable polymers such as polylactic acid (PLA), [15] but also other biodegradable and renewable constituents such as natural vegetable fibers, resins and natural additives etc. It is marketed by the German company Tecnaro in the form of granules, [16]. The purchased granules were used to obtain parts by injecting them into the mold and then to be cut with abrasive water jet. There are known results regarding different mechanical and thermal properties of the Arbofill Fichte biopolymer which indicates the possibility of its use in different industrial applications without studying the machinability, [17, 18].
Obtaining the samples involved the use of the injection machine SZ800 H, the injected samples have the following dimensions (58·48·10) mm. Working parameters used for the proper injection moulding of the samples, thus that its have subsequently homogeneous structures were as follows: melting temperature 155 °C, pressure 90MPa, injection speed 80mm/s, cooling time 25s, mold temperature 50 °C.

The experimental tests were performed on a water jet processing machine with Hydro Jet Eco 0615 abrasive. Constant working parameters set in order to obtain parts with the lowest possible roughness were: type of abrasive material - Garnet [mesh # 80]; distance between machining head and workpiece (h) - 3mm; the length of the focusing tube - 76.2mm; water hole diameter - 0.35mm; focusing tube diameter - 1.02mm; material thickness 10mm.
The experimental plan followed is the one presented in Table 1.

Table 1. Factorial plan for cutting biopolymer injected samples

No.	Input parameters		
	Pressure [MPa]	Traverse speed, $v_{f,}$ [mm/min]	Abrasive material flow, Q [g/min]
1	100	100	150
2	100	100	300
3	100	150	150
4	100	150	300
5	150	100	150
6	150	100	300
7	150	150	150
8	150	150	300

In order to determine the output parameter, roughness (R_a), two methods were used: the first was made according to SR ISO 468: 1997 (Surface roughness. Parameters, their values and general rules for setting specifications), [19], which indicates as the test area surface of (5·0.8) mm from the entrance in the material, both for the entrance area of the water jet and for the exit area of the water jet with abrasive. After obtaining the values regarding the surface roughness of the cut Arbofill Fichte material, it was found that some surfaces of the samples generated anomalies / deviations in the measurement due to some “unevenness”. Thus, the second method of determining / measuring the roughness Ra was also used, by performing 3 measurements for each sample debited within the 8 experiments of the factorial plan. The determinations followed the measurement at the same points of the surface resulting from the AWJ process: entry, middle and exit. An average of the R_a roughness was made between the three resulting measurements.
The measurements were performed on the Zygo optical profilometer (Zegage-series) to "topography" based on the analysis in coordinates the profile of the surface resulting from the abrasive water jet cutting. By surveying, a single point can be chosen to offer a single dimension, depending on the magnification size of the eyepiece, in the present study a magnification power of 10X was used, covering, during a single scan, an area of (0.8 · 0.8) mm). The topography was made on the entry and exit areas of the water jet with abrasive from the cut piece.

Following this profilometric analysis, it was possible to represent the surface profile created by the water jet with abrasive, Figure 3, in order to obtain the "morphology" of the surface, practically the topography of the heights and / or depressions created in the manufacturing process; default of roughness.

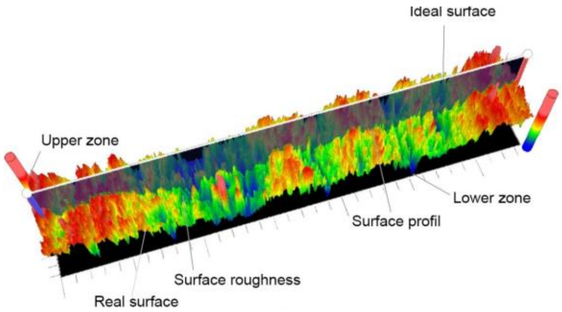


Fig. 3. The profile of surface created by abrasive water jet

With the 10X power ocular (it has higher accuracy due to the thinning of the beam) the following measurements were made:

a) from the material entry of the water jet, 5 mm / 0.8 mm; this was obtained by programming the scanner to survey in 8 steps on 8 different areas, so that in the end the surface profile of the entire analyzed sample is obtained;

b) in order to have a clearer picture and to reduce the error rate, 3 point measurements were made on the entire output line, at the input, in the middle and at the output; with these the media was then made. At each measurement the same pattern was maintained both in size and in column and row. The scan depth was 600μm to cover the tilt angle.

3. RESULTS AND DISCUSSIONS

In order to determine the surface roughness resulting from the cutting of the biodegradable polymer Arbofill Fichte, a series of measurements were performed using the optical profilometer mentioned in subchapter 2 available in the Dimensional Control Laboratory "Vasile Alecsandri" University of Bacau, Romania. Table 2 shows the summative results for the most relevant answers, namely the experiment with number 2 of the factorial plan.

The meaning of the terms from the Table 2 is as follows: R_a is the roughness of the processed surface determined according to the ISO 1997 standard, [μm]; R_a-M_1, R_a-M_2, R_a-M_3 - average values of roughness measured in line, [μm]; R_a- (M_1: M_3) is the average roughness measured in line, [μm]; L_i - width of the processed surface at the jet inlet, [mm]; L_o - width of the processed surface at the jet outlet, [mm]; u - deviation from perpendicularity, [mm]; α - the tilt angle of the machined surface, [°]; MR - The amount of material removed, [g]; g - the thickness of the part, [mm].

For the values of the set of micro irregularities identified following the indications of the surface roughness standard, comparing the two areas resulting from water jet cutting with abrasive, it is observed that at the entrance of the jet into the material, the first 5 mm of the sample, R_a values both on the left as well as on the right side of the jet are similar, the differences being almost imperceptible. However, for R_a measured at the exit of the sample it is observed that the values differ, R_a for the right surface being much smaller, by almost 4μm, compared to the R_a value at the exit from the left surface. This difference may be due to the presence of impurities on the surface of the cut part (corresponding non-degreasing) or the structural inhomogeneity of the part. For this reason, another way of measuring the roughness was used, by choosing 3 areas of equal dimensions (0.8mm · 0.8mm) from the start area (M_1) of the cut, the middle area (M_2) and the end area (M_3). By using this method, the surface topography of the part for both surfaces both at the entrance and at the exit has much lower shape deviations than in the case of the first measurement method.

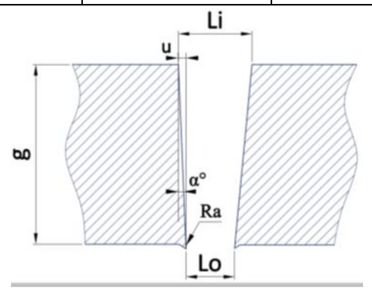
Regarding the influence of variable process parameters (feed rate, pressure and abrasive material flow) on the surface roughness of all samples cut, for the entire experimental plan, the following can be stated:

- the parameter "abrasive material flow" has the greatest influence on the roughness, i.e. lower values of roughness for the situation of using a larger abrasive material flow (300 g/min);
- the influence of the abrasive material flow is visible especially in the case of M_1:M_3 average (on the entire cut surface), where the R_a values are lower than the R_a values according to the standard (on 5mm);
- the best experiment, in terms of roughness, was experiment number 2, in which the following process parameters were used: low pressure - 100MPa, traverse speed 100 [mm/min] and abrasive material flow bigger, 300g / min.

The MR parameter was determined based on the relation: MR = ρ / volume, [g], where the density *ρ* was measured using an analytical balance, the calculated surface took into account the width of the processed surface at the jet inlet (L_i), the width of the surface processed at the jet outlet (L_o) and the height (g) of the isosceles trapezoid made by the water jet at the time of cutting which coincides with the thickness of the material cut. Normally the surface on the left and on the right should not differ significantly, but variations may occur due to possible irregularities / inhomogeneities of samples cut.

Table 2. Experimental data on measurements recorded and / or calculated for experiment number 2, material Arbofill Fichte

Exp no.	Side	Start-Stop Cutting	R_a (ISO 1997) [µm]	R_a-M_1 [µm]	R_a-M_2 [µm]	R_a-M_3 [µm]	R_a- (M_1:M_3) [µm]	L_i [mm]	L_o [mm]	u[mm]	α[°]	MR[g]
1	Left	input	8.39	11.17	7.45	5.36	7.99	1.07	0.91	0.08	0.45	0.43
	Left	output	13.94	12.25	7.90	9.45	9.86					
	Right	input	8.09	9.31	5.32	6.43	7.02					
	Right	output	8.94	7.38	10.13	5.53	7.68					
2	Left	input	7.31	7.21	6.24	4.26	5.90	1.10	0.96	0.07	0.40	0.44
	Left	output	14.44	9.68	7.13	6.28	7.69					
	Right	input	7.18	7.63	7.15	5.43	6.73					
	Right	output	8.71	9.24	8.50	7.59	8.44					
3	Left	input	7.17	5.20	5.75	9.80	6.91	1.08	0.94	0.08	0.40	0.44
	Left	output	8.94	6.93	10.28	6.93	8.04					
	Right	input	7.42	6.18	6.77	7.37	6.77					
	Right	output	8.33	6.65	7.24	5.94	6.61					
Average	Left in		**7.62±0.66**	8.78±2.16	7.28±1.47	6.68±1.90	**7.58±1.14**	**1.08±0.01**	**0.93±0.02**	**0.07±0.005**	**0.42±0.03**	**0.44±0.008**
	Left out		**12.44±3.04**	9.62±1.56	8.43±0.96	7.55±0.97	**8.53±0.15**					



Dimensions of the cut surface: ISO/WD/TC 44 N 1770:2010, [20] Taking into account this aspect, in this paper will be presented the roughness diagram only for the lowest values of roughness, input and output for the right surface resulting from cutting, Figure 4. In this figure, you can also see some deviations of shape, depths or maximums of the roughness R_a, which are normal, can be neglected because the deviation being so small, the deviations can be attributed to the abrasive powder involved in the cutting process.

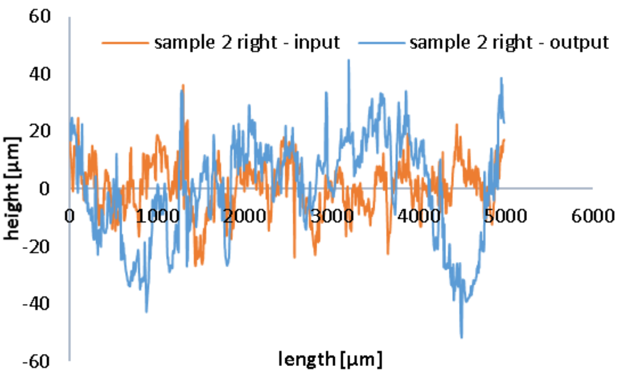


Fig. 4. Roughness variation for the right surface of the cut, inlet - outlet, cutting 2 from experiment number 2

Figures 5 and 6 offer the possibility to create an overview of the average values obtained for roughness by the two measurement methods previously presented. The largest deviations and deviations are obtained for the experimental test with number 4, both at the entrance of the jet and at its exit, the results being negatively influenced, most likely, by the value of the parameter "traverse speed" having the value of 150mm/s.

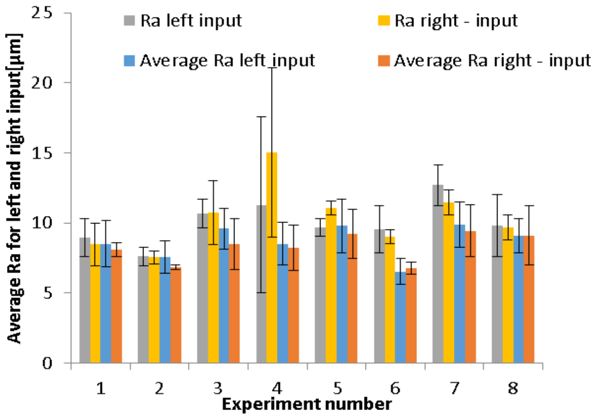


Fig. 5. Average roughness values at the entrance of the abrasive water jet for the two measurement methods

Since the values of the width machined surface at the jet inlet (L_i) are greater than those of the widths of the machined surface at the outlet of the jet (L_o), a taper of the cut results, influenced by parameters such as material thickness (g) and traverse speed, Figure 7. The taper is in the shape of a "V", the entrance in the material on the side of the cutting nozzle being wider and on the reverse side of the piece being slightly narrower. In this sense, the deviation from the perpendicularity of the abrasive jet was determined by finding the tilt angle of the processed surface, their values being visible in Table 2 (for experiment 2) but also in Figure 8 (for the entire experimental plan).

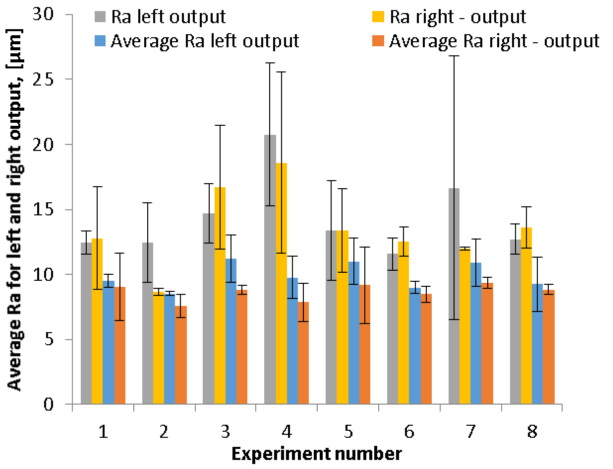


Fig. 6. Average roughness values at the water jet outlet with abrasive for the two measurement methods

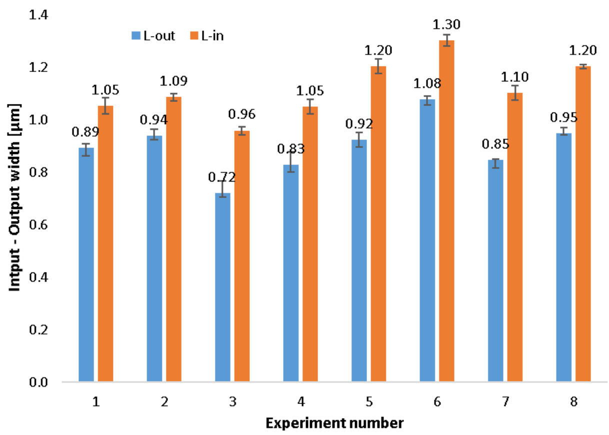


Fig.7. The variation of the widths resulting at the moment of cutting at the entrance and exit of the water jet with abrasive

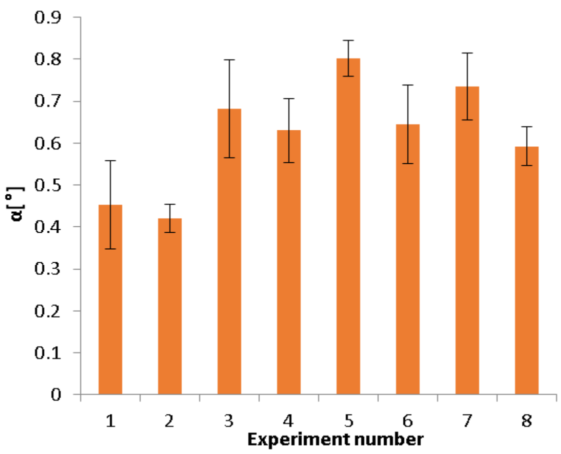


Fig 8. Variation of the tilt angle of the processed surface for the entire experimental plan

The lowest value of the tilt angle is (0.42 ± 0.33) ° for the experimental test with number 2, which offers in

addition to obtaining surfaces with minimal dimensional deviations and low material consumption (MR), (0.44 ± 0.008) g , the two output factors of the cutting process, being closely related.
Regarding the roughness on the entire surface of the part, the values are slightly lower than in the case of determinations on restricted portions of the sample, for experiment 2, Table 3. The meaning of the terms in Table 3 is: Sa_{in} represents the surface roughness at the jet entrance of water, [μm]; Sa_{out} is the roughness on the surface at the exit of the water jet, [μm].

Table 3. Surface roughness values in case of experiment 2

Sample Cut	Side	Sa_{in} [μm]	Average Sa_{in} [μm] Left	Average Sa_{in} [μm] Right	Sa_{out} [μm]	Average Sa_{out} [μm] Left	Average Sa_{out} [μm] Right
1	Left	6.114	6.25±0.18	6.09±1.14	8.441	8.48±0.22	8.05±0.48
	Right	5.104			7.925		
2	Left	6.186			8.29		
	Right	7.344			8.6		
3	Left	6.47			8.726		
	Right	5.842			7.654		

For the whole experimental plan, the surface roughness values are also lower, as can be seen in Figure 9.

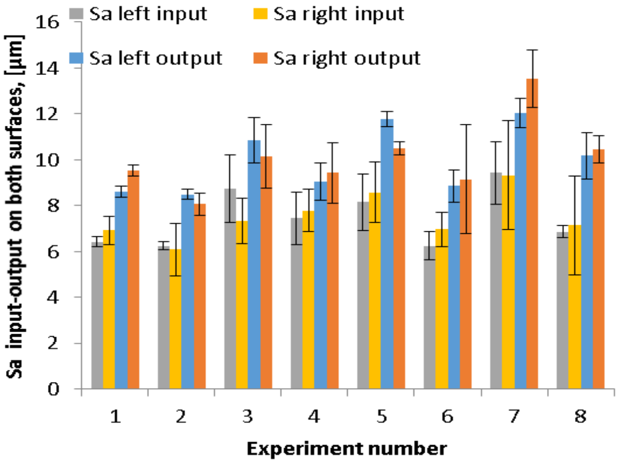


Fig. 9. The surface roughness of the cut piece in the experiment number 2

4. CONCLUSIONS

The evaluation of the quality of the abrasive water jet cutting of the biodegradable material Arbofill Fichte highlighted an admissible quality of the resulting surfaces. The most used component of R_a roughness was measured and analyzed.
Following the analysis of the experimental results, there are some important conclusions regarding the influence of the technological parameters used, as follows:
- the temperature involved in the process of cutting with water jet with abrasive usually has values in the range (78-80) °C, which does not affect the structure and chemical stability of the Arbofill Fichte material, this range being well below the temperature thermal degradation of the cut biopolymer. Water, from the processing process AWJ, has the role not only of acceleration medium, transfer of kinetic energy on the abrasive particles in order to remove the polymeric material but also of cooling medium, also taking over the residues resulting from the cutting;
- the thickness of the piece, allowed to obtain an admissible surface roughness, for the field of industrial engineering. However, in order to improve this parameter, R_a, it is possible to recommend the modification of the adjustable parameters as follows: increasing the pressure of the water and abrasive mixture, decreasing the traverse speed of the cutting head and increasing the abrasive material flow. Therefore, the R_a values (determined according to the standard but also the chosen method) depend not only on the material cut or the depth of the cut, but also on the quantity, quality and size of the abrasive material;
- it is recommended to use a higher abrasive mass flow to increase the smoothness of the surface. As the cutting speed increases, the surface roughness increases. This means that the reduced traverse speed should be used to have a smoother surface, but it is to the detriment of decreased productivity.
This research has demonstrated, from an experimental point of view, that the proper selection of cutting parameters is very important, otherwise the AWJ process can greatly reduce the cutting performance, which is reflected in the surface quality of the surfaces resulting from cutting.

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