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Technological parameters influence on biodegradable injected polymers during water jet cutting

DANIEL MĂRGUȚĂ[1], EUGEN HERGHELEGIU[2], CĂTĂLIN TÂMPU[2], SIMONA-NICOLETA MAZURCHEVICI[1], DUMITRU NEDELCU[*]

[1] " Gheorghe Asachi" Technical University of Iasi, Department of Machine Manufacturing Technology, Blvd. Mangeron, No. 59A, 700050, Iasi, Romania
[2] "Vasile Alecsandri" University of Bacau, Faculty of Engineering, Calea Maraserti 157, 600115, Bacau, Romania

Abstract. Arbofill Fichte and Arboblend V2 Nature are polymers with high-performance functional characteristics and which have the potential to replace plastics based on non-renewable resources from various sectors of activity. The present study aims to analye from topographical point of view the behavior of injected parts during the processing by cutting with abrasive water jet. The materials behavior, as expected, in any machining or manufacturing process is influenced by the technological parameters, whether they are kept constant (for example the part thickness, the abrasive material, the distance between the cutting head and the part) or variable (pressure, traverse speed and abrasive material flow). In this sense, the purpose was to obtain data regarding the most used roughness parameter, R_a, and based on them some solutions for optimizing the working parameters will be provided, so that the surfaces quality to be as good as possible. The results showed that the technological parameter "abrasive material flow" has the greatest influence on the roughness, ie lower values of roughness for the situation of using a larger amount of abrasive.

Keywords: AWJ, biopolymers, R_a, MRR.

1. Introduction

Biopolymers based on renewable resources find their applicability more and more often in various industrials due to their physical and mechanical performance. However, their processing is quite difficult because they cannot be subjected to processes which are involving heat sources because their melting point is low,

[*]Correspondence address: dnedelcu@tuiasi.ro

around 180°C. Due to this fact, the polymeric materials were generally cut with a traditional saw, and when a cut with a high heat source, laser, was applied, the cutting quality was very poor, showing damage by burning the material in the cutting area front, large dimensional deviations, excessive burr formation, etc. Thus, Abrasive Waterjet (AWJ) processing has appeared in industries, being a technology that has no negative effects on the structural stability of polymers because it is a "cold" one. Other advantages of AWJ are: reduced cutting forces, high flexibility, high versatility in execution, admissible quality of the resulting surfaces, [1 - 3]. The technology is based on the use of a high speed and pressure water jet but also on an abrasive suspension that has the role of cutting the part by erosion.

Researchers' concerns regarding AWJ of polymers have generally focused on determining surface quality by measuring roughness, dimensional and geometric accuracy but also the amount of material removed during processing (MRR - Material Removal Rate), [4, 5]. The studied polymers generally are from the synthetic and polymeric matrix composites category, [4 - 9], most probably due to their adequate structural behavior highlighted during cutting.

The novelty of this study consists in the analyze of the cutting performances of two types of biopolymers (Arbofill Fichte and Arboblend V2 Nature) by varying the process parameters in order to obtain an admissible surface quality for industrial applications.

2. Materials and methods

Arboblend V2 Nature and Arbofill Fichte biopolymers were used for abrasive water jet processing, having as chemical constituents lignin, PLA (polylactic acid), cellulose, bio-PA (bio-polyamides), bio-PE (bio-polyolefins) and as binders, natural additives such as waxes, resins, fatty acids, oils, but also natural vegetable fibers, [10]. The material was designed and made by Tecnaro in collaboration with the Fraunhofer Institute for Chemical Technology (IKT) and the distributor of this material is the Tecnaro company itself (Ilsferd, Germany). The material was purchased in the granules form in order to inject it into the mold, and then the obtained samples to be subjected at abrasive water jet cutting.

In order to obtain samples, the SZ800 H industrial injection machine from the Fine Mechanics and Nano Technologies laboratory, "Gheorghe Asachi" Technical University of Iasi was used. The samples from biodegradable polymers had the size of (58x48x10) mm and the mold temperature 50°C. The considered injection moulding parameters during the process are presented in table 1:

Table 1**.** Parameters used to inject the samples from biodegradable polymers

Biopolimer	T_{inj} [°C]	P_{inj} [MPa]	s_{inj} [mm/s]	t_r [s]
Arboblend V2 Nature	170	110	90	25
Arbofill Fichte	155	90	80	25

where: T_{inj} - injection temperature, [°C]; P_{inj} - injection pressure; s_{inj} - injection speed; t_r - cooling time.

Regarding the AWJ, it was made on the Hydro Jet Eco 0615 equipment and the input parameters kept constant throughout the cutting cycle were: the thickness of the part - 10mm; distance between machining head and sample - 3mm; water hole diameter - 0.35mm; the length of the focusing tube - 76.2mm; focusing tube diameter - 1.02mm; abrasive material - Garnet.

The abrasive water jet cutting was carried out following a factorial experimental plan 2^3 type (involving 8 experiments) by varying three variable process parameters each on 2 levels. The presentation of the experimental plan is given in table 2:

For each of the 8 proposed experiments, three cuts were performed (on the same sample) using the same process parameters. The repeats were performed in order to demonstrate the experimental repeatability but also the structural homogeneity of the injected biopolymers into the mold. The cut was made on a length of 30mm, and the distance between the cuts was 7mm.

Table 2. Factorial experimental plan - abrasive water jet cutting

No. crt.	Input parameters		
	P [MPa]	v_f, [mm/min]	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

P – pressure, [MPa]; v_f - traverse speed, [mm/min]; Q – debit material abraziv, [g/min].

The present study is focused especially on determining the most used component of roughness, R_a, for determining the surface quality of the profile obtained by abrasive water jet cutting. Two distinct methods were used to determine this parameter:

The *first method* was realised in accordance with SR ISO 468: 1997 standard, [11], which stipulates that the test area should be in the first (5x0.8) mm surface from the entrance and respectively from the exit of the abrasiv water jet, Fig.1.a. Due to the registred microneregularities, it was considered necessary to apply another test method, that follow the measurement of several areas from the resulting surface. The *second method* of roughness measuring, Fig.1.b, required the selection of three areas of analysis, input, middle and output of the cut surface. The recording data were summed in order to obtain an average R_a for all three areas taken into account in this method. The determinations of both the first and the second method were performed for all 8 experiments, for each biopolymeric material separately.

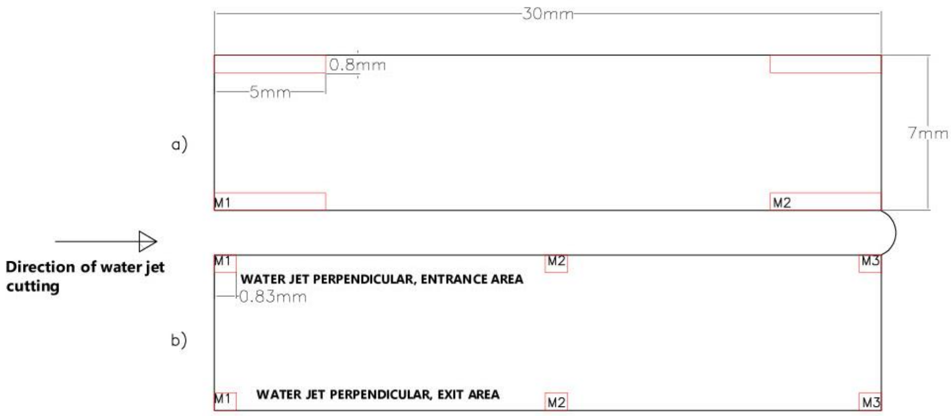


Fig. 1. Roughness analysis methods: a) method 1; b) method 2.

The determination of the surface topography of the parts cut with abrasive water jet was performed on the Zygo optical profilometer (Zegage series), the determination method being based on the coordinate analysis of the surface profile. The magnifying power of the eyepiece was 10X covering, during a single scan, an area of (0.83 · 0.83) mm. The following measurements were made with the eyepiece with magnification of 10X:

a) for the method according to the standard - scanner programming for surveying in 8 steps on 8 different surfaces, so that the entire analysis surface is covered;

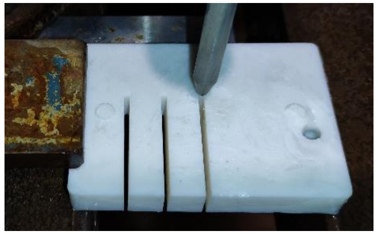
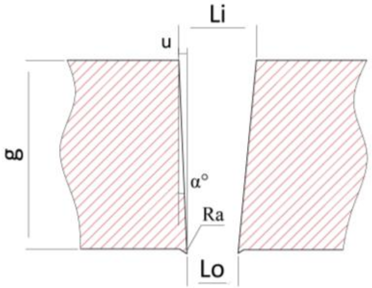
b) for the second method of data collection the scanning depth was 600µm to cover the inclination angle, at each measurement the same pattern and the same dimensions per column and row being maintained.

Also, it was possible to represent the surface profiles, topographic images of heights and depressions resulted from the processing. For these images, a 2.75X magnifying glass eyepiece was used to capture in more depth all the shape deviations.

3. Results and discussions

Following the measurements performed with the optical probillometer available in the Dimensional Control laboratory, "Vasile Alecsandri" University of Bacau were collected data on the analyzed surfaces roughness according to the two methods mentioned in subchapter 2. Also, the deviations values from the perpendicularity, the inclination angles of the machined surfaces, the amount of material removed and the width of the machined surface at the entrance and exit were determined by measurement and calculation. The average values recorded for the experiment in which the lowest roughness values were identified for both materials, experiment number 2, are presented in table 3. Process parameters for this experiment were: low flow pressure - 100MPa, low traverse speed - 100 [mm / min] and high abrasive material flow, 300g / min.

Table 3. Experimental data on the measurements recorded and / or calculated for experiment number 2, Arboblend V2 Nature and Arbofill Fichte biopolymers

Material	Exp no.	Side	Start-Stop Cut	R_a (ISO 1997) [µm]	$R_a(M_1{:}M_3)$ [µm]	L_i [mm]	L_o [mm]	u [mm]	α [°]	MRR [g]
Arboblend V2 Nature	Average	Left in		7.10±0.98	6.62±0.92	1.14±0.01	0.95±0.01	0.09±0007	0.53±0.04	0.45±0.005
		Left out		7.87±0.69	7.50±0.84					
		Right in		7.06±0.30	5.92±0.48					
		Right out		8.21±1.34	7.69±0.55	*Arboblend V2 Nature cutted sample*			*Arbofill Fichte cutted sample*	
Arbofill Fichte	Average	Left in		7.62±0.66	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	8.53±0.15					
		Right in		7.56±0.47	6.84±0.15					
		Right out		8.66±0.30	7.57±0.92	ISO/WD/TC 44 N 1770:2010, [13]				

R_a – roughness of the processed surface determined according to the SR ISO 468: 1997 standard, [µm]; $R_a(M_1{:}M_3)$ – average roughness measured according to the second method of data collection, [µm]; L_i - width of the machined surface at the jet inlet, [mm]; L_o - width of the machined surface at the jet outlet, [mm]; u - deviation from perpendicularity, [mm]; α - inclination angle of the machined surface, [°]; MRR – Material Removal Rate, [g]; g – thickness of the sample, [mm].

For the situation in which the measurements complied with the SR ISO 468 1997 standard indications, it was observed for both materials that the dimensions of the micronegularities for the input area on both, left and the right side, of the cut have similar values which confirms that the processing was stable in the first 5mm of testing (acting uniformly on either side of the cut). But, the roughness in the output areas for the two analyzed zone (left, right) no longer coincides, the differences being very large especially in the case of Arbofill Fichte material. For the Arboblend V2 Nature material, the deviations are not so big, about 1µm. These differences between the input and output values for the two analyzed areas can be attributed to the uneven structure of the materials, but also to the presence of impurities.

Due to these differences between the resulting areas roughness, the second method was proposed by analyzing three areas from the total machined surface: entrance (M_1), middle (M_2) and exit (M_3) as was shown in Fig. 1. Using this last method, the roughness values decrease in the case of both materials, but the most visible effect is for the Arbofill Fichte material. This difference between the two ways of measuring R_a comes from considering an additional area from the resulting surfaces, thus collecting a clearer image, reducing the error rate.

To determine MRR, the density and volume of material were taken into account. MRR values are slightly higher for Arboblend V2 Nature material, probably due to its slightly higher density comparative with Arbofill Fichte material. This fact derives from its structure which is almost 100% biodegradable, containing vegetable fibers and natural biopolymers. Arbofill Fichte has a lower biodegradation rate of up to 60%, and also contains synthetic polymers that have a much lower mass than natural biopolymers. It is known that one of the biodegradable polymers limitations is their mass, considerably higher than that of conventional polymers, [12].

To provide an overview of all experiments, the graphs presented in Fig. 2 and Fig. 3 were plotted. These figures outline very well the influence of process parameters on the obtained results, as follows:

- it is observed that the experiments with even number (2, 4, 6, and 8) show lower values of roughness (in the case of both materials) than in the case of odd experiments. This beneficial decrease is caused by the high *amount of abrasive material* used, 300g / min;
- this decrease is more visible in the case of the data collection method number two $R_a(M_1{:}M_3)$ compared to the method for determining R_a based on the standard requirements;
- the *traverse speed* also has a significant role because with the decrease of it, smoother surfaces are obtained and the cut is even more precise;

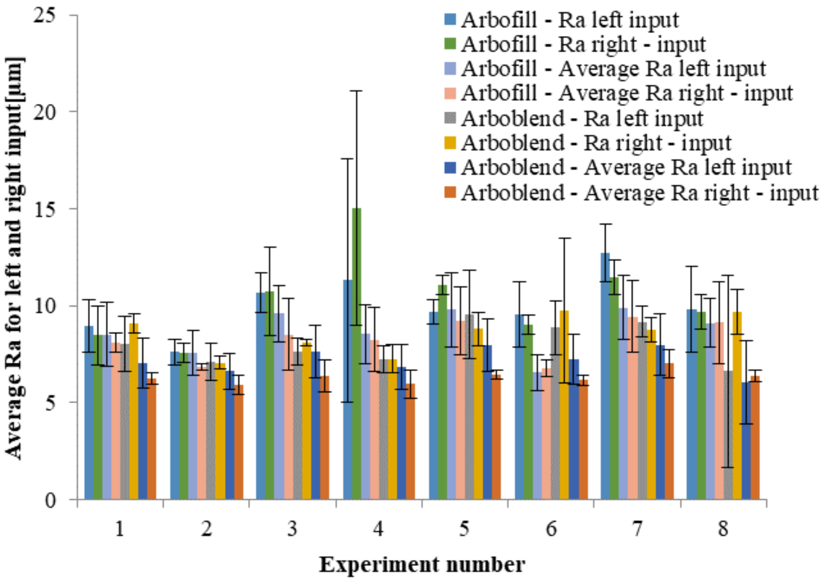


Fig. 2. Average roughness values at the abrasive water jet inlet for the two measurement methods.

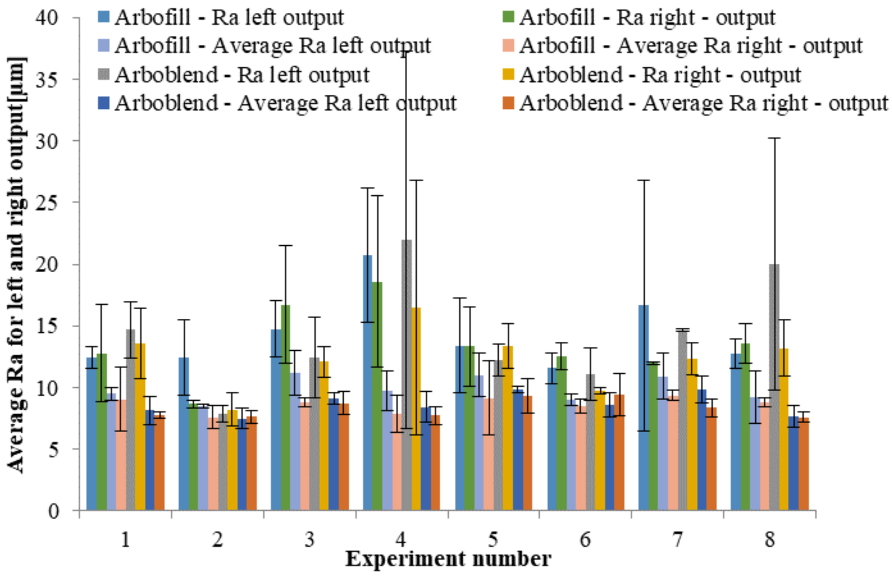


Fig. 3. Average roughness values at the abrasive water jet outlet for the two measurement methods.

- the *injection pressure* offers satisfactory quality even at 100MPa value, it is not necessary to increase it to 150MPa valu. For situations where all parameters would be set according to the specialized recommendations, [14-17], high abrasive water jet pressure, large amount of abrasive material and low traverse speed - the resulting surfaces should be smooth and with reduced deviations from linearity, ripples. However, in the experimental plan this situation is found in the case of the experiment with number 6, and is noted that the setting of the parameters of these values did not highlight the best behavior of the material during cutting. Thus, it is considered that the value of 100MPa was sufficient to obtain low deviations of micronegularities.

The roughness values in case of a perfectly homogeneous model and free of defects and impurities should be identical for both surfaces resulted from cutting, but in practice these values may vary within limited values and are closely influenced by a number of factors such as small defects / pores, or impurities due to imperfect / defective sandblasting of the cutting sample. Also, the R_a values differ for the analysed area at the entrance to the material and for the analysed area at the exit of the abrasive water jet. Fig. 4, presents the variable roughness results for their lowest values, experiment number 2, for each studied material. There is a series of maxima (heights) and minima (depressions) for both materials that can be disregarded or even eliminated when interpreting the results, as their presence is known and the causes can often be diminished.

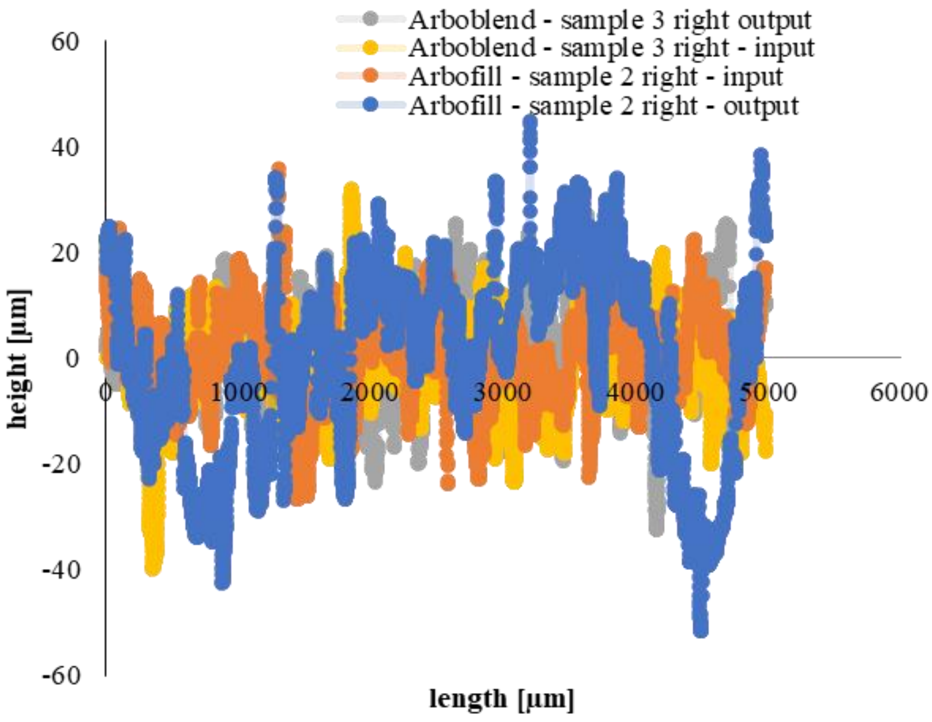


Fig. 4. Graphical representation of the roughness for the right surface of the cut, input - output: Arboblend V2 Nature - cutting number 3; Arbofill Fichte - cutting number 2.

Following the data from table 3 and Fig.5, regarding the width of the processed surface at the jet inlet (L_i) and the width of the processed surface at the jet outlet (L_o), the form of abrasive water jet erosion can be determined. Since the L_i values are higher than the L_o values, the cut conicity is in the "V" form, the shape being determined by the cutting speed and the thickness of the cutting piece (g). Once the cut conicity was determined, the deviation from the perpendicularity of the abrasive water jet (u) could be calculated by finding the inclination angle of the cut surfaces (α), table 3.

The L_i and L_o values for the Arboblend V2 Nature material are higher due to its chemical structure, being a more rigid material than Arbofill Fichte and thus yielding faster under the influence of water jet pressure, very visible effect in the case of experiment number 6, (Fig. 5), when the pressure is high, 150MPa.

The lowest values of the inclination angle for the two materials were recorded for the samples from experiment number 2: Arboblend V2 Nature (0.53 ± 0.04)° and Arbofill Fichte (0.42 ± 0.33)°, Fig. 6. And in these results the influence of the chemical structure and morphology of the biopolymer with a higher biodegradation degree is felt. Consequently, the dimensional deviations and MRR values being lower for Arbofill Fichte.

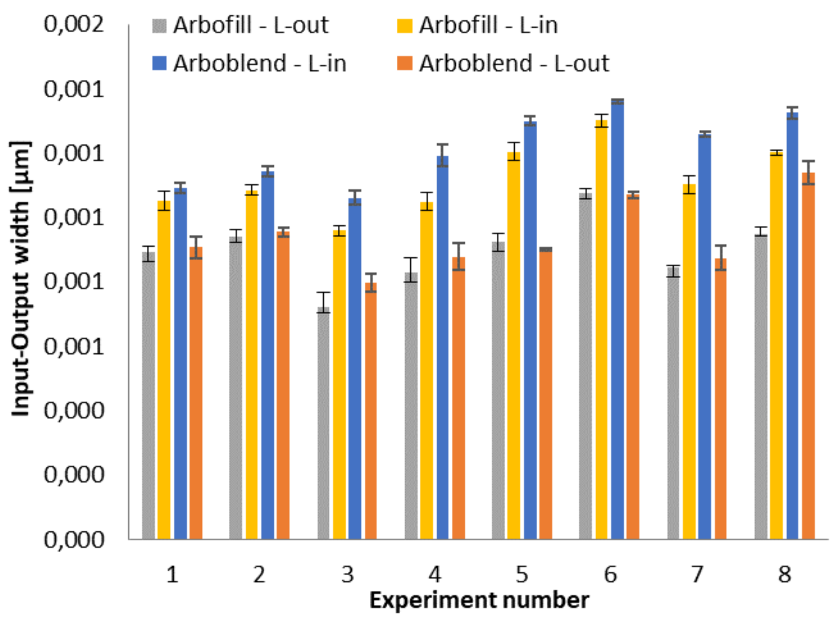


Fig.5. Variation of the widths resulting at the cutting moment for the abrasive water jet entrance and exit.

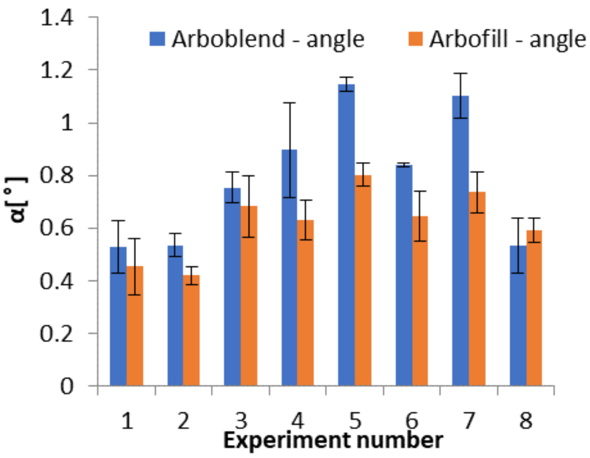
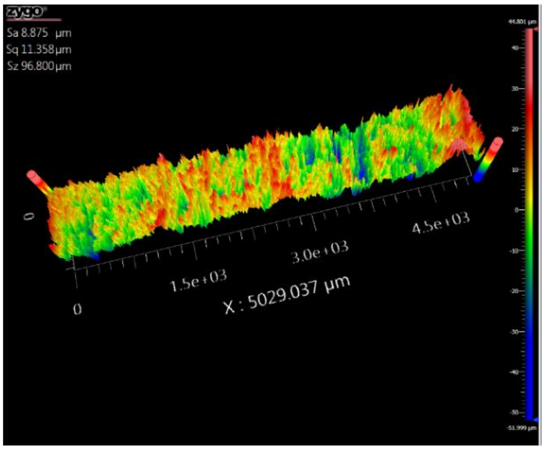
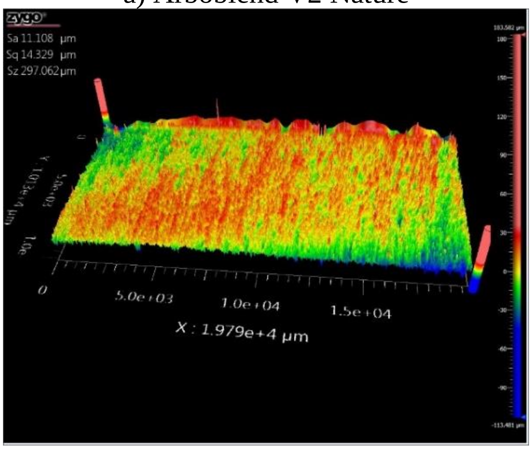


Fig 6. Variation of the inclination angle for all the performed experiments.



a) Arboblend V2 Nature



b) Arbofill Fichte

Fig. 7. Surface profile of cut samples by using AWJ.

In order to have an overview image regarding the surface roughness of the entire cut area, surface topographies were realised, Fig. 7. Regarding the topographies, the presence of some maxims and minimums of the roughness caused by the abrasive material effect and injection pressure is observed.
Table 4 and Figs. 8 shows the average Sa_{in} (surface roughness at the entrance) and Sa_{out} (surface roughness at the exit) values where the Arboblend V2 Nature material for the entry area reveals higher linearity deviations than the other analysed material. However, when the water jet leaves the material, higher values are recorded for the Arbofill Fichte material.

Table 4. Surface roughness values, experiment number 2

Sample cut	**Average Sa_{in}**		**Average Sa_{out}**	
	Left side	Right side	Left side	Right side
Arboblend V2 Nature	6.97± 1.09	6.54± 0.51	8.35± 1.11	7.66± 1.72
Arbofill Fichte	6.25±0.18	6.09±1.14	8.48±0.22	8.05±0.48

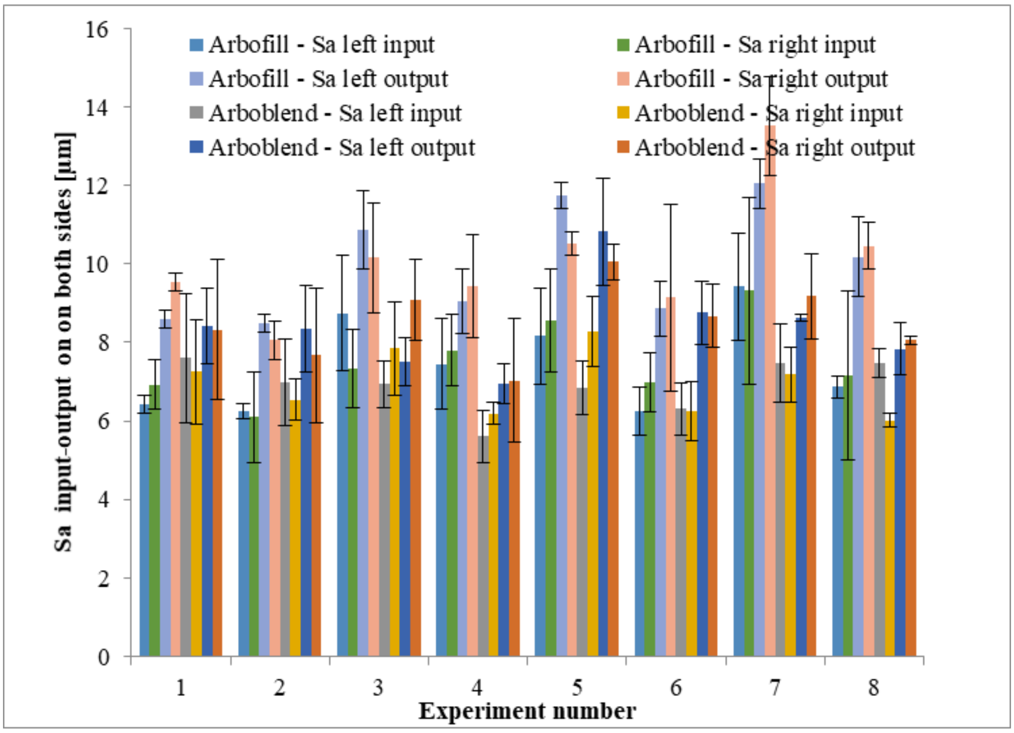


Fig. 7. The surface roughness of the cutting sample, experiment number 2, for both studied materials.

Conclusions

Following the experimental results analysis, the influences of the process parameters on the resulting surfaces roughness were noticed of the parameters. The parameters that had a significant effect were as follows:

- *quantity of abrasive material*: in the case of both studied materials it was observed that with the increase of abrasive material proportion, the surface roughness decreases especially for R_a measured in the jet exit area;

- - *traverse speed*: positively influence the results when it was set to level one of variation (100mm / min), an observation valid for all measurements, both at the beginning and at the end of the cut;

- *cutting pressure*: it is a parameter as important as the traverse speed, its variation at high values producing smoother surfaces. However, this parameter must be limited to values below 400MPa, otherwise it produces negative effects such as cavitation, delamination, splitting, shearing, disintegration, etc.

An important role in abrasive water jet processing is also played by the sample thickness, the quality and size of the abrasive material, material type and temperature involved in the process.

It can be concluded that the samples from eco-friendly polymers can be processed with the help of AWJ technology since it does not impress a thermal effect on them as is it happens usual in case of conventional processing such as LASER jet processing, drilling and milling.

It is recommended after noticing the influence of the process parameters, setting them as follows: increased water jet pressure, low traverse speed of the cutting head but also large amount of abrasive material.

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