Behavior of Arboblend V2 Nature under AWJ machining

D Marguta1, E Herghelegiu2, C Tampu2, S-N Mazurchevici1 and D Nedelcu1,3
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 Marasesti 157, 600115, Bacau, Romania
3Academy of Romanian Scientists, Str. Ilfov, Nr. 3, Sector 5, Bucharest, Romania
E-mail: dnedelcu@tuiasi.ro

Abstract. The harmful effects on the environment caused by the overexploitation of fossil resources and their industrial processing have attracted the attention of researchers worldwide. Their interest is not only in the use of biodegradable materials based on renewable natural resources but also in the use of manufacturing and processing technologies that minimize as much as possible the negative footprint left on the natural ecosystem. In the present paper, the thermoplastic material processed using abrasive water jet cutting technology (AWJ) is Arboblend V2 Nature. Thus, both the processed material and the technology closely follow the interests of the researchers. The study aims to obtain surfaces with higher quality than other synthetic polymers by appropriate variation of process parameters (abrasive material flow, traverse speed and pressure). Two methods for determining the roughness were used, one in accordance with the standard and one adopted by the authors in order to render more accurately the surface roughness value. Other output parameters observed were: the amount of material removed, the width of the machined surface, the deviation from the perpendicularity and the inclination angle of the machined surface. The output parameters result confirms the possibility of using the parts obtained by AWJ in engineering applications and not only because the shape deviations fall within the limitations imposed at the industrial level.

1. Introduction
AWJ (Abrasive-Waterjet) is an unconventional processing technology that due to its versatility finds its applicability in various fields: cutting, surgery, nuclear plant dismantling, cutting soft materials, paint removal, drilling, etc. The extended applicability is due to the possibility of working with various classes of materials: steels, alloys, polymers, composites, stone-granite, concrete, reinforced plastics, wood, metal and polymer laminates and others.

Considering that currently the global interest is directed towards on harmful effects of manufacturing processes on the environment, all these are in a continuous process of re-evaluation. Regarding the process of machining with abrasive water jet, it takes into account the following aspects related to pollution: water recycling, recovery of material removed by erosion, disposal of wastewater (domestic), recovery and reuse of abrasive material. All these concerns have led to the permanent development and innovation of AWJ, and today there is the possibility of using a high-pressure cryogenic jet machine. By using this alternative, the water is replaced with liquid nitrogen and the abrasive material with dry ice crystals, thus eliminating the factors that destabilized the balance in the
environment, [1]. Compared to most machine-tools that use other working methods (LASER, photochemical engraving, EDM, plasma), AWJ has multiple and even unique facilities:

- **common advantages**: automated procedure, position accuracy, ergonomics, ease of handling, qualitative results;
- **individual advantages**: cold cutting, large variety of workable materials, high cutting speed (compared to thermal methods), small or large thicknesses; maintains the chemical and structural integrity of the basic material, ecological (without toxic by-products), multiple processing by using a single tool assisted with accessories, economic efficiency, precision at micro and macro level; reduced force exerted on the work piece;

Cutting through this procedure is quite simple involving the use of process parameters that decide the quality and efficiency of the whole process. Process parameters can be classified into four groups, which aim: cutting - travel speed, angle of inclination and separation distance (water jet width); hydraulic - pressure and flow; mixture - the size of the mixing tube; abrasive material - material, particle size and flow, [2, 3].

The process parameters, as in the case of all technologies, have significant effects on the expected results. One of the most important parameters is the abrasive material. The most used abrasive in AWJ is Garnet due to the performances obtained by using it but also to the low acquisition cost. The size and flow of the grenade are very important, they must be constant and the abrasive particles size must not be larger than 1/3 of the diameter of the mixing tube nozzle. If the nozzle size is reduced, the abrasive needs to be finer, but it is more difficult to flow under gravitational feeding, [4]. The surface roughness of the edges treated with abrasive water jet is proportional to the particle size. In this sense, permanent improvements are made, so that the surface quality is as high as possible.

Over time, polymers, composite and brittle materials have encountered major difficulties in processing through the use of conventional machine tools. The main limitations were related to thermal sensitivity, low tensile strength, brittleness, [5 - 7]. Another aspect pursued by the researchers was to eliminate the contact between the tool and the work piece. This drawback was solved by using nozzles, their wear being independent of the functional characteristics of the material to be cut, [4].

Following the above mentioned aspects, care for the environment and the influence of process parameters on the surface quality obtained by using AWJ, the present study aims to characterize in terms of surface roughness parts made of Arboblend V2 Nature biopolymer.

### 2. Materials and Methods

Arboblend V2 Nature biopolymer was used for abrasive water jet processing, which has as chemical constituents lignin, PLA (polylactic acid), cellulose, bio-PA (bio-polyamides), bio-PE (bio-polyolefins) and as binders. natural additives have been added such as waxes, resins, fatty acids, oils, but also natural vegetable fibers, [8, 9]. 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 company Tecnaro itself (Ilserfeld, Germany). The material was purchased in the form of granules in order to inject into the mold samples that can then be subjected to abrasive water jet cutting. The SZ800 H industrial injection machine from the Fine Mechanics laboratory, “Gheorghe Asachi” Technical University of Iasi was used for obtaining samples. The following process parameters were set to obtain the injection samples: injection temperature, $T_{\text{inj}} = 170 \ [^\circ\text{C}]$; injection pressure, $P_{\text{inj}} = 110 \ [\text{MPa}]$; injection speed, $s_{\text{inj}} = 90 \ [\text{mm/s}]$; cooling time, $t_r = 25 \ [\text{s}]$.

In order to machine the samples from Arboblend V2 Nature by cutting abrasive with water jet, the Hydro Jet Eco 0615 equipment was used. The pressed stable process parameters were: the distance between the processing head and the part - 3 \ [mm]; focus tube length - 76.2 \ [mm]; diameter of the water hole - 0.35\[mm]; focusing tube diameter - 1.02 \ [mm]; abrasive material type - Garnet [mesh # 80]; thickness of the cut sample – 10 \ [mm].

The experimental plan followed in order to make the cuts on the injected samples was a complete factorial plan of 2$^3$ type (8 experiments), ANOVA methodology - table 1. For each of the 8 experiments of the plan three identical dimensional cuts were made on the same sample. Repeating the
cutting was performed in order to follow the repeatability and homogeneity of the results obtained by varying on two levels the three selected process parameters (traverse speed, cutting pressure and abrasive material flow). The length of the cuts was 30 [mm] and the distance between them of 7 [mm].

Table 1. Complete experimental factorial plan for cutting samples.

| Level of variation | Q [g/min] | v_f [mm/min] | P [MPa] |
|-------------------|----------|--------------|---------|
| I<sup>st</sup>    | 150      | 100          | 100     |
| II<sup>nd</sup>   | 300      | 150          | 150     |

where: Q - abrasive material flow, [g/min]; v_f - traverse speed, [mm/min]; P – pressure, [MPa]

To determine the surface characteristics (R<sub>a</sub>) of the areas resulting from the processing, a Zygo optical profilometer (Zegage-series) from the Dimensional Control laboratory, "Vasile Alecsandri" University of Bacau was used. The equipment can also map, based on the analysis in coordinates profile of the resulting surface. Two methods of analysis were used to determine the surface roughness. The first method was the one conforming to the SR ISO 468: 1997 standard - which follows the analysis of the inlet and outlet area of the abrasive water jet on a portion of (5x0.8) mm. As the results recorded by this method were not very conclusive, due to too large deviations, it was decided to use a second measurement method. The second measurement method involved determining the surface roughness in three areas of the cut (inlet, middle and outlet) on a surface of (0.8 x 0.8) mm, which then outline the average surface roughness. The determinations were made each time in the same points of the cut for all the cuts made.

3. Results and Discussions

The results regarding the surface characteristics of the samples from Arboblend V2 Nature cut with abrasive water jet for the best experiment, number 2, are presented in table 2. Analysing the obtained values for the surface roughness determined according to the SR standard ISO 468: 1997, [10], it is observed that the results fluctuate both in the case of R<sub>a</sub> for the inlet area of the abrasive water jet and for its outlet area. The same variation takes place when the two resulting areas / surfaces are compared: the surface from the left of the cut and the surface to the right of it. The biggest difference between the R<sub>a</sub> values is visible in the case of the cut number two, when the roughness differs by up to 2μm for the input area (first 5mm) and the output area (last 5mm) of the cut. These differences are primarily due to the presence of impurities on the surface of the cut part, whether it is dust particles or other elements that were not removed before cutting. Another disruptive factor that may occur are particles of abrasive material remaining on the cut surface. Also, not excluded is the appropriate hypothesis that the homogeneity of the injected sample from the Arboblend V2 Nature biopolymer is not uniform. This structural non-uniformity is influenced by the imprecise setting of the material injection parameters in to the mould. These differences are also visible in the case of the best values of R<sub>a</sub>, namely for the right side of the cut, figure 1. These minimums and maximums of R<sub>a</sub> can be eliminated when on the basis of a structural and morphological analysis the causes of their appearance/production are detected.

Due to these micron irregularities identified during the determination of R<sub>a</sub> by the standard method, it was decided to apply another method of data collection which involved measuring the surface roughness for three areas of the cut, inlet (M<sub>i</sub>), middle (M<sub>2</sub>) and outlet (M<sub>3</sub>) on an area of (0.8 x 0.8) mm. Then, averaging the three R<sub>a</sub> values (R<sub>a</sub>-M<sub>i</sub>, Ra-M<sub>2</sub>, Ra-M<sub>3</sub>) obtained for each area analysed separately is obtained the R<sub>a</sub> (M<sub>1</sub>: M<sub>3</sub>). Looking at the data from table 2 but, also the graphs from figures 2 and 3, there is a visible improvement of the average values of the surface roughness, with up to (1.5 - 2) μm for each analysed area. This decrease in R<sub>a</sub> comes from taking into account a larger number of analysed areas, namely 6, on the entire surface of the cut.
| Exp no. | Side   | Start-Stop Cut | $R_a$ (ISO 1997) [μm] | $R_a$-M1 [μm] | $R_a$-M2 [μm] | $R_a$-M3 [μm] | $R_a$(M1:M3) [μm] | $L_i$ [mm] | $L_o$ [mm] | $u$ [mm] | $α$ [°] | MR [g] |
|--------|--------|----------------|-----------------------|---------------|---------------|---------------|-------------------|-----------|-----------|---------|--------|--------|
| 1      | Left   | input          | 6.93                  | 5.31          | 4.79          | 5.85          | 5.32              | 1.16      | 0.96      | 0.1     | 0.57   | 0.46   |
|        | Right  | input          | 7.09                  | 6.94          | 5.99          | 6.49          | 6.47              |           |           |         |        |        |
|        | Left   | output         | 7.19                  | 7.88          | 6.98          | 6.75          | 7.20              |           |           |         |        |        |
| 2      | Left   | input          | 8.16                  | 7.13          | 5.30          | 5.53          | 5.99              | 1.13      | 0.96      | 0.08    | 0.48   | 0.45   |
|        | Right  | input          | 6.75                  | 6.47          | 4.84          | 5.77          | 5.69              |           |           |         |        |        |
|        | Left   | output         | 9.74                  | 7.18          | 9.69          | 7.86          | 8.24              |           |           |         |        |        |
| 3      | Left   | input          | 6.22                  | 5.83          | 7.52          | 6.07          | 6.47              | 1.13      | 0.94      | 0.09    | 0.54   | 0.45   |
|        | Right  | input          | 7.82                  | 8.57          | 7.26          | 9.06          | 8.30              |           |           |         |        |        |
|        | Right  | output         | 7.36                  | 7.14          | 4.23          | 5.43          | 5.60              |           |           |         |        |        |
|        | Left   | input          | 7.70                  | 8.18          | 7.89          | 6.25          | 7.44              |           |           |         |        |        |
|        | Left   | output         | 7.10±0.98             | 6.92±0.97     | 6.82±1.17    | 6.10±0.86     | 6.62±0.92         | 1.14±0.01 | 0.95±0.01 | 0.09±0.007 | 0.53±0.04 | 0.45±0.005 |
|        | Right  | input         | 7.87±0.69             | 8.06±0.81     | 7.87±0.56    | 6.57±2.22     | 7.50±0.84         |           |           |         |        |        |
|        | Right  | output         | 7.06±0.30             | 6.85±0.34     | 5.02±0.89    | 5.89±0.54     | 5.92±0.48         |           |           |         |        |        |

where: $R_a$ is the roughness of the processed surface (ISO 1997 standard), [μm]; $R_a$-M1, $R_a$-M2, $R_a$-M3 - average values of roughness measured in line, [μm]; $R_a$(M1:M3) 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]; $α$ - tilt angle of the machined surface, [°]; MR - amount of material removed, [g]; $g$ - thickness of the part, [mm].
Figure 1. Graphical representation of the roughness for the right surface of the cut, input - output, cutting 3 from experiment number 2.

Figures 2 and 3 graphically reflect the differences between the two methods of measuring surface roughness. The most significant deviations of \( R_a \) in the jet entry area were recorded for experimental number 6. For the cut-out area the experiment with the highest \( R_a \) value was experimental number 4. These differences between the results recorded for each part of the experiment were influenced by the variation of the cutting parameters used.

Figure 2. Average roughness values at the abrasion water jet inlet for the two measurement methods.
Figure 3. Average roughness values at the abrasion water jet outlet for the two measurement methods.

The various technological parameters (traverse speed, pressure and amount of abrasive material) in the experimental plan have a significant influence on the results obtained:
- the amount of abrasive material seems to have the greatest influence on the surface roughness at the entrance of the abrasive water jet because it is observed that for experiments (odd) where the amount of abrasive material was lower (150g/min) are recorded higher values of $R_a$, $R_t$ ($M_1$; $M_3$). Otherwise, when the amount of abrasive material was increased to 300g/min (even number experiments) the roughness values decreased significantly;
- for the exit area of the abrasive water jet it is observed that there are two experiments, 4 and 8 for which the value of the surface roughness and the standard deviations are visibly higher than in the case of the other experiments. This increase in roughness is due to the high traverse speed, 150mm/min. In this situation it is recommended to maintain a constant amount of abrasive material (300g/min) and reduce the traverse speed to 150mm/min. The negative effect of the processing speed is also highlighted by other researchers who found that the surfaces cut at high traverse speed show deviations of shape, undulations and inaccurate dimensions, [11-14];
- the cutting pressure is a parameter that has a major influence on the roughness, [14, 15], and with its increase the surfaces become smoother. However, following the graphs and table 2, we cannot observe its positive effect. In this sense, a more in-depth analysis of the parameters influence should be performed with the help of a calculation program.

Experiment number two, used the most appropriate variation of the process parameters, pressure at level one of variation - 100MPa, traverse speed at level one of variation 100 [mm/min] and amount of abrasive material at level two of variation - of 300g/min, thus obtaining the lowest values of the output parameters: $R_a$, $R_t$ ($M_1$; $M_3$), $L_o$, $L_i$, $u$, $α$ and MR.

Determining the amount of material removed was determined by achieving the ratio between the density of the cut material and the volume of material removed. The volume of material removed took into account the measured values for the width of the processed surface at the entrance and exit of the abrasive water jet and the thickness of the cut piece / processing depth (10mm). The lowest value of the material removed amount during cutting with abrasive water jet is obtained for experiment number 2, for which only a quantity of $(0.45 \pm 0.005)$g is lost to make a cut of 30mm, depth of 10mm, input width of $1.14 \pm 0.01μm$ and output width $0.95 \pm 0.01μm$.

The width values of the machined surface at the inlet of the jet ($L_o$) are higher than those registered for the machined surface at the outlet of the jet ($L_i$), which makes the cut conical, in "V", figure 4. The
the taper of the cut is influenced by traverse speed and of the part thickness, the higher their values are, the more the taper increases and implies the deviation from the perpendicularity.

Figure 4. The variation of the widths resulting at the moment of cutting at the entrance and exit of the water jet with abrasive.

Another output parameter that can be calculated based on the inlet and outlet widths of the abrasive water jet but also on the deviation from the perpendicularity is the inclination angle of the machined surface. The mean values of this output parameter are presented for the entire experimental plan in figure 5. The smallest angle, as can already be guessed, is for experiment number 2, \((0.53 \pm 0.04)^\circ\) closely followed by experiments 1 and 8 \((0.53 \pm 0.1)^\circ\), the difference being very small and influenced by process parameters and structural homogeneity of the cut part. It is observed that the standard deviations are higher for experiments number 1 and 8.

Figure 5. Variation of the inclination angle of the processed surface for the entire experimental plan.
To determine the resulting surface roughness after cutting the entire part was used an eyepiece magnification, 10X, because it has greater accuracy due to thinning beam. The scanner was programmed to survey in eight steps on eight different areas so that at the end of the scan to obtain the surface profile and roughness for the entire analysed sample (Sa). Figure 6 shows the values of the surface roughness for the entire resulting cutting area and it is observed that the lowest value of Sa is recorded by the experiment with number 4 (table 3). Also, the influence of the parameter “amount of abrasive material” is visible because all experiments (2, 4, 6 and 8) that had the second level of variation of the input factor, 300g/min, presents average values of $S_{a_{in}}$ and $S_{a_{out}}$ with much lower than the other experiments (1, 2, 5 and 7).

![Figure 6](image)

**Figure 6.** The surface roughness of the cutting part in the experiment number 2.

Following the roughness values for $S_{a_{in}}$ and $S_{a_{out}}$, it is observed that the surface from the left and right of the cut reflects similar values, the differences being reduced by only 0.58[$\mu$m] for the entrance area and the exit area, 0.08 [$\mu$m].

| Sample Cut | Side | $S_{a_{in}}$ [$\mu$m] | Average $S_{a_{in}}$ [\mu m] | $S_{a_{out}}$ [$\mu$m] | Average $S_{a_{out}}$ [\mu m] |
|------------|------|----------------------|-------------------------------|------------------------|-------------------------------|
| 1          | Left | 6.36                 | 6.36±0.66                     | 6.41                   | 6.41±0.51                     |
|            | Right| 6.30                 | 6.30±0.28                     | 8.84                   | 8.84±0.51                     |
| 2          | Left | 5.08                 | 5.69±0.28                     | 7.43                   | 7.43±0.58                     |
|            | Right| 5.86                 | 5.86±0.28                     | 5.91                   | 5.91±0.58                     |
| 3          | Left | 5.39                 | 6.19±0.28                     | 7.02                   | 7.02±1.58                     |
|            | Right| 6.40                 | 6.40±0.28                     | 6.35                   | 6.35±1.58                     |

4. **Conclusions**

Determination of the abrasive water jet cutting behavior on the Arbobland V2 Nature biopolymeric material showed admissible values of the output parameters ($R_a$, $S_{a_{in}}$, $S_{a_{out}}$, $u$, $\alpha$, MR, $L_i$ and $L_o$) thus, the obtained surfaces by this process and from this material can be used in industrial applications.
The values of the input parameters had a considerable effect on the output parameters, influencing the results:
- the increase of the quantity of abrasive material at the second level of variation of the parameter, 300g/min, led to the improvement of the surface roughness, thus obtaining smoother cut surfaces;
- the increase of the traverse speed decreased the surface quality, a particularly visible effect for the cut exit area;
- the value of the high level pressure generally leads to obtaining fine surfaces, but exceeding a certain threshold (400MPa) and the use of a small width of the processing slot has negative effects on the surface quality;
- the processing temperature is a very important parameter in the case of polymeric materials, especially in the case of biodegradable ones because they are thermally sensitive, having phase changes at temperatures of maximum 60°C. The AWJ process being a "cold" one eliminates the possibility of material thermal degradation.

Following the analysis of the obtained results, it is recommended that in order to obtain the best possible surface quality for biodegradable polymers, the process parameters should be set as follows: large amount of abrasive material (300g/min), low traverse speed (100mm/min) and high flow pressure (150MPa).

5. References

[1] Andrew J Jefferson, Vellayaraj Arumugam, Hom Nath Dhakal 2018 Key stages of adhesively bonded repairs, Repair of Polymer Composites, Methodology, Techniques and Challenges, Woodhead Publishing Series in Composites Science and Engineering 3 97-224 https://doi.org/10.1016/B978-0-08-102263-4.00003-X.

[2] Srinath Reddy N., Dinesh Tirumala, Rajyalakshmi Gajjela, Raja Dasb 2018 ANN and RSM approach for modelling and multi objective optimization of abrasive water jet machining process Decision Science Letters 7 Growing Science Ltd. doi: 10.5267/j.dsl.2017.11.003.

[3] G. Gopichand, M. Sreenivasarao 2020 Multi-response parametric optimisation of abrasive waterjet milling of Hastelloy C-276 SN Applied Sciences 2 1764 https://doi.org/10.1007/s42452-020-03512-5.

[4] H.-T. (Peter) Liu, Vanessa Cutler, Chidambaram Raghavan, Peter Miles, Ernst Schubert and Nathan Webers 2018 Advanced Abrasive Waterjet for Multimode Machining Abrasive Technology - Characteristics and Applications Anna Rudawska, IntechOpen, doi: 10.5772/intechopen.75313. Available from: https://www.intechopen.com/books/abrasive-technology-characteristics-and-applications/advanced-abrasive-waterjet-for-multimode-machining.

[5] Liu H-T 2017 “7M” advantage of abrasive waterjet for machining advanced materials. Mint: Journal of Manufacturing and Materials Processing 1(11) 1-19 MDPI, Basel, Switzerland. doi: 10.3390/jmmp1010011. http://www.mdpi.com/2504-4494/1/11/1/pdf.

[6] Liu H-T, Schubert E. 2009 Piercing in delicate materials with abrasive-waterjets. Mint: The International Journal of Advanced Manufacturing Technology 42(3-4) 263-279 doi: 10.1007/s00170-008-1583-5.

[7] Liu H-T, Schubert E, McNiel D, Soo, K. 2010 Applications of abrasive-waterjets for precision machining of composites. In: Proceedings of SAMPE 2010 Conference and Exhibition, 17-20 May 2010 Seattle, Washington.

[8] TECNARO - The Biopolymer Company - https://www.tecnaro.de/en/, accessed at 12.11.2020.

[9] Nedelcu, D., Mazurchevici, S.-N., Popa, R.-I., Lohan, N.-M., Maldonado-Cortés, D., Carausu, C. 2020 Tribological and Dynamical Mechanical Behavior of Prototyped PLA-Based Polymers Materials 13 3615 https://doi.org/10.3390/ma13163615.

[10] SR ISO 468:1997: Rugozitatea suprafeţei. Parametri, valorile lor şi reguli generale pentru stabilirea specificaţiilor, available at http://resource.npl.co.uk/softgauges/pdf/Specification.pdf, accessed at 06.02.2021.
[11] ISO/TC 44 N 1770, available at: http://farsungroup.com/assets/farsun-group-waterjet-iso.pdf, accessed at 15.02.2021.

[12] Akkurt A, Kulekci M K, Seker U, Ercan F 2004 Effect of feed rate on surface roughness in abrasive waterjet cutting applications. *Journal of Materials Processing Technology*, 147(3) 389-396, https://doi.org/10.1016/j.jmatprotec.2004.01.013.

[13] Radu C, Herghelegiu E, Schnakovszky C, Tampu C 2015 Experimental analysis of the influence of feed rate on quality of cuts performed by AWJ *Journal of Engineering Studies and Research* 21(1) 76-80.

[14] Li, R., Ekevad, M., Guo, X., Cao, P., Wang, J., Chen, Q., and Xue, H. 2015 Pressure, feed rate, abrasive mass flow rate influence on surface roughness for recombinant bamboo abrasive water jet cutting *Bio. Res.* 10(2) 1998-2008.

[15] Pelit, H., Yaman, Ö. 2020 Influence of processing parameters on the surface roughness of solid wood cut by abrasive water jet *Bio Res.* 15(3), 6135-6148.