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TECHNICAL OPTIMIZATION OF WATER JET CUTTING OF BIODEGRADABLE MATERIALS

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Abstract: The main purpose of the technical optimization is to determine the optimal values of the processing parameters in order to increase the processing performance or decrease the processing time. Abrasive material water jet cutting is a processing process whose applicability is increasing in the conditions of the appearance of high-performance equipment. The technical optimization of this machining process aims at determining the distance between the machined material and the cutting head, determining the optimum length of the focusing tube, establishing the optimum machining pressure and determining the optimum amount of abrasive material so as to ensure maximum penetration depth of water jet with abrasive or minimizing surface roughness. During the research, the part subjected to abrasive water jet cutting was obtained by injection from Arboblend V2 Nature. The experiments were carried out according to a complete factorial plan 2^3, where the parameters on two levels were: water jet pressure, cutting speed and abrasive material flow. The optimization criterion followed was to minimize the standard roughness R_a. The experimental results showed that the parameter flow rate of abrasive material has the greatest influence on the roughness; the highest values of roughness are obtained when using a larger amount of abrasive (300g / min). The lowest value of the roughness of the cut surfaces is obtained for the following process parameters: low water pressure - 100MPa, high cutting speed - 150 mm / min and high flow of abrasive material - 300g / min.
Key words: optimization, cutting, water jet, biodegradable materials, roughness.

1. INTRODUCTION

In the case of technical optimization of the water jet machining process, the quality of the machined surface can be influenced by several parameters, such as: nozzle, focusing tube, pressure, feed rate, distance between machine head and part, amount of material abrasive, processed material and material thickness.
The technical optimization is based on the relations between the process parameters, and its main purpose is to determine their optimal values, in order to obtain either the maximization of the penetration depth of the jet, or the minimization of the roughness of the processed surface.

1.1 Optimization of water jet cutting parameters with abrasive to maximize the penetration depth

Optimizing the distance between the processed material and the cutting head, h
The distance h, (Figure 1) has a major influence on the quality of the machined surface, in the sense that the cutting depth decreases almost linearly with increasing distance between the cutting head and the machined part, according to research by Barton, [9, 10] (Figure 2), result also confirmed by A. Brent Strong [11] and Srikanth Pilla et al. [12], which proposed an optimal value of this distance of 2 mm, corresponding to the points on the left of the graphs.
In equation (1) is presented a calculation relation for the distance *h* proposed by the authors [13, 14].

$$h = \frac{0.29}{a} \cdot \frac{d}{2}, \text{ [mm]} \tag{1}$$

where: *a* represents a jet structure coefficient with values between (0.08-0.113), and *d* is the diameter of the focusing tube, [mm].

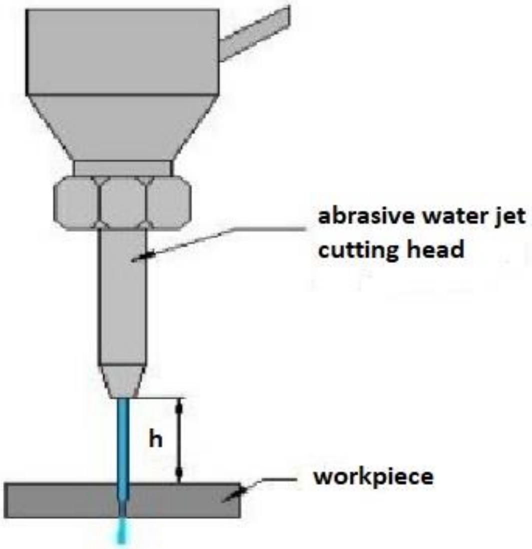


Fig. 1. The distance between the processed material and the cutting head *h*, [28]

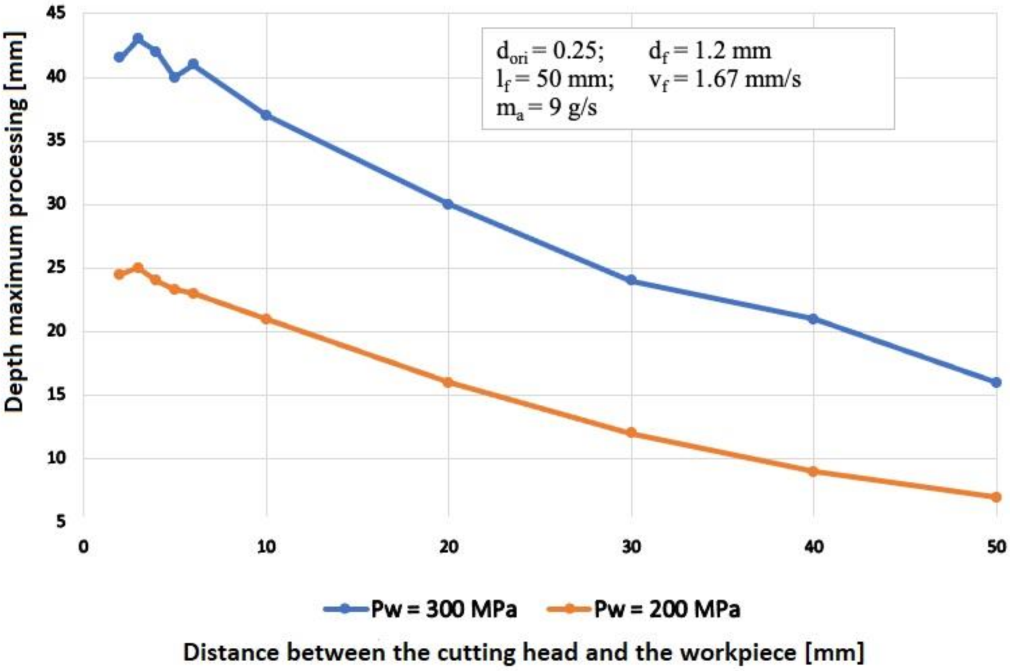


Fig. 2. The influence of the distance between the cutting head and the workpiece, *h*, on the processing depth, [28]

Determining the optimal length of the focusing tube

The influence of the length of the focusing tube on the depth of penetration can be explained by its role on the acceleration of abrasive particles. Figure 3 shows that the penetration depth of the abrasive water jet increases to a critical length of the focusing tube, which ensures that the speed of the abrasive particle is increased to a maximum value. Above this value of the length of the focusing tube, the friction of the abrasive particle by the tube wall causes the abrasive particle speed to decrease at the exit of the tube, thus decreasing the penetration depth. Low density abrasive materials, such as quartz sand, need longer lengths to reach maximum speed, which is why the influence of the friction process mentioned above is less noticeable.

In order to determine the optimal length of the focusing tube, the author A. Brent Strong, [11] proposed the equation (2).

$$\frac{l_f}{d_f} = 25...50 \tag{2}$$

where: l_f is the length of the focus tube, [mm] and d_f represents the diameter of the focusing tube, [mm].
In practice, the length of the focus tube is determined by the cutting performance (depth) and the life of the focus tube (Figure 3).

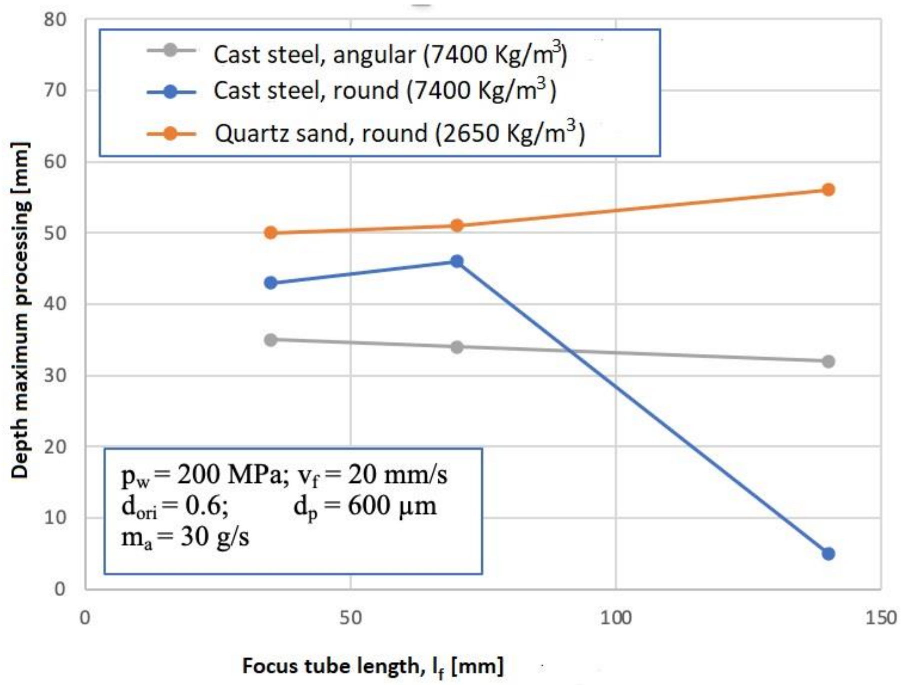


Fig. 3. Influence of focusing tube length on cutting depth, [28]

Establishing the optimal processing pressure
The author, Mustafa Kemal Kulekci, conducted studies on the influence of pressure on the processed material and proposed the equation (3) for calculating the critical water pressure.

$$P_{cr} = 1.664 \cdot R_m \tag{3}$$

where: R_m is the breaking strength of the material, [MPa].

It should be mentioned that as the water pressure increases, the processing depth also increases, but a better surface quality is also ensured, according to the results obtained by the authors of the works [16, 17].

Determining the optimal amount of abrasive material
The variation of the optimal quantity of abrasive and the cutting depth is shown in Figure 4, where it is observed that the depth increases linearly with the abrasive mass used, at the beginning of cutting, up to the amount of 10g/s, and above this quantity, a decrease in cutting depth. The optimum amount of abrasive for proper efficiency depends on water pressure, hole diameter, focus tube diameter, focus tube length. The optimum values for the abrasive flow are shown in Table 1.

Table 1. Optimal values for abrasive flow, m_a [g/s], [18]

Focusing tube diameter / hole diameter	m_a/ m_w* for h_{max}	m_a/ m_w for $0.85 \cdot h_{max}$
0.76 mm / 0.25 mm	0.3	0.17
1.14 mm / 0.38 mm	0.19	0.12
1.65 mm / 0.53 mm	0.19	0.1

* m_w – water flow [g/s]

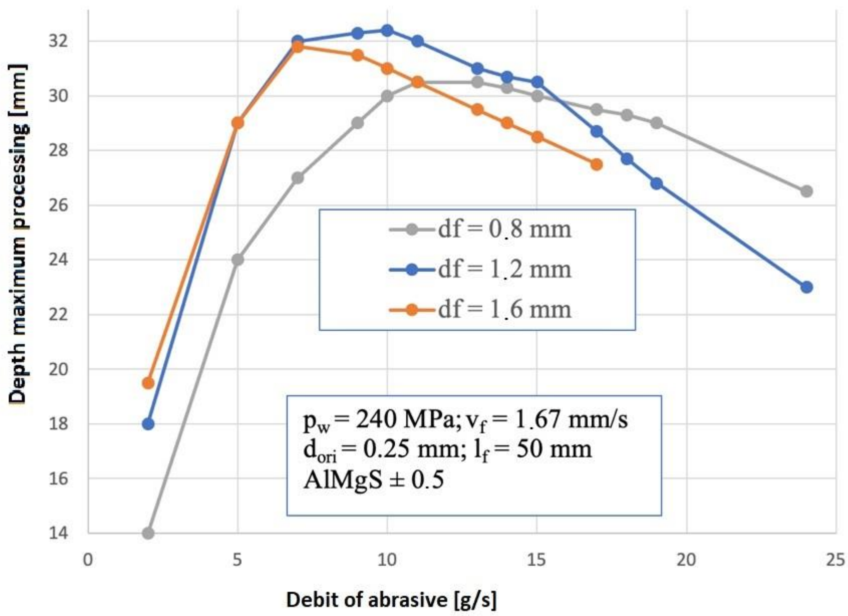


Fig. 4. Influence of abrasive material flow on cutting depth, [28]

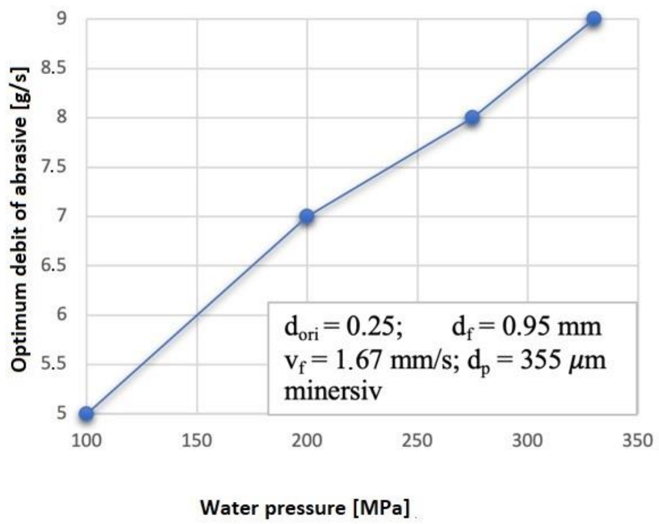
According to the experiments performed, the author M. Hashish established a calculation relation of the abrasive flow rate (equation 4).

$$V_{awj} = \eta \cdot \frac{V_{wj}}{1 + m_a / m_w} \text{, [m/s]} \tag{4}$$

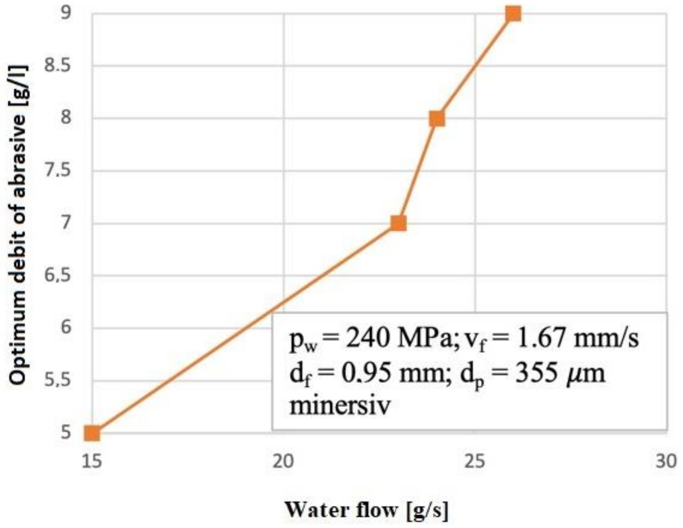
where:V_{wj} is the speed at which the water flows through the hole [m/s], V_{awj} is the speed of the abrasive particles at the entrance to the hole [m/s], η is the efficiency transfer efficiency, m_s is the flow rate of the abrasive mass [g/s] and m_w is the water flow, [g/s].

The diagram of the influence of the water pressure on the abrasive flow is shown in Figure 5(a), where with the increase of the water pressure there is an increase and the optimal flow of abrasive material.

With the increase of the water flow (Figure 5(b)) there is an increase and the optimal flow of the abrasive material. Also, increasing the diameter of the focusing tube (Figure 5(c)) leads to an increase in the optimum flow rate of the abrasive material, while increasing the length of the focusing tube has the effect of decreasing the optimum flow rate of the abrasive material (Figure 5(d)).



a)



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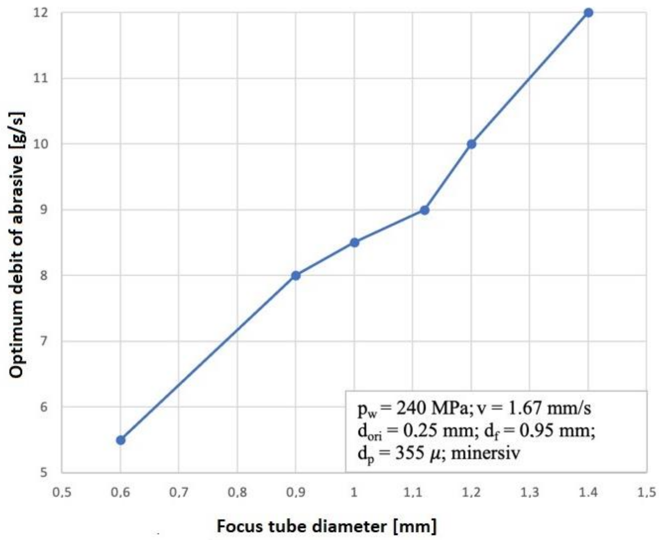
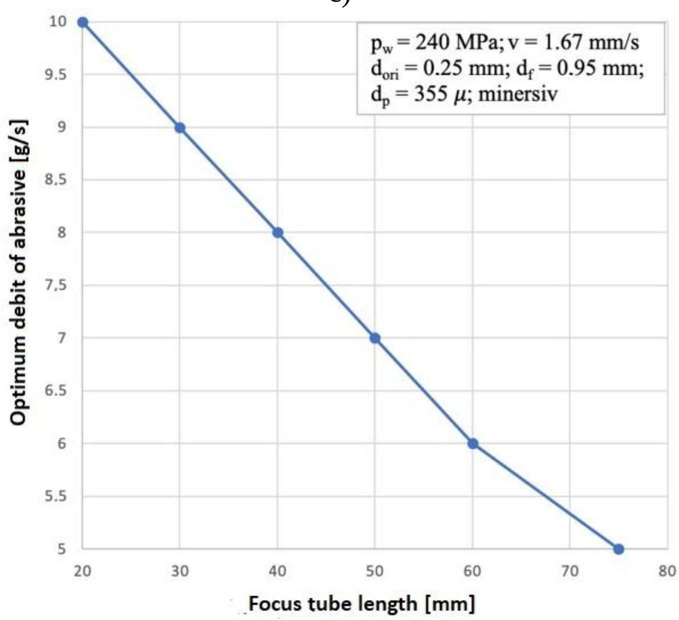


c)



d)

Fig. 5. Influence diagrams of some parameters on the optimal abrasive flow, [28]:

a) water pressure inflence; b) water flow influence; c) focus tube diameter; d) focus tube length

1.2 Abrasive materials used in AWJ processing

A large number of abrasive materials are used in abrasive water jet processing (aluminum oxide, copper slag, minersiv), glass powder, olivine, fine granite particles, silicon carbide, sand, granulated steel, etc.).

The main abrasive materials used in abrasive water jet processing and their hardness are shown in Table 2, and garnet is used in research because it is widely used in this industry due to its good mechanical properties and competitive price. The main characteristics of the grenade are presented in Table 3.

Table 2. The main abrasive materials used in AWJ processing [29]

Abrasive materials	Hardness [Moh]	Hardness [Knoop]
Aluminum oxid	8-9	2.100
Minersiv	7.5	1.350
Fine granite particles	8	-
Olivine	5.5	1.100
Silicon carbide	9.15	2.500
Sand	-	700
Granulated steel	-	400-800
Copper slag	-	1.050
Glass powders	5.5	400-600
Zirconium	-	1.300

Table 3. Characteristics of minersiv abrasive material, [19]

Characteristics	Observations
General description	- homogeneous minerals - does not remove chemicals - chemical combination of oxides and dioxides as follows: $Fe_3Al_2(SiO_4)_3$ - aluminum and iron ions are partially replaced by calcium, magnesium and manganese.
Chemical composition	- silicon dioxide (SiO_2) 41.34 % - iron oxide (FeO) 9.72 % - ferric oxide (iron trioxide) (Fe_2O_3) 12.55 % - aluminum oxide (Al_2O_3) 20.36 % - lime (CaO) 2.97 % - magnesium oxide (MgO) 12.35 % - manganese oxide (MnO) 0.85 %
Hardness	between 7 and 9 on the Mohs scale
Power	hard to break
Particle shape	sharp, with sharp edges, irregular
Cleavage	pronounced lamination, the cleavage plane is irregular
Color	red to pink
Stripes	whites
Transparentă	transparency
Gloss	glassy
Specific weight	3.9 g/cm^3 up to 4.1 g/cm^3
Refraction index	1.83
Facet angle	37º and 42º
Crystallization	Cubic (isometric) rhombic (12-sided polyhedron) or tetragonal system or combinations of the two
Melting point	1.315 °C (2.300°F)
Magnetism	slightly magnetic (volume = 9.000375)
Electrostatic properties	- conductivity: 18.000V - no reverse
Moisture absorption	nehygroscopic, inert
Release	self scattered

2. MATERIALS AND METHODS

The aim of the study is to determine the influence of some parameters (water pressure, jet feed rate and abrasive material flow) on the surface roughness of biodegradable parts cut with abrasive water jet.
The R_a parameter of the roughness of the surfaces treated with water jet with abrasive material was made with the HOMMEL TESTER T 500 roughness meter.
The biodegradable material Arboblend V2 Nature was used, whose studies on mechanical, thermal and structural properties were carried out by a number of authors according to [20-26], and which were extremely useful in establishing the research and selection methodology of the parameters of the water cutting process. The cut parts of the two materials are shown in Figure 6.
In order to achieve the complete factorial experimental plan 2^3, the ANOVA method was used because it allows the quantitative highlighting of the effects of the input parameters on the parameters measured at the output. Three input parameters were selected (abrasive water jet pressure, P, feed rate, peak, and flow rate of abrasive material used, Q). Each input parameter had two levels of variation.

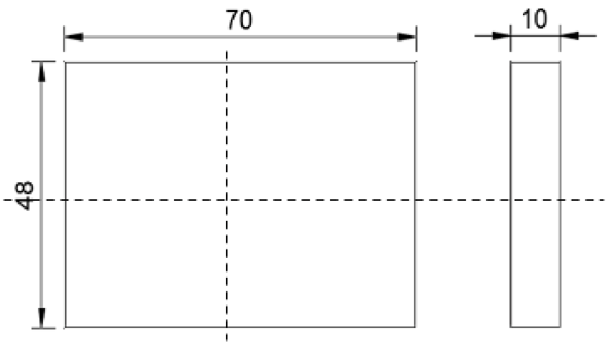


Fig. 6. The parts dimensions obtained from biodegradable materials through injection moulding

The cutting was performed on the Hydro-Jet Eco 0615 machine, using the water jet cutting with abrasive. After the abrasive particles mix, another nozzle focuses the resulting water jet and accelerates the abrasive granules to high pressure (Figure 7). The result is a strong jet that can cut, separate or drill holes of different thicknesses and densities.

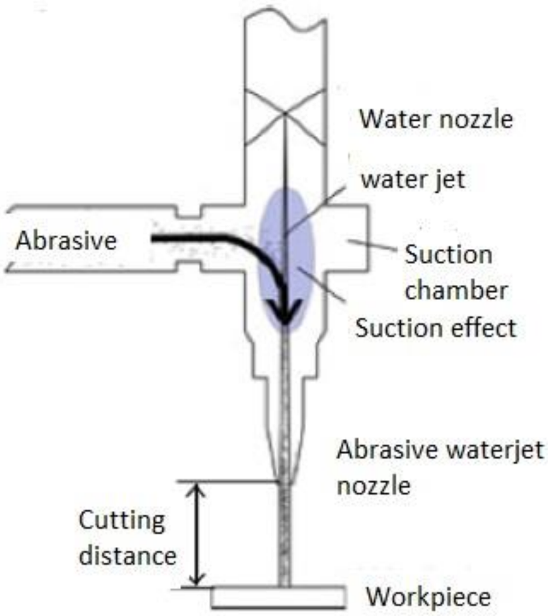


Fig. 7. Conventional method of cutting water jet with abrasive, [30]

2. RESULTS AND DISCUSSION

3.1 R_a standard in *the area on the right - entrance*

Table 4 presents the results of the analysis of the variance of the influence of the input parameters considered on the roughness of the cut surface in the Arboblend V2 Nature material by cutting with water jet with abrasive. The significant influence on the roughness (R_a determined according to the standard) has at the entry into the material on the surface to the right of the cut the cutting pressure, the value of the Fisher test is 4.7. The other two parameters (peak and Q) have a statistically insignificant influence.

Table 4. The results of the analysis of the variance by the ANOVA method, the area on the right - entrance

Parameter	Degrees of freedom	Adj SS	Adj MS	Fisher Value
Pressure [MPa]	1	3.70	3.70	4.70
Advance speed [mm/min]	1	0.1	0.1	0.13
Abrasive material flow [g/min]	1	0.12	0.11	0.15
Error	4	3.15	0.79	
Total	7	7.08		

where: Adj SS -Adjusted Sums of Squares; Adj MS-Adjusted Mean Squares

The equation of the matrix model of the influence of the parameters on the standard roughness R_a is given by the equation (5):

$$R_a = 8.554 + \begin{bmatrix} -0.681 \\ 0.681 \end{bmatrix} \cdot P + \begin{bmatrix} 0.112 \\ -0.112 \end{bmatrix} \cdot v_f + \begin{bmatrix} 0.12 \\ -0.12 \end{bmatrix} \cdot Q, \text{ [µm]} \qquad (5)$$

where P, v_f and Q are the two-dimensional vectors of pressure, feed rate and abrasive flow rate, respectively:

$$P = \begin{bmatrix} 100 \\ 150 \end{bmatrix}, v_f = \begin{bmatrix} 100 \\ 150 \end{bmatrix} \text{ and } Q = \begin{bmatrix} 150 \\ 300 \end{bmatrix}$$

Optimal values for minimum R_a = 7.64 µm are: P-100MPa and peak - 150 mm / min; Q - 300 g / min.
Figure 8 shows the influence of the analyzed parameters on the standard roughness, R_a. The roughness decreases for pressure values at the level of variation one (100MPa) in the experimental plan. The graph shows the insignificant influence of the other two parameters, the feed rate and the flow of abrasive material. The average value of the model is 8.54µm.

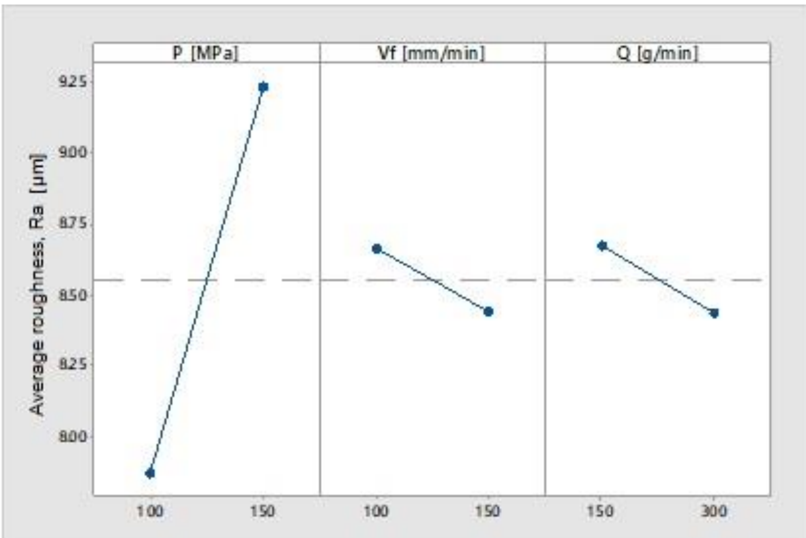


Fig. 8. Influence of parameters on standard roughness - input, right side

3.2 R_a standard in the *area on the right - exit*

In order to highlight the influence of the three input parameters on the standard roughness R_a of the surface on the right side of the cut in the outlet area of the abrasive water jet, a similar procedure was performed. Table 5 presents the results of the analysis of the variance of these influences. According to the results of the ANOVA analysis, it is found that the relevant influence is only the cutting speed, the value of the file being 1.32. The pressure and the amount of material having a negligible influence.

Table 5. The results of the analysis of the variance by the ANOVA method, the area on the right - exit

Parameter	Parameter	Degrees of freedom	Adj SS	Adj MS	Fisher value
Pressure [MPa]	Presiune [MPa]	1	0.37	0.37	0.05
Advance speed [mm/min]	Viteză de avans [mm/min]	1	10.4	10.40	1.32
Abrasive material flow [g/min]	Debit material abraziv [g/min]	1	1.81	1.81	0.23
Error	Eroare	4	31.55	7.89	
Total	Total	7	44.14		

where: Adj SS -Adjusted Sums of Squares; Adj MS-Adjusted Mean Squares

The matrix equation (6) that expresses the influence of the parameters is given by the following equation:

$$R_a = 12.378 + \begin{bmatrix} 0.215 \\ -0.215 \end{bmatrix} \cdot P + \begin{bmatrix} -1.14 \\ 1.14 \end{bmatrix} \cdot v_f + \begin{bmatrix} 0.476 \\ -0.476 \end{bmatrix} \cdot Q, \text{ [µm]} \quad (6)$$

where P, v_f and Q are the two-dimensional vectors of pressure, feed rate and abrasive flow rate, respectively:

$$P = \begin{bmatrix} 100 \\ 150 \end{bmatrix}, v_f = \begin{bmatrix} 100 \\ 150 \end{bmatrix} \text{ and } Q = \begin{bmatrix} 150 \\ 300 \end{bmatrix}$$

For the minimum standard roughness R_a = 10.55 µm the parameter values are: P = 150 MPa; v_f = 100 mm / min and Q = 300 g / min.
Figure 9 shows the main effects of the factors on the surface roughness determined according to the standard (output area, right side of the cut). It is observed that the roughness value decreases in proportion to the reduction of the cutting speed (100mm / min). Cutting pressure and abrasive flow have no relevant influence. The average value of the model is 12.38µm.

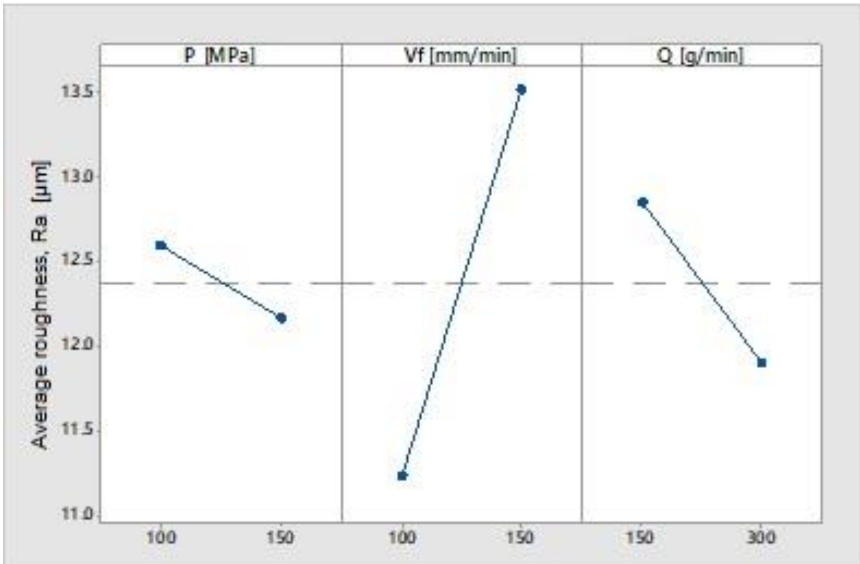


Fig. 9. Influence of parameters on standard roughness - output, right side

3.3 R_a (M_1:M_3) in the area on the right - entrance

Table 6 presents the results of the ANOVA analysis of the influence of the parameters P, v_f, Q on the average roughness, R_a (M1: M3), of the right surface at the entrance to the water jet cut with abrasive. All parametrically reveal significant influence. The influence of the abrasive material flow is the strongest (Fishter value is 15.97) while the lowest influence is exerted by the cutting speed (Fisher value 5.13).

Table 6. The results of the analysis of the variance by the ANOVA method, the area on the right - entrance

Parameter	Degrees of freedom	Adj SS	Adj MS	Fisher value
Pressure [MPa]	1	0.26	0.26	11.63
Advance speed [mm/min]	1	0.11	0.11	5.13
Abrasive material flow [g/min]	1	0.36	0.36	15.97
Error	4	0.09	0.02	
Total	7	0.82		

where: Adj SS -Adjusted Sums of Squares; Adj MS-Adjusted Mean Squares

The model of the influence of the parameters on the average roughness Ra is given by equation (7):

$$R_a = 6.3125 + \begin{bmatrix}-0.1802\\ 0.1802\end{bmatrix} \cdot P + \begin{bmatrix}-0.1197\\ 0.1197\end{bmatrix} \cdot v_f + \begin{bmatrix}0.2112\\ -0.2112\end{bmatrix} \cdot Q,\ [\mu m] \quad (7)$$

where P, v_f și Q are the two-dimensional vectors of pressure, feed rate and abrasive flow rate, respectively:

$$P = \begin{bmatrix}100\\150\end{bmatrix},\ v_f = \begin{bmatrix}100\\150\end{bmatrix} \text{ and } Q = \begin{bmatrix}150\\300\end{bmatrix}$$

In the model, the minimum value of the average roughness R_a = 5.8 µm is reached for the following values of the parameters: P = 100 MPa; v_f = 100 mm / min; Q = 300 g / min.
The graph of the influence of the parameters (Figure 10) shows that the minimum roughness is reached at the maximum value of the flow (300g / min), reduced pressure and flow rate (100MPa, respectively 100mm / min), which corresponds to the values determined for the optimal. The average value of the model is 6.31µm.

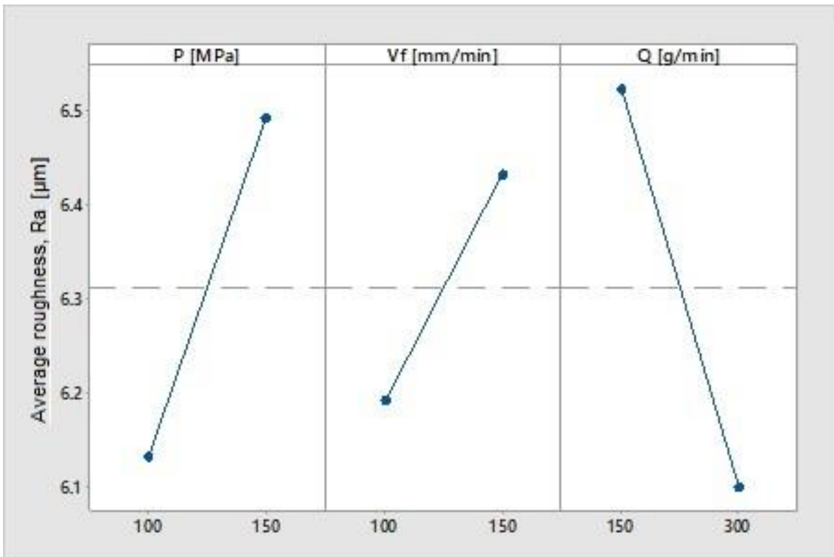


Fig. 10. The influence of the parameters on the average roughness - inlet, right side

3.4 R_a (M_1:M_3) in the area on the right - exit

Table 7 shows the analysis of the influence of the parameters on the average roughness R_a (M1: M3) for the right area at the exit of the abrasive water jet cut. None of the analyzed parameters exert a statistically significant influence on the average roughness, the Fisher test values are low.
The matrix model of the influence of the parameters on the average roughness is given by the equation (8):

$$R_a = 8.318 + \begin{bmatrix}-0.342\\ 0.342\end{bmatrix} \cdot P + \begin{bmatrix}0.216\\ -0.216\end{bmatrix} \cdot v_f + \begin{bmatrix}0.225\\ -0.225\end{bmatrix} \cdot Q,\ [\mu m] \quad (8)$$

where P, v_f and Q are the two-dimensional vectors of pressure, feed rate and abrasive flow rate, respectively:

$$P = \begin{bmatrix}100\\150\end{bmatrix},\ v_f = \begin{bmatrix}100\\150\end{bmatrix} \text{ and } Q = \begin{bmatrix}150\\300\end{bmatrix}$$

Table 7. The results of the analysis of the variance by the ANOVA method, the output area

Parameter	Degrees of freedom	Adj SS	Adj MS	Fisher value
Pressure [MPa]	1	0.94	0.94	1.66
Advance speed [mm/min]	1	0.37	0.37	0.66
Abrasive material flow [g/min]	1	0.40	0.40	0.72
Error	4	2.25	0.56	
Total	7	3.96		

where: Adj SS -Adjusted Sums of Squares; Adj MS-Adjusted Mean Squares

The minimum value of the average roughness R_a is 7.54 µm for the following values of the parameters: P=100MPa; v_f = 150 mm/min and Q = 300 g/min. As none of the parameters showed a statistically significant influence, their graphical representation was abandoned.

4. CONCLUSIONS

The abrasive water jet processing (AWJ) process can be used to cut parts made of various materials and used in many fields of activity without the need for other finishing operations. water jet, led to some values of some parameters, such as: the optimal distance between the part and the machining head between (2-4) mm; the optimum length of the focusing tube is 76 mm; the optimum diameter of the granules of 80µm having an average size of 100µm, the minersiv being the most used abrasive material in the abrasive water jet processing.

The technical solutions recommended by the literature in order to optimize the processing with water jet with abrasive refer to the processing angle between 15 - 20º, the values over 200 lead to a decrease in the quality of the processed surface and the way of processing, if possible , to be done through several passes.

Regarding the influence of the variable process parameters (feed rate, pressure and amount of abrasive material) on the surface roughness of the cut samples, it can be stated that the parameter "amount of abrasive material" has the greatest influence on the roughness, ie lower values of roughness for the situation of using a larger amount of abrasive (300g/min). The influence of the amount of material is visible especially in the case of M1-3 (on the entire cut area), 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, high feed rate - 150 mm/min and high abrasive material flow, of 300g/min.

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