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EXPERIMENTAL RESEARCH INTO MARBLE CUTTING BY ABRASIVE WATER JET

Andrzej Perec, Aleksandra Radomska-Zalas, Anna Fajdek-Bieda

The Jacob of Paradies University, Faculty of Technology, Gorzow Wlkp., Poland

Abstract. *The article presents research on the erosion of the metamorphic rock - marble by the Abrasive Water Jet (AWJ). The fragmentation of abrasive grains during the erosion process is demonstrated. The effect of the cutting process's most important parameters as traverse speed, nozzle ID, and abrasive mass flow rate, on the maximum cutting depth, is shown. To create a mathematical-statistic model of the erosion process, the methodology of the response surface (RSM) was used for modeling. The polynomial equation of the second degree is chosen for developing the regression model. Studies have shown the optimal parameters of the process, to reach the highest depth of the cut. Additionally, the erosion wear of a focusing tube under different process conditions is presented.*

Key Words: *AWJ, Abrasive Waterjet Machining, Modeling, Erosion wear, Marble*

1. INTRODUCTION

High-speed water jet machining is a fast-growing advanced manufacturing technology. The features of this technology are particularly environment friendly [1,2]. Additionally, it successfully competes with traditional materials cutting methods. To a large extent, this is due to the wide possibilities of cutting various materials [3,4], including multi-layer materials with different properties [5,6] and precise cutting complex contour [7], or conducting them in uncommon conditions [8,9] (risk of detonation, conflagration, etc.) and low temperature of the process [10].

The materials treatment by high-speed AWJ is much further elaborate than the traditional cutting processes. A high-pressure pump (an intensifier or triplex pump) is a source of high pressure, which is, in the water nozzle, converted into a high-speed jet; next it grabs abrasive grains in the mixing chamber and accelerates them to a high speed.

The admixture of abrasive grains to the water jet results in a dramatic growth of machining performance [11]. Thanks to that, it is feasible to cut almost any material [12].

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Corresponding author: Andrzej Perec
AJP University in Gorzow Wlkp., Teatralna 25, 66-400 Gorzow Wlkp. Poland
E-mail: aperec@ajp.edu.pl

Generally, the most utilized abrasive material is garnet [13]. Other natural and synthetic abrasives, such as olivine [14], crushed glass [15], and aluminum oxide [16], may also be used. To achieve a trade-off between a long nozzle life and the big performance of the workpiece machining, the heedful selection of abrasive material is endorsed [17,18].

Research on cutting rock materials was realized in different scientific centers. Karakut et al. [19] presented research on the granite and Aydin et al. [20] presented research on the marble cutting, in which it was noticed that increasing the feed reduces the slot width, while increasing the abrasive flow and stand-off distance increases the slot width. Patel et al. [21] also conducted experimental investigations on the effect of abrasive water jet machining control parameters on the granite rock removal rate. Khana et al. [22] published details on measuring the marble removal rate by AWJ. Sitek et al. [23] introduced the effect of the traverse speed of the head and the stand-off distance on the quality of the processed surface and proposed the special variograms for the analysis of cut surface properties. However, the tests focused mainly on achieving the highest removal rate or the smallest roughness of the cut slot.

Arab and Celestino [24] carried out research related to the cutting process of different rocks by AWJ and estimation of the impact of their properties on the AWJ erosion efficiency. The test effects demonstrate that the erosion phenomenon and thus the cutting performance depend on the rock kind and its microstructures. Hloch et al. [25] demonstrated that the abrasive waterjet (AWJ) is a suitable technological method for sandstone cutting. The research was conducted on the surfaces that were created after machining at a pressure of 400 MPa with a focusing tube diameter of 1.02 mm. Barton Garnet 80 Mesh was used as the abrasive material. Oh et al. [26,27] also published research into abrasive waterjet cutting of granite and shale rocks, carried out under variables conditions of the water pressure (up to 314 MPa only), traverse speed, abrasive flow rate, cutting pass numbers, and stand-off distance.

Based on the above presented state of the art, it should be noted that cutting of rock materials, especially granite was the subject of research in various centers. This paper is focused on offering a model of the process of cutting another rock - the marble.

2. Materials and Methods

2.1 Cut material

Marble is a crystalline rock consisting mainly of calcium carbonate - calcite grains. This type of rock was created by the transformation of limestone rocks. Marble is a very valuable decorative stone and a construction material. It is widely utilized for carving, as an architectonic material, and in other different applications. It comes in a variety of colors: white, cream, red, up to shades of black. Marble powder can be merged with cement or synthetic resins to perform restructured marble. The marble used for the test came from the Nanutarra White Marble Quarry, Nanutarra Station, Ashburton Shire, Western Australia. This material is visually appealing, hard, and with high gloss. It is described by the following properties:

- Density: 2730 kg/dm^3,
- Compression strength: 45 - 47.5 MPa,
- Mohs hardness: 7.

2.2 Abrasive material

In the research, garnet grains were used as abrasive. The garnets group of minerals contains closely related isomorphic minerals. Garnet grains are isostructural, which means they have the identical crystal structure. This leads to similar form and properties of crystals. The most frequently used in the AWJ technology is almandine garnet. The chemical formula of this garnet is $Fe_3Al_2(SiO_4)_3$. Details of typical GMA80 garnet particle distribution are shown in Fig. 1.

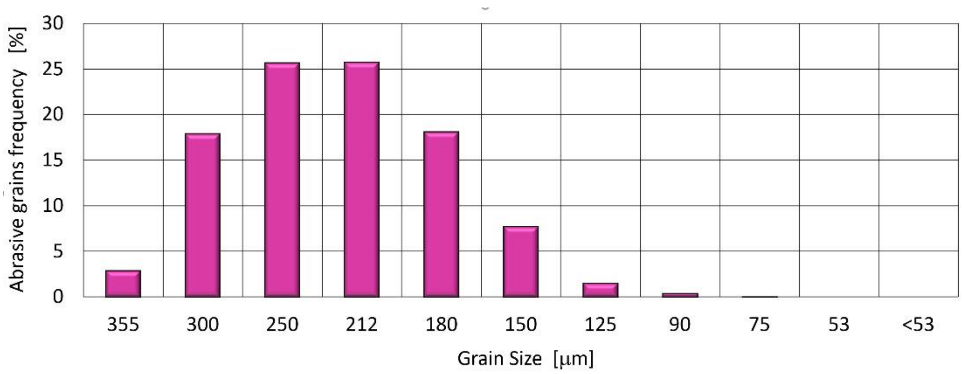

Fig. 1 Typical GMA80 garnet grain size distribution

A normal, almost symmetric, density function approximating the abrasive particle distribution is visible. The most important garnet properties are shown in Table 1.

Table 1 Properties of GMA80 abrasive grains [28]

Crystal system	Cubic
Twinning	None
Unit cell	a = 11.53 Å
Habit	Crystals usually dodecahedrons or trapezohedrons; also, in combination or with hexoctahedron; massive; granular
Cleavage	1; {110} parting sometimes distinct
Fracture	Conchoidal to uneven
Tenacity	Brittle
Color	Deep red to reddish-brown, sometimes with a violet or brown or brownish black
Hardness (Mohs)	6.5-7.5
Density	4.1-4.3

The alluvial, almandine garnet comes from Geraldton deposits in Western Australia, from the dune sands garnet-bearing. Through a unique geological history of erosion and deposition, it contains the highest quality garnet [29].

2.3 Test procedure

The experiments were done on the test rig with the I50 intensifier (KMT), and 2 axes CNC machine type ILS55 by Techni Waterjet controlled by a PC system. The maximal pressure is 400 MPa at a flow rate of 5 dm^3/min. To grab abrasive grains after they were shot out from the cutting head, a special collector was used [15]. The collector was customized to grab the abrasive grains and to preclude any extra grains disintegration. The underside PVC collector was shielded by a mild steel target to avert perforation. No wear marks were noticed on the safeguarding target after the termination of tests [2]. The caught abrasive grains are then dried. For the used abrasive grain size distribution tests, the Retsch sieving system was used. The fragmented garnet left on the sieves was weighed on the laboratory digital scale.

The materials were cut by pointing the jet at the material and moving it at a constant speed relative to the material. The cutting sample thickness was selected so that the undermost effective processing parameters do not result in a through-cutting. In this way, potential inaccurate measurements of cutting depth were eliminated.

Process parameters were chosen based on previous works involving authors of the present work [30,31], and the works of other investigators [22,32,33]. The abrasive concentration determines the ratio of the abrasive mass to the water mass in the AWJ. The mass of the abrasive is set on the feeder, while the mass of water in the jet arises from the flow rate for a given ID of the water nozzle at a given pressure, considering discharge coefficient (c_d).

The maximum cutting depth was selected as the output parameter. This is a widely used parameter [31,37] that clearly defines the effectiveness of this process. Measurements of cutting depth were made by a digital caliper altimeter.

The experiment design was utilized to minimize the tests numbers and cut its time [34,35]. The tests were led with a full factorial design. The response surface methodology(RSM) with 36 tests [36] was used (Table 2).

RSM is a fusion of statistical and mathematical modeling methods. It can be utilized in multi-criteria optimization[37]. In addition, it also ensures a join amid process control parameters and the perceived responses. The polynomial equation for making the value of a regression model [38] follows:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 \pm \varepsilon \quad (1)$$

where y is dependent variable (response), x_i is values of the i-th control parameter, k is number of control parameters, β_0, β_i, β_{ii} are the coefficients of regressions and ε is the error.

Table 2 Values of parameters used in experiments and results of cutting depth

Test No	Nozzle ID [mm]	Abrasive concentration [%]	Traverse speed [mm/s]	Cutting depth [mm]
1	0.25	15	2	64.10
2	0.25	15	4	54.40
3	0.25	15	6	41.20
4	0.25	17.5	2	67.50
5	0.25	17.5	4	57.00
6	0.25	17.5	6	47.00
7	0.25	20	2	69.70
8	0.25	20	4	60.10
9	0.25	20	6	47.10
10	0.25	22.5	2	66.67
11	0.25	22.5	4	55.60
12	0.25	22.5	6	43.70
13	0.3	15	2	72.00
14	0.3	15	4	62.60
15	0.3	15	6	46.50
16	0.3	17.5	2	76.20
17	0.3	17.5	4	65.70
18	0.3	17.5	6	54.10
19	0.3	20	2	79.80
20	0.3	20	4	69.10
21	0.3	20	6	54.70
22	0.3	22.5	2	75.10
23	0.3	22.5	4	64.60
24	0.3	22.5	6	50.50
25	0.33	15	2	80.10
26	0.33	15	4	70.10
27	0.33	15	6	54.70
28	0.33	17.5	2	86.90
29	0.33	17.5	4	74.20
30	0.33	17.5	6	61.50
31	0.33	20	2	88.60
32	0.33	20	4	78.28
33	0.33	20	6	62.20
34	0.33	22.5	2	85.60
35	0.33	22.5	4	72.80
36	0.33	22.5	6	57.18

3. Results and Discussion

3.1 Abrasive grain fragmentation

GMA80 abrasive grain fragmentation tests were performed for cutting heads with the water nozzle and focusing tube following sets:

- 0.25 mm/0.76 mm
- 0.33 mm/1.02 mm

The fragmentation test results for a cutting head equipped with a 0.25 mm ID water nozzle and a 0.76 mm ID focusing tube are illustrated in Fig. 2.

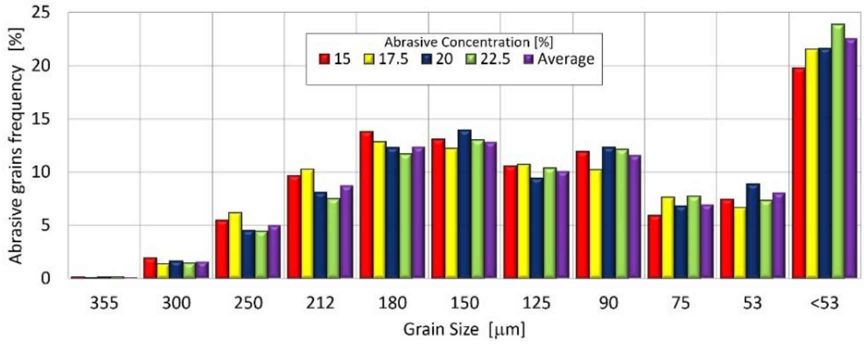

Fig. 2 The disintegration of the effect of the GMA80 grain at water nozzle ID 0.25 mm, focusing tube ID 0.76 mm, pressure 390 MPa

This distribution is similar to the bimodal one with negative asymmetry (skewness = 0.248), in which two clearly outlined observation focal points can be seen, for grains 180-150 μm and with the particles below 53 μm predominancies, which previously has not occurred. The number of 355-250 μm particles reduced remarkably. Abrasive grain distribution is very platykurtic, (kurtosis<0.67).Overall, a considerable grain size reduction was observed. The abrasive concentration change had a very small impact on grain fragmentation[39].

Fig. 3 shows the outcomes of the breakage of GMA80 abrasive under 390 MPa pressure for a cutting head equipped with a 0.33 mm ID water nozzle and a 1.02 mm ID focusing tube. This distribution is also similar to the bimodal one, with similar focal points, for grains 180-150 μm and for grains smaller than 53 μm. The largest fraction (almost 20%) was smaller than 53 μm. Particle size also decreases significantly. In this case, abrasive concentration had almost no impact on grain fragmentation, either.

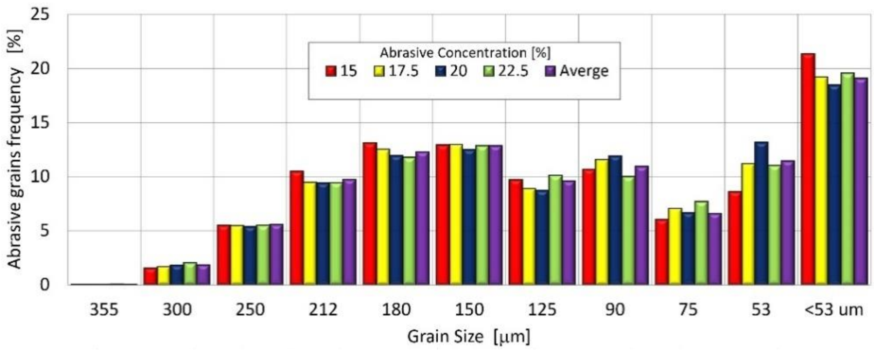

Fig. 3 The disintegration of the effect of the GMA80 grain at water nozzle ID 0.33 mm,

focusing tube ID 1.02 mm, and pressure 390 MPa

Fig. 4a shows exemplification particles of fresh (not used) abrasive. The abrasive grains are round and isometric. The grain size is not very diverse. Fig. 4b presents the view of abrasive grains after escape the focusing tube. Most grains have been fragmented. One can notice various size grains, still, mainly isometric in the shape, although with sharp edges. Between them, a small number of grains with bigger dimensions occur.

a) b)

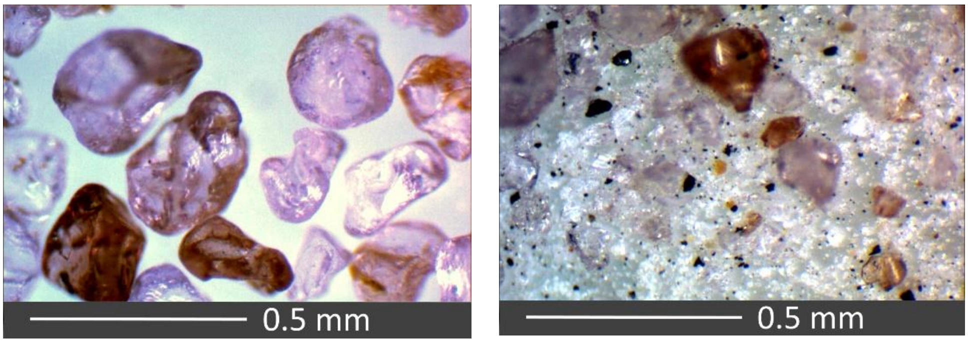

Fig. 4 GMA80 abrasive grains a) fresh, b) after disintegration in the cutting head

3.2 Cutting results

The outcomes of studies on the impact of process control parameters (independent variables) on the cutting depth (dependent variable) are indicated in Table 3.

Table 3 Details of analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value	VIF
Model	6	5499.48	916.58	278.06	0.000	
Linear	3	5305.94	1768.65	536.54	0.000	
Nozzle	1	1658.18	1658.18	503.03	0.000	1.02
Concentration	1	63.64	63.64	19.31	0.000	1.00
Traverse speed	1	3584.13	3584.13	1087.29	0.000	1.00
Square	3	235.28	78.43	23.79	0.000	
Nozzle*Nozzle	1	42.21	42.21	12.81	0.001	1.02
Concentr. * Concentr.	1	176.14	176.14	53.43	0.000	1.00
Traverse speed*Traverse speed	1	16.93	16.93	5.13	0.031	1.00
Error	29	95.59	3.30			
Total	35	5595.08				
S = 1.34181	R^2 = 99.06%		R^2adj = 98.87%		R^2pred = 98.57%	

The method of analysis of variance (ANOVA) for the 95% level of confidence ($\alpha = 0.05$) was made. The model coefficient is statistically significant when it reaches p-value <0.05 [40].To estimate multicollinearity, the variance inflation factor (VIF) was calculated. It quantifies the intensity of multicollinearity. VIF reveals how much the variance of the evaluated regression factor is inflated caused by multicollinearity in the model.

When VIF is 1.0, multicollinearity does not occur. For all tested factors, no multicollinearity was observed because VIF ≤ 1.02. The regression standard error S = 1.34181 and all R^2factors (R^2, R^2_{adj}, and R^2_{pred}) are little differing and take on values over 98%. It confirms that the raw data satisfactory match to the line of regression.

On the ground of research results, the final cutting depth model(2) was introduced:

$$D_c = 13.7 – 663d_n + 14.14C_a – 3.055S_t + 1499d_n^2 - 0.3655C_a^2 - 0.378S_t^2 \qquad (2)$$

where D_c is depth of cut [mm], d_n is water nozzle ID [mm], C_a is abrasive content in the jet [%], and S_t is traverse speed [mm/s].

The scattering of the actual and predicted depth of cut values is shown in Fig. 5. All points are localized near to a straight line; this confirms the formulated model is satisfactory.

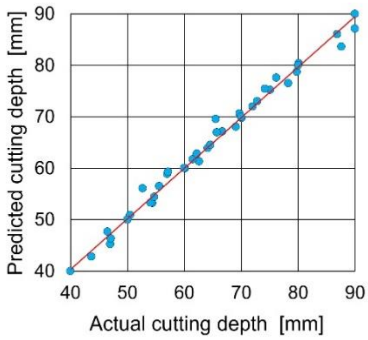

Fig. 5 Scattering plot for actual and predicted cutting depth

The impact of traverse speed and abrasive concentration on the depth of cut is shown in Fig. 6. The cutting depth is directly proportional to the diameter of the water nozzle. The highest value can be observed for a nozzle ID of 0.33 mm. This is due to bringing the most energy to the cutting zone.

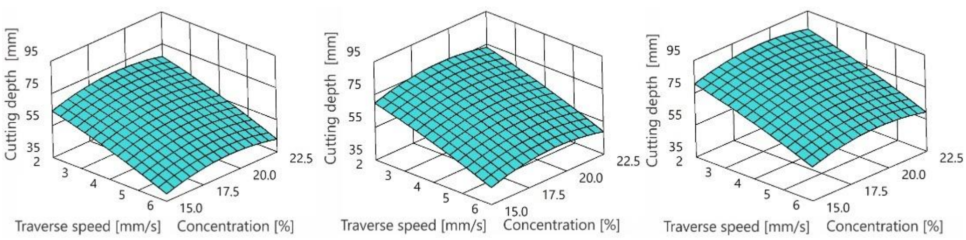

Fig. 6 Effect of abrasive concentration and traverse speed on cutting depth with water nozzle diameter's: a) 0.25 mm, b) 0.29 mm, c) 0.33 mm

However, in the case of the impact of the abrasive concentration (Fig. 7), which indirectly characterizes the mass flow rate of the abrasive, a clear extremum of the cutting depth for the abrasive concentration at the middle-value zone can be observed. The abrasive concentration value at this condition, calculated based on the model Eq. (2) is 19.3%. Exceeding this value results in a decrease in cutting depth. This is mainly due to the reduction in the speed of abrasive grains in the stream because the water energy is too low to keep the maximum speed of an increased number of abrasive grains in the jet. In addition, the interaction between abrasive grains in the jet is adversely affected on cutting depth. This was observed for the entire range of both tested nozzles and feed.

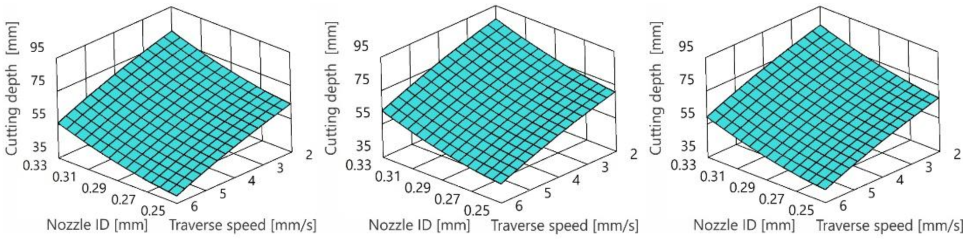

Fig. 7 Effect of traverse speed and water nozzle ID on cutting depth with abrasive concentration: a) 15%, b) 18.75%, c) 22.5%

The impact of the traverse speed on the cutting depth (Fig. 8) is inversely proportional. The greatest cutting depths are achieved for the lowest feed rates. The maximum value of cutting depth was observed for a traverse speed of 2 mm/s. The nature of this relationship is primarily due to a greater number of abrasive grains affecting the workpiece in the cutting zone per unit of time.

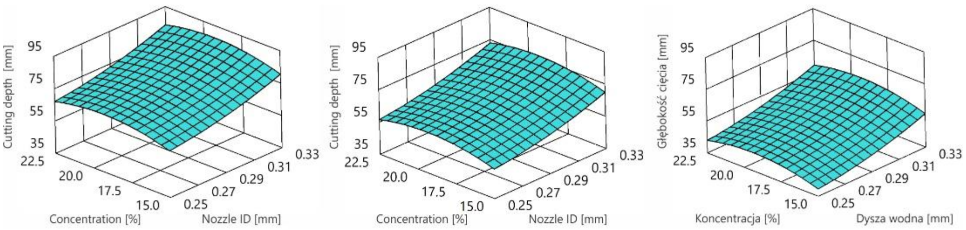

Fig. 8 Effect of water nozzle ID and abrasive concentration on cutting depth with traverse speed: a) 2 mm/s, b) 4 mm/s, c) 6 mm/s

3.3 Focusing tube wear

Erosion possibilities of AWJ have an impact similar to the one related to the cutting efficiency of the target material and the wear rate of the focusing tube [41, 42].The erosion wear rate was computed based on measuring the focusing tube mass loss at fixed time intervals. Fig. 9 presents an exemplification view (after EDM cutting along the axis) of the internal surface of the worn focusing tube.

Uneven wear of the interior surface was observed, created by the process of forming an abrasive waterjet. The pure water jet at high speed (over 700 m/s) comes into the focusing tube and reduces the practicable open inlet diameter for the abrasive particles.

Before abrasive particles come into the jet, they are bounced few times from the external water jet surface and the focusing tube inside the surface and cause its varied wear.

Fig. 9 Exemplification view of the internal surface of the worn focusing tube

Fig. 10 shows the influence of focusing tube mass loss from abrasive flow for GMA80 garnet. The average focusing tube wear factor (the slope of a line) reaches the value of 0.067 mg/s.

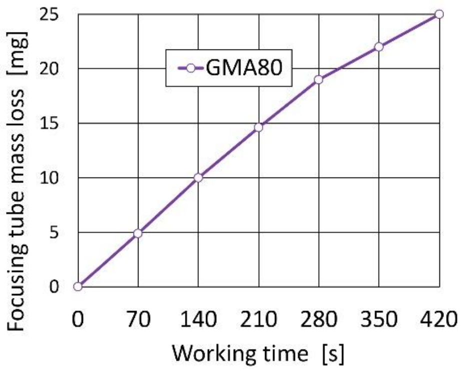

Fig. 10 Effect of the running time on focusing tube mass loss for GMA80 garnet

4. CONCLUSION

Based on the conducted research related to the modeling of marble cutting, the following conclusions were obtained:

- Abrasive concentration has no effect on abrasive particle fragmentation.
- Each tested control factors of the AWJ have a significant influence on erosive abilities, measured in the form of cutting depth.
- In the entire tested range of control parameters, the biggest depth of cut was observed for the abrasive concentration = 19.3%.
- The cutting depth is directly proportional to the water nozzle ID in the tested range.
- R-squared (the percentage of variation in the response that is explained by the model) over 99% shows the model fits very well to experimental data.
- Adjusted R^2 value = 98.87%, which is R^2, adjusted for the number of predictors in the model relative to the number of tests, also confirms a very good model fit.
- Predicted R^2 over 98% shows a very good predicting of the model reaction for the new observations.
- For regression coefficients of the model was observed no multicollinearity.

• Optimal settings of AWJ cutting parameters from the maximum cutting depth point of view for the examined area are as follows: nozzle ID = 0.33 mm, abrasive concentration = 19.3%, and feed speed = 2 mm/s. At the above parameters of cutting, the maximal depth of cut of more than 87.3 mm was attained.

In further research, the machining model will be extended with additional control parameters, e.g., standoff distance and water pressure.

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