FACTA UNIVERSITATIS
Series:**Mechanical Engineering**
https://doi.org/10.22190/FUME211123010P

Original scientific paper

PROCESS OPTIMIZATION BY APPLYING THE RESPONSE SURFACE METHODOLOGY (RSM) TO THE ABRASIVE SUSPENSION WATER JET CUTTING OF PHENOLIC COMPOSITES

Andrzej Perec[1], Aleksandra Radomska-Zalas[1], Anna Fajdek-Bieda[1], Frank Pude[2]

[1]Jacob of Paradies University, Faculty of Technology, Gorzow Wlkp., Poland
[2]Steinbeis Consulting Center High-Pressure Waterjet Technology, Horgau, Germany

Abstract. *The paper introduces the study on the cutting of the industrial composite phenolic resin, based on the thermoset materials reinforced with cotton cloth by the Abrasive Water Suspension Jet (AWSJ). The size reduction of abrasive grains during the formation of the jet and the erosion phenomenon are shown. The results of the machining process's critical factors as nozzle length, nozzle diameter, and abrasive mass flow rate on the maximal cutting depth, are indicated. To build a model of the process, the method of the response surface (RSM) was applied. The second-degree multinomial equation is selected for creating the cutting model. The research indicates the optimal control factors of the process, to achieve the best cutting depth performance.*

Key Words: *AWSJ, Abrasive Water Jet Cutting, Abrasive Water Suspension Jet, Process Optimization, Erosion, Composite*

1. INTRODUCTION

Polymer-based composites assure superior mechanical, physical, and thermal properties; over the last few years they have come to be considered a better option than conventional materials [1]. The traditional treatment of composites induces high temperatures. Moreover, cutting forces generate different types of damages, i.e., tool wear, fiber extraction, delamination, and surface failure because of non-homogeneous and anisotropic properties of these materials [2]. Machining of composite materials with the use of water jet is a desirable alternative in relation to the traditional machining technologies [3].

---

[*]**Received:** November 23, 2022 / Accepted March 10, 2022

Corresponding author: Andrzej Perec
Jacob of Paradies University, Faculty of Technology, Teatralna 25, 66-400 Gorzow Wlkp., Poland
E-mail: aperec@ajp.edu.pl

A common defective phenomenon in abrasive water jet (AWJ) cutting of layered composites materials can be delamination. It is, therefore, essential to predict the depth of penetration to eliminate delamination. Wang et al. [4] have introduced such a model in the semi-empirical way for predicting the depth of jet cutting in the abrasive water injection jet (AWIJ) cutting of polymer matrix composites. The model feasibility was then assessed by analyzing the predicted tendencies of performance measures and by comparison with the test effects. Authors have shown that the model allows proper predictions and can be used for cutting processes planning.

For the creation of machining models the design of experiment (DoE) method can be used, that is, the one which allows us to minimize the needed numbers of tests and to cut the related process time. The tests can be led with a full factorial design. RSM is a fusion of statistical and mathematical modeling methods. It can be utilized in multi-criteria optimization [5]. In addition, it also ensures a join amid process control parameters and the perceived responses. The multinomial equation for making the regression value [6] follows:

$$\mathrm{y} = \beta_0 + \sum_{i=1}^{k} \beta_i\, x_i + \sum_{i=1}^{k} \beta_{ii}\, x_i^2 \pm \varepsilon \tag{1}$$

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.

The theory of DoE allows us to simplify the method of determining process parameters, such as in the case of using it to evaluate quality of cuts after cutting aluminum alloy by AWIJ [7], for optimization of abrasive water cutting process using the TOPSIS method [8],or even multi response optimization of process parameters based on the Taguchi-Fuzzy model for coal cutting by water jet technology [9] and multi response optimization on the AWIJ machining of Stainless Steel by the VIKOR approach coupled with S/N ratio methodology [10]. Due to different importance of the conflicting criterions, the multi-criteria methods are extremely useful in the selection process of the proper machining type [11].

Design of experiments is an interdisciplinary field of science bordering on metrology, mathematics, statistics, and computer science. The use of this method has been used in modeling both conventional machining processes such as turning [12], grinding[13]or advanced manufacturing processes such as analysis on numerical modeling and flow monitoring of micro continuous water jet [14], but also in chemical processes optimization with VIKOR method [15], optimization of catalytic systems [16], and even in the studies of credit decision based on real set of cash loans by machine learning algorithms [17]. The use of DoE gives a lot of important information at relatively low cost and time.

DoE enables, among others: selection of input variables significantly influencing the controlled process, building a mathematical model of the process, i.e. mathematical relationships between the number of input and output devices, determination of input values serving the most desired process effect (optimization process) and determination of the impact of variability of input values on variability of the entire process.

Cutting composite materials with methods characterized by low temperature in the cutting zone has recently been the subject of research in various research centers. Dhanawade et al. [18] noticed that a carbon composite, treated by high jet pressure and low traverse speed, characterize a low roughness of the cut surface. Vigneshwaran et al. [19]

tested the impact of slot taper and cutting efficiency on sisal polyester composite. Traverse speed was accepted to be the most significant parameter affecting the cutting efficiency, while stand-off distance was approved to be the most meaningful coefficient affecting slot taper. Azmi et al. [20] tested the slot taper and delamination on hybrid carbon/glass composite. Lower traverse speed and stand-off distance were accepted to be proper for optimal slot taper.

The preliminary research of piercing the CFRP with abrasive water injection jet (AWIJ), which can reduce delamination published Popan et al. [21]. The research folds of adding the abrasive particles to the water jet at the very start of jet generation, thus obtaining a mix of abrasive and water jet at first impact with the composite work piece. In the presented research authors must have designed special device and set up based on the proposed piercing method and it is impossible to use for standard cutting head used in the common AWJ cutting system.

Possibility of the Titanium (Ti6Al4V) and CFRP multilayer composite machining was tested by the AWIJ machining process presented by Pahuja et al. [22]. The erosion properties, slot width and surface roughness were studied as a function of control parameters. Authors observed that the surface roughness and slot width variability was strong at poor jet power level. Mathematical regression models were made to predict slot width. An energy grounded semi-analytical model was proposed to predict the slot properties.

Putz et al. [23] have compared the AWIJ principle and the AWSJ principle and shown that abrasive water jet cutting is an appropriate alternative to commonly used diamond grinding or laser cutting processes. Also, they have tested the machining quality of technical ceramics. The investigation effects illustrate that the AWSJ technology characterizes higher accuracy than the AWIJ technology in range of slot geometry and roughness properties. Additionally, the AWSJ technology provides achievement a higher cutting efficiency.

Ramesha et al. [24] presented the comparison of the different control parameters results on slot width and surface roughness while using the AWSJ method for machining GFRP composite in submerged condition. The test outcomes have validated that the surface roughness and slot width decreased in under water machining in relation to free air condition machining. Authors shown that the treatment by AWSJ used with an optimized set of parameters make better efficiency as compared to machining by abrasive water injection jet (AWIJ).

Perec and Radomska-Zalas [25] introduced the impact of important machining parameters by Abrasive Water Suspension Jet (AWSJ): abrasive flow rate, AWSJ nozzle ID, and length on cutting depth of an aluminum marine grade material. The test determined the best dimensions of the AWSJ nozzle and abrasive flow to reach the biggest cutting depth were gained. Perec et al. also published research on the optimization of metamorphic rock - marble cutting by AWSJ [26].The disintegration of abrasive grains phenomenon over the erosion process was shown. To model the erosion process, the method of the response surface (RSM) was exerted and the polynomial equation of the second degree was chosen for developing the regression model. Studies have exposed the optimal set of parameters for achieving the maximal depth of the cut.

Abrasive material use is recognized as one of the major abrasive cutting expenses. Abrasive recycling can be an effective way for reducing the cost. In addition, it is also beneficial to environmental protection. AWSJ is more suitable for abrasive recycling than traditional abrasive water injection jet (AWIJ) because AWSJ does not use dry abrasives. Grounded on the idea of concerning for the recycling process easily and efficiently, Guo et al. [27] studied the abrasive recycling in the AWSJ process and found that the reused abrasives with only big particle impurity being sieved out still have a strong cutting ability. A simplified abrasive recovery scheme of the AWSJ cutting system has been proved to be feasible. With 30% of recharge in each cycle, the abrasive can be fully utilized, and its cutting performance can remain the same in every reuse cycle of continuously recycling process.

Guo et al. [28] also presented their investigation of the effects of pressure, traverse speed, and radius upon the cut surface roughness of the circular arc cut by abrasive suspension jet (AWSJ). An orthogonal matrix with design of experiments was utilized for analyzing the control parameters on cutting surface roughness at various depths. Decreasing the traverse speed is the most effective way of lowering surface roughness. Multiple linear regressions were used to create the cutting surface roughness model at different depths, which was proved to be reliable by experiments. The conclusions can provide theoretical guidance for improving the AWSJ cutting efficiency.

Based on the state of art analysis of the problem, it can be concluded that the use of AWSJ for processing composite materials is possible and justified due to the a cutting efficiency and the achievement of better surface roughness properties of the cut slot. The most numerous groups of composites that are the subject of research in the field of water abrasive cutting are carbon and glass fiber composites. However, the use of this technology for cutting the phenolic composite is not known in the available literature. Therefore, the authors have decided to conduct research on cutting the phenolic composite with AWSJ. Also, the authors have chosen one of the DoE methods - response surface methods (RSM) for the given modeling.

Additionally, motivation for this research study was to test the feasibility and cutting performance of a phenolic composite that is sensitive to temperature rise in the cutting zone by conventional machining methods.

2. MATERIALS AND METHODS

2.1 Processed Material

In this research study, phenolic composite, known under the commercial name micarta, was used as the cut material. Phenolic composite is a laminate plastic created when linen, paper, fiberglass, or other fabrics are impregnated with PF (Phenol Formaldehyde) resins. This is then cured under pressure and high temperature to create the thermoset plastic laminate. Phenolic composite was developed by George Westinghouse at least as early as 1910 using phenolic resins invented by Leo Baekeland [29].

Phenolic laminate offers excellent heat, stress, and chemical resistance. It tolerates extreme temperatures, is moisture-resistant and provides excellent electrical insulation making it a popular choice in electric and semiconductor applications. It can also be manufactured in a wide variety of colors and does not become brittle over time. This makes it a popular choice for countertops and tool & knife handles in consumer applications.

2.2 Abrasive Material

For the AWSJ machining quartz sand was used as abrasive material. As the research concerns the feasibility of using the AWSJ technology to cut material sensitive to temperature increase during cutting only, the cheapest of the available abrasives - quartz sand was used. The price of this abrasive is more than ten times lower than the commonly used garnet, and the cost of the abrasive is more than 60% of the total processing costs. The harmfulness of quartz dust is especially dangerous in dry conditions. In this research study, it was as much as 60 $dm^3 \cdot min^{-1}$, which significantly reduces or even eliminates the volatility of quartz dust. It can be used for parameter optimization under laboratory conditions with a limited amount of consumption but should not be used under significant business conditions with a high amount of consumption because of health endangering reasons by inbreathing of sand dust particles [30].

The quartz group consists of all SiO_2 oxides. There are several different ways of organizing SiO_2. Silicon and oxygen are the two most common elements in the Earth's crust, so perhaps their diverse modes of organization are not so unexpected. The basic form of SiO_2 is represented by low quartz with its color varieties: violet, rose quartz, smoke quartz (dark brown), and yellow. For the tests, the abrasive was used with the grain distribution shown in Fig. 1, with the predominant fraction of 630 µm at the level of 62%, the fraction of 800 µm (18%), and the fraction of 500 µm, amounting to almost 13%.

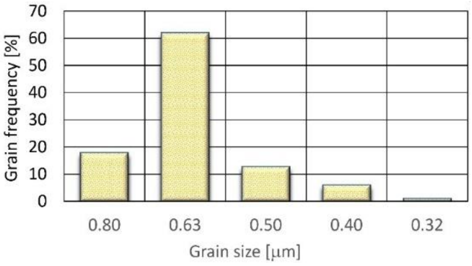

Fig. 1 Quartz sand #30 grain distribution

2.3 Experimental set-up

There are basically two systems for generating abrasive water jets. Their main difference is the moment of adding the abrasive leading to specific properties of the stream.

In the Abrasive Water Injection Jet (AWIJ) method, a stream of water that passes through the mixing chamber is generated and enters into the focusing tube (Fig. 2a). This creates a vacuum in the chamber which sucks in the dry abrasive. There, the abrasive is mixed and accelerated by the water jet and concentrated in the focusing tube [31].

The method of generating Abrasive Water Suspension Jets (AWSJ) used in the research consists of mixing the water and the abrasive suspension directly under high pressure before the AWSJ nozzle (Fig. 2b). A part of the flow is led through the bypass branch, passing through a high-pressure vessel that is filled with abrasive slurry. The abrasive slurry is pushed out of the vessel and joins the main flow in the mixing chamber where the cutting slurry is formed. Next, it is then transported *via* a flexible high-pressure hose to the cutting head, where it is finally accelerated inside the nozzle and directed to the workpiece [32].

The hydraulic diagram of the test stand is shown in Fig. 3. It consists of two high-pressure vessels: Z1 and Z2 with abrasive cut-off valves (Za1, Za2) and four independent hydraulic branches. This allows the basic flow parameters to be adjusted. Each branch consists of valves: shut-off valve (ZO), throttle valve (ZD) and check valve (ZZ), as well as pressure gauge (M). The function of the element protecting against pressure increase is performed by the overflow valve (ZP1). The high-pressure abrasive suspension water jet flows out of the device through a flexible hose (W1) and is finally accelerated in a cutting head (G) equipped with a AWSJ nozzle (D).

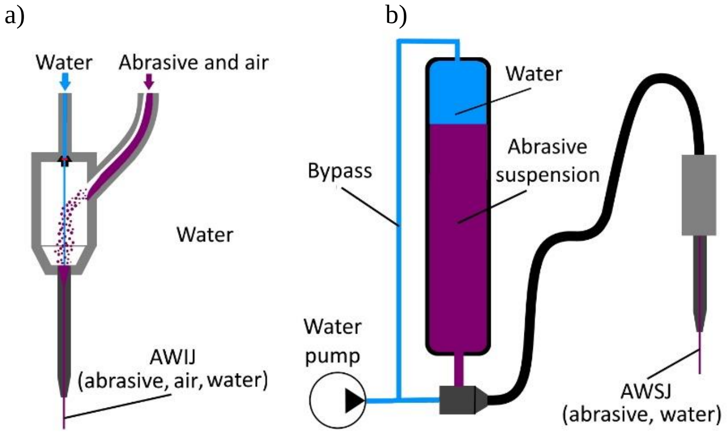

Fig. 2 High-pressure jet cutting systems: a) Abrasive Water Injection Jet (AWIJ), b) Abrasive Water Suspension Jet (AWSJ)

The source of high pressure is the P26 type pump (Fig. 4) made on the basis of high-pressure ceramic plungers and a set of seals by WOMA.

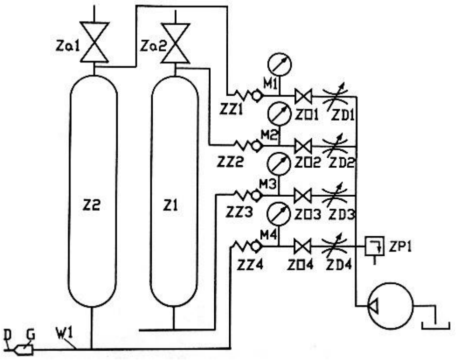

Fig. 3 Schematic diagram of test stand: ZO-shut-off valve, ZD-throttle valve ZZ-check valve, M - pressure gauge, ZP1-overflow valve

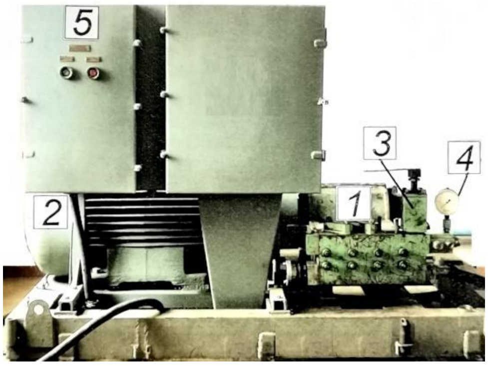

Fig. 4 Source or high pressure - P26 pump:1 - high pressure pump, 2 - electric motor, 3 - pressure regulation system, 4 - pressure gauge, 5 - controller

It allows us to achieve a maximum pressure of 75 MPa at a water flow rate of 60 $dm^3 \cdot min^{-1}$. It consists of a plunger pump driven by an 89 kW three-phase electric motor with a nominal speed of 1500 rpm.

2.3 Test Methodology

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 (Table 1, Fig. 5) were chosen on the basis of previous works involving the authors of the present study [33], and the studies of other investigators [34,35,36].

Table 1 Process parameters used in research

Parameter	Unit	Values		
Nozzle length l	[mm]	50	75	100
Nozzle ID d_n	[mm]	2.00	2.25	2.50
Abrasive flow rate (AFR)m_a	$[g \cdot s^{-1}]$	50	70	90

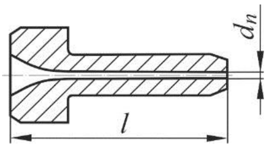

Fig. 5 Example details of AWSJ nozzle

The abrasive concentration determines the ratio of the abrasive mass to the water mass in the AWSJ. 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 [37, 38] that clearly defines the effectiveness of this process. Measurements of cutting depth were made by a digital caliper altimeter.

3. RESULTS AND DISCUSSION

3.1 Cutting depth

The outcomes of studies on the impact of process control parameters (independent variables) on the cutting depth (dependent variable) are indicated in Table 2.

The method of analysis of variance (ANOVA) for the 95% level of confidence ($\alpha = 0.05$) was made (Table 3). The model coefficient is statistically significant when it reaches p value <0.05. This is illustrated in Fig. 6. 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 as 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 =1.000.

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

Test No	***Nozzle length l [mm]***	***Nozzle ID ·d_n [mm]***	***AFR ·m_a [g·s^{-1}]***	***Depth h [mm]***
1	50	2.00	50	24.76
2	50	2.00	70	29.33
3	50	2.00	90	25.30
4	50	2.25	50	25.23
5	50	2.25	70	29.44
6	50	2.25	90	26.14
7	50	2.50	50	25.49
8	50	2.50	70	28.03
9	50	2.50	90	24.97
10	75	2.00	50	36.74
11	75	2.00	70	37.82
12	75	2.00	90	36.40
13	75	2.25	50	36.56
14	75	2.25	70	37.37
15	75	2.25	90	36.49
16	75	2.50	50	35.58
17	75	2.50	70	35.32
18	75	2.50	90	33.83
19	100	2.00	50	28.31
20	100	2.00	70	31.34
21	100	2.00	90	32.61
22	100	2.25	50	29.32
23	100	2.25	70	31.87
24	100	2.25	90	34.82
25	100	2.50	50	29.41
26	100	2.50	70	33.67
27	100	2.50	90	31.06

Table 3 Analysis of variance details

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**VIF**
Model	9	471.008	52.334	29.75	0.000	
Linear	3	113.525	37.842	21.51	0.000	
Nozzle length l	1	106.191	106.191	60.36	0.000	0.000
Nozzle ID d_n	1	1.531	1.531	0.87	0.364	0.000
AFR m_a	1	5.803	5.803	3.30	0.087	0.000
Square	3	345.432	115.144	65.44	0.000	
Nozzle length*Nozzle length l^2	1	318.379	318.379	180.96	0.000	0.000
Nozzle ID*Nozzle ID d_n^2	1	3.899	3.899	2.22	0.155	0.000
AFR*AFR m_a^2	1	23.154	23.154	13.16	0.002	0.000
2-Way Interaction	3	12.051	4.017	2.28	0.116	
Nozzle length*Nozzle ID $l·d_n$	1	0.644	0.644	0.37	0.553	0.000
Nozzle length*AFR $l·m_a$	1	9.223	9.223	5.24	0.035	0.000
Nozzle ID*AFR $d_n·m_a$	1	2.185	2.185	1.24	0.281	0.000
Error	17	29.910	1.759			
Total	26	500.918				

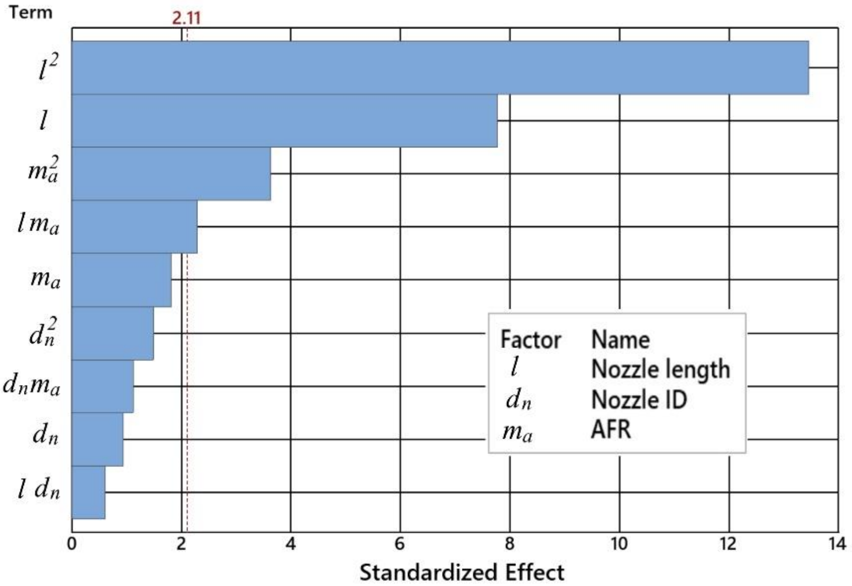

Fig. 6 Pareto chart of the standardized effect. Response is cutting depth h, ($\alpha = 0.05$)

The regression standard error S = 1.3264 and R^2 factors (R^2, R^2_{adj}) are little differing and take on values over 90%. This confirms that the raw data satisfactory match with the line of regression.

$$h = -121.5 + 1.639\,l - 0.011655\,l^2 - 0.00491\,{m_a}^2 + 0.001753\,l \cdot m_a \qquad (2)$$

where h is depth of cut [mm], l is nozzle length [mm], m_a is AFR [$g \cdot s^{-1}$].

Figs. 7, 8, and 9 are illustrations of Eq. (2). The diameter of the water nozzle change has no significant influence on the cutting depth unlike the nozzle length having a bigger influence. The highest value of the cutting depth can be observed for 80 mm nozzle length in whole AFR range.

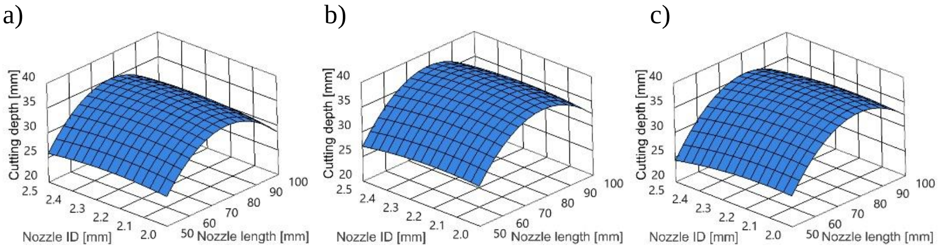

Fig. 7 Effect of nozzle length and nozzle ID with AFR:
a) 50 $g \cdot s^{-1}$, b) 70 $g \cdot s^{-1}$, c) 90 $g \cdot s^{-1}$

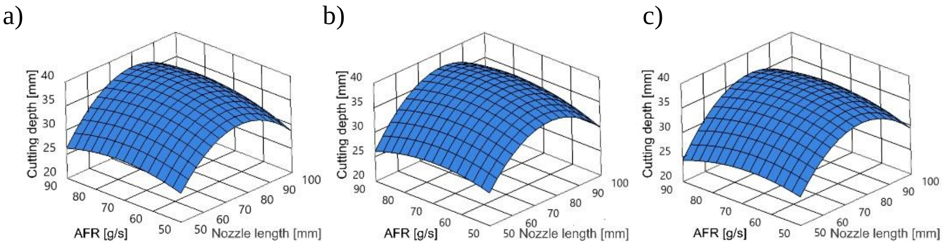

Fig. 8 Effect of nozzle length and AFR for ID: a) 2.00 mm, b) 2.25 mm, c) 2.50 mm

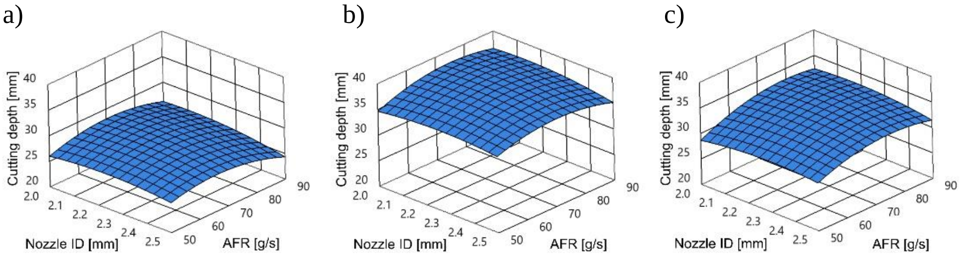

Fig. 9 Effect of nozzle ID and AFR for nozzle length a) 50 mm, b) 75 mm, c) 100 mm

The scattering of the actual and predicted depth of cut values is shown in Fig. 10. All points are localized near a straight line and this confirms that the formulated model is satisfactory.

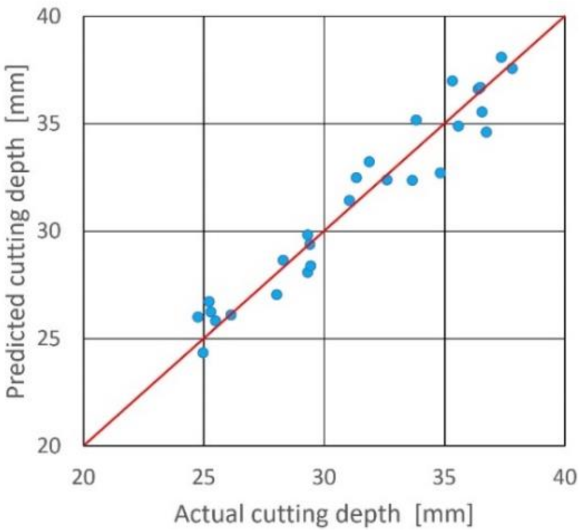

Fig. 10 Example scattering plot for actual and predicted cutting depth

Based on Eq. (2), the optimal values of all three tested control parameters were determined in terms of the depth of cut (Fig. 11). Optimal nozzle length is near 80 mm, optimal nozzle ID is 2.2 mm and optimal flow rate is 74.2g·s^{-1}.

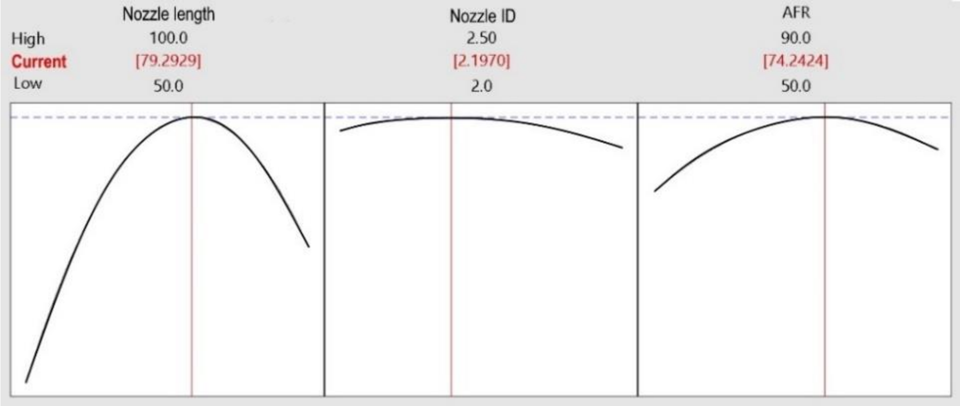

Fig. 11 Variability of control parameters and their optimal values

This is also confirmed on the contour charts presented in Fig. 12. The biggest values of the cutting depth, shown as deep green zones, are reached in the middle of the control parameters for: nozzle length: 75 - 90 mm, nozzle ID: 2.1 - 2.3 mm, AFR: 70-80 g·s^{-1}. Moving the value of each control parameter in any direction beyond the selected deep green areas causes the cut depth value to drop.

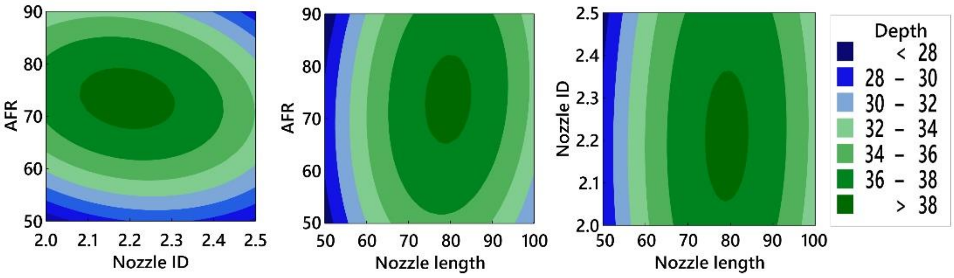

Fig. 12 Example contour plot of the range of control parameters at optimal conditions

Fig. 13 presents a microscopic view of the surface of the material cut under optimal conditions. The arched machining traces (Fig. 13a) in this material are much clearer than in the case of metal materials, for example, nickel-based superalloy [39], cooper [40] or steel [41], and are visible on the entire surface, although slightly in its upper part weaker than at the bottom. The surface is not dull. In the right part, there is a triangular material undercut, which is a given characteristic of AWJ cutting. Fig. 13b shows a typical SEM image of the surface of the cut material, localized in the mid part of the sample. The chains of fibers can be seen, but there are no visible traces of processing.

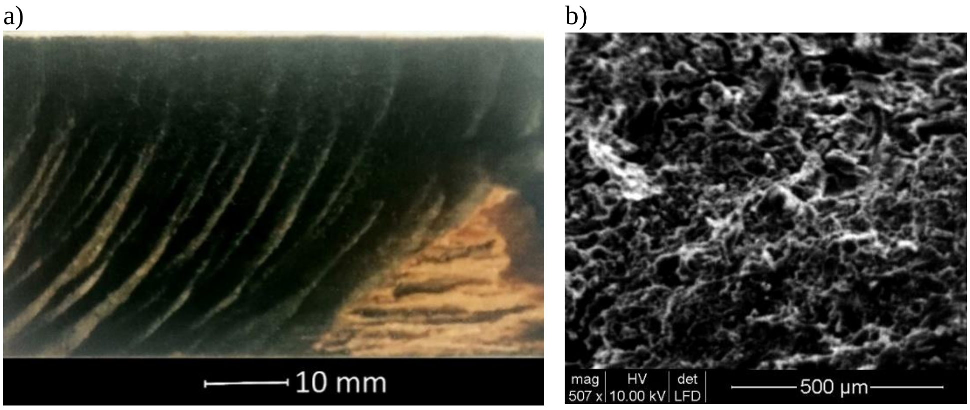

Fig. 13 Example of cut surface, machined at optimal control parameters:
a) optical microscope view, b) SEM view

3.2 Abrasive grain disintegration

Additionally, abrasive grain fragmentation tests were performed. To catch abrasive grains after their exit from the cutting head, a special collector was used [42]. The collector was customized to catch 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. The caught abrasive grains were 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 fragmentation test results for a cutting head equipped with a 2.25 mm ID nozzle, 75 mm length and 75 g·s^{-1} AFR are presented in Fig. 14.

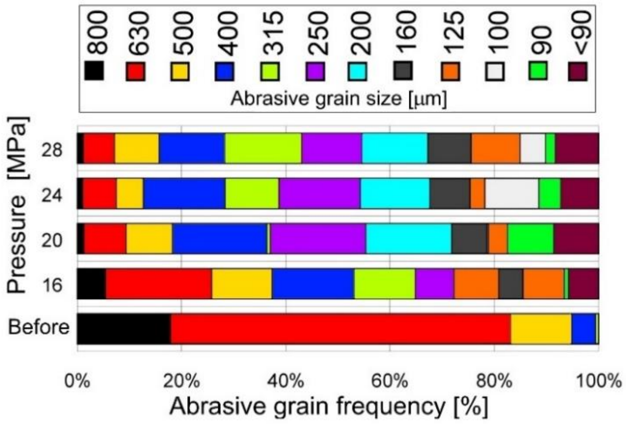

Fig. 14 Example disintegration of the quartz #30 grain at nozzle 75 mm length, ID 2.25mm,and AFR 70 g·s^{-1}

3.3 Discussion

Cutting test results suggest that the depth of cut of the phenolic composite is most dependent on the traverse speed and it complies with other research studies by Perec et al. in aluminum [25] and limestone [33] as well as Ramesha et al. [24] on GFRP composite by AWSJ. A similar phenomenon also occurs in the cutting by AWIJ [26].

The effect of pressure on the depth of cut of the phenolic composite in the case of AWSJ is as important as in the AWIJ and is directly proportional as in the case of natural fiber composites cutting, published by Müller et al. [43].

The amount of abrasive has the smallest influence on the depth of cut; however, this happens only when it oscillates around the theoretical optimum, equal of 18% abrasive by mass in the jet. Under these conditions, no delamination and surface burn were observed when cutting the phenolic composite by AWSJ, unlike the cutting tests of other composite materials by AWIJ. Wang et al. [4] confirmed the delamination is a major component defect when machining composites or layered materials and Popan et al. [21] observed strong delamination of composites, especially with a small flow rate of abrasive.

In the case of investigating abrasive behavior in the AWSJ machining, an intense disintegration of the most numerous fractions of abrasive grains depending on the working pressure was observed. The influence of pressure on the breakage degree is directly proportional. The higher pressure generates bigger abrasive grains velocity in the AWSJ nozzle, and the processed material and the disintegration process takes place more intensively. This observation is in line with the research on the disintegration of the abrasive in the AWIJ cutting process [42, 44].

4. CONCLUSIONS

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

- The processing of the phenolic composite by AWSJ did not cause any thermal changes in the cutting zone; therefore, it seems advisable to continue the research.
- Length of nozzle has a significant influence on erosive abilities, measured in the form of cutting depth.
- Abrasive flow rate (AFR) has a poor influence and nozzle ID has smallest influence on cutting depth.
- R-squared (the percentage of variation in the response that is explained by the model) over 94% shows the model fits very well to experimental data.
- Adjusted R^2 value = 90%, 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.
- For regression coefficients of the model was observed no multicollinearity.
- In the entire tested range optimal settings of AWSJ cutting parameters from the maximal cutting depth point of view for the examined area are as follows: nozzle length near 80 mm, Nozzle ID equal 2.2 mm and for 75 $g \cdot s^{-1}$ AFR. At the above parameters of cutting, the maximal depth of cut of more than 38 mm was attained.
- In further tests the almandine garnet should be used, because it is safer for the environment and commonly used in the AWIJ technology

- Additionally in the next research, the machining model can be extended by additional control parameters, e.g., standoff distance and water pressure.

REFERENCES

1. Thakur, R., Singh, K., 2020, *Experimental investigation and optimization of abrasive water jet machining parameter on multi-walled carbon nanotube doped epoxy/carbon laminate*, Measurement, 164, 108093.
2. Bañon, F., Sambruno, A., Batista, M., Simonet, B., Salguero, J., 2020, *Study of the surface quality of carbon fiber–reinforced thermoplastic matrix composite (CFRTP) machined by abrasive water jet (AWJM)*, International Journal of Advanced Manufacturing Technology, 107(7–8), pp. 3299-3313.
3. Abidi, A., Salem S., Bezazi, A., Boumediri, H., 2021, *A Comparative Study on the Effect of Milling and Abrasive Water Jet Cutting Technologies on the Tensile Behavior of Composite Carbon/Epoxy Laminates*, Mechanics of Composite Materials, 57(4), pp. 539–550.
4. Wang, J., Guo, D., 2002, *A predictive depth of penetration model for abrasive waterjet cutting of polymer matrix composites*, Journal of Materials Processing Technology, 121(2–3), pp. 390–394.
5. Ananthakumar, K., Rajamani, D., Balasubramanian, E., Paulo Davim, J., 2019, *Measurement and optimization of multi-response characteristics in plasma arc cutting of Monel 400TM using RSM and TOPSIS*, Measurement, 135, pp. 725–737.
6. Perec, A., 2018, *Experimental research into alternative abrasive material for the abrasive water jet cutting of titanium*, International Journal of Advanced Manufacturing Technology, 97(1–4), pp. 1529–1540.
7. Cierna, H., Tavodova, M., 2013, *Using the design of experiment method to evaluate quality of cuts after cutting aluminum alloy by AWJ*, Manufacturing Technology, 13(3), pp. 303–307.
8. Radomska-Zalas, A., Perec, A., Fajdek-Bieda, A., 2019, *IT support for optimisation of abrasive water cutting process using the TOPSIS method*, IOP Conference Series: Materials Science and Engineering, 710, 012008.
9. Sharma, V., Chattopadhyaya, S., Hloch, S., 2011,*Multi response optimization of process parameters based on Taguchi-Fuzzy model for coal cutting by water jet technology*, International Journal of Advanced Manufacturing Technology, 56(9–12), pp. 1019–1025.
10. Chaturvedi, V., Singh, D., 2015, *Multi Response Optimization of Process Parameters of Abrasive Water Jet Machining for Stainless Steel AISI 304 Using VIKOR Approach Coupled with Signal to Noise Ratio Methodology*, Journal of Advanced Manufacturing Systems, 14(02), pp. 107–121.
11. Temuçin, T., Tozan, H., Vayvay, Ö., Harničárová, M., Valíček, J., 2014, *A fuzzy based decision model for nontraditional machining process selection*, International Journal of Advanced Manufacturing Technology, 70(9–12), pp. 2275–2282.
12. Taneja, J., Bector, M., Kumar, R., 2012, *Application of Taguchi Method for Optimizing Turning Process by the effects of Machining Parameters*, International Journal of Engineering and Advanced Technology, 2(1), pp. 263-274.
13. Wójcik, R., Nadolny, K., 2017, *The effect of the grinding wheel modification on the state of the workpiece surface layer after internal cylindrical grinding of steel C45*, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231(6), pp. 1162–1173.
14. Zelenak, M., Riha, Z., Soucek, K., Pude, F., 2019, *Analysis of Micro Continuous Water Jet Based on Numerical Modelling and Flow Monitoring*, Advances in Manufacturing Engineering and Materials ICMEM 2018, Series: Lecture Notes in Mechanical Engineering, Springer International Publishing, Cham, Switzerland, pp.144–155.
15. Ziemba, P., Becker, J., Becker, A., Radomska-Zalas, A., Pawluk, M., Wierzba, D., 2021, *Credit Decision Support Based on Real Set of Cash Loans Using Integrated Machine Learning Algorithms*, Electronics, 10(17), 2099.
16. Fajdek-Bieda, A., Perec, A., Radomska-Zalas, A., 2021, *Orthogonal Array Approach Optimization of Catalytic Systems*, Procedia Computer Science, 192, pp. 4200–4207.
17. Fajdek-Bieda, A., 2021, *Using Entropy-VIKOR method in chemical processes optimization*, Procedia Computer Science, 192, pp. 4208–4217.
18. Dhanawade, A., Kumar, S., 2019, *Abrasive water jet machining of carbon epoxy composite: Cutting performance, predictive models and optimization*, Indian Journal of Engineering and Materials Science, 26(3–4), pp. 265–275.

19. Vigneshwaran, S., Uthayakumar, M., Arumugaprabu, V., 2020, *Prediction and Analysis of Abrasive Water Jet Machining Performance on Hybrid Composite*, Journal of Testing and Evaluation, 48(2), 20180593.
20. Wong, I., Azmi, A., Lee, C, Mansor, A., 2018, *Kerf taper and delamination damage minimization of FRP hybrid composites under abrasive water-jet machining*, International Journal of Advanced Manufacturing Technology, 94(5–8), pp. 1727–1744.
21. Popan, I., Balc, N., Popan, A., 2021, *Avoiding carbon fibre reinforced polymer delamination during abrasive water jet piercing: a new piercing method*, International Journal of Advanced Manufacturing Technology, doi: 10.1007/s00170-021-08294-7.
22. Pahuja, R., Ramulu, M., Hashish, M., 2019, *Surface quality and kerf width prediction in abrasive water jet machining of metal-composite stacks*, Composites Part B: Engineering, 175, 107134.
23. Putz, M., Dix, M., Morczinek, F., Dittrich, M., 2018, *Suspension Technology for Abrasive Waterjet (AWJ) Cutting of Ceramics*, Procedia CIRP, 77, pp. 367–370.
24. Ramesha, K., Santhosh, N., Kiran, K., Manjunath, N., Naresh, H.,2019, *Effect of the Process Parameters on Machining of GFRP Composites for Different Conditions of Abrasive Water Suspension Jet Machining*, Arabian Journal for Science and Engineering, 44(9), pp. 7933–7943.
25. Radomska-Zalas, A., Perec, A., 2019,*Modeling of abrasive water suspension jet cutting process using response surface method*, AIP Conference Proceedings, 2078(1), 020051.
26. Perec, A., Radomska-Zalas, A., Fajdek-Bieda, A., 2021, *Modeling of High Pressure Abrasive Water Jet Cutting of Marble*, Facta Universitatis-Series Mechanical Engineering, Online first: doi: 10.22190/FUME210203037P.
27. Ma, Q., Lin, J., Yang, K., Xie, H., Guo, C., 2021, *Experimental study on abrasive recycling in cutting with abrasive suspension water jet*, International Journal of Advanced Manufacturing Technology, 114(3–4), pp. 969–979.
28. Wang, F., Guo, C., Zhao, W., Zhu, L., 2016, *Research on surface roughness of circular arc cut by ASJ*, Tehnički Vjesnik, 23(3), pp. 885-891.
29. Trade, J., 1913, *Micarta is a new insulating material developed by Westinghouse*, American Machinist, 39(3), p. 122.
30. Vašek, J., Martinec, P., Foldyna, J., Sitek, L., Ščučka, J.,2002, *Abrasives for AWJ cutting*, Institute of Geonics Academy of Sciences of the Czech Republic, Ostrava, Czech Republic.
31. Wessels, V., Grigoryev, A., Dold, C., Weingaertner, E., Pude, F., Wegener, K., Loeffler, J., 2012, *Abrasive waterjet machining of three-dimensional structures from bulk metallic glasses and comparison with other techniques*, Journal of Materials Research, 27(8), pp. 1187–1192.
32. Louis, H., Pude, F., von Rad, Ch., Versemann, R., 2007, *Abrasive Water Suspension Jet Technology Fundamentals, Application and Developments*, Weld World, 51(9–10), pp. 11–16.
33. Perec, A., 2019, *Investigation of Limestone Cutting Efficiency by the Abrasive Water Suspension Jet*, Advances in Manufacturing Engineering and Materials, Springer International Publishing, Cham, Switzerland, pp. 124-134.
34. Kim, J., Song, J., Han, S., Lee, C.,2012, *Slotting of concrete and rock using an abrasive suspension waterjet system*, Korean Society of Civil Engineers Journal of Civil Engineering, 16(4), pp. 571–578.
35. Hu, G., Zhu, W., Cai, H., Xu, C., Bi, Y., Cheng, J., Juan, J., Yu, T., 2009,*Mathematical model for abrasive suspension jet cutting based on orthogonal test design*, Journal of Shanghai University (English Edition),13(1), pp. 37–44.
36. Shimizu, S., Sakuma, M., Hitomi, K., Akiyama, K., Peng, G., 2011, *Submerged Cutting by Abrasive Suspension Jets*, Transactions of the Japan Society of Mechanical Engineer Series B, 77(775), pp. 437–445.
37. Kumar R, Chattopadhyaya S, Dixit AR, Bora, B., Zelenak, M., Foldyna, J., Hloch, S., Hlavacek, P., Scucka, J., Klich, J., Sitek, L., Vilaca, P., 2017, *Surface integrity analysis of abrasive water jet-cut surfaces of friction stir welded joints*, International Journal of Advanced Manufacturing Technology, 88(5–8), pp. 1687–1701.
38. Qiang, C., Wang, F., Guo, C., 2021,*Effect of outlet pressure and polymer addition on accuracy of machining stainless steel by abrasive suspension jet*, International Journal of Advanced Manufacturing Technology, 117(3–4), pp. 889–903.
39. Liao, Z., Sanchez, I., Xu, D., Axinte, D., Augustinavicius, G., Wretland, A., 2020, *Dual-processing by abrasive waterjet machining - A method for machining and surface modification of nickel-based superalloy*, Journal of Materials Processing Technology, 285, 116768.
40. Lehocka, D., Simkulet, V., Legutko, S., 2018, *Assessment of Deformation Characteristics on CW004A Copper Influenced by Acoustically Enhanced Water Jet*, Advances in Manufacturing, Series: Lecture Notes in Mechanical Engineering, Springer International Publishing, Cham, Switzerland, pp. 717–724.

41. Perec, A., 2022, *Desirability Function Analysis (DFA) in Multiple Responses Optimization of Abrasive Water Jet Cutting Process*, Reports in Mechanical Engineering, 3(1), pp. 11–19.
42. Perec, A., 2021, *Research into the Disintegration of Abrasive Materials in the Abrasive Water Jet Machining Process*, Materials, 14(14), 3940.
43. Müller, M., Valášek, P., Linda, M., Kolář, V., 2018, *Research on water jet cutting of composites based on epoxy/microparticles from coconut shell*, MATEC Web of Conference, 244, 02001.
44. Perec, A., 2018, *Environmental Aspects of Abrasive Water Jet Cutting*, Annual Set the Environment Protection – Rocznik Ochrona Srodowiska, 20(1), pp. 0258–0274.