ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
ID: TG-20171101192113

Original scientific paper

OPTIMIZATION OF ABRASIVE WATERJET MACHINING PROCESS PARAMETERS

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Abstract: Currently, more than 50 000 different construction materials are available on the market and that number is increasing. Many new materials are often difficult to machine with conventional methods that are currently dominating in production facilities, so the industry is more and more turning to non–traditional machining processes such as abrasive waterjet cutting (AWJC). With the exceptional capabilities that it provides, abrasive waterjet cutting has disadvantages such as surface roughness and striation marks on the cutting surface, which represents a limitation for further application in production. The experimental part of the paper focuses on the verification of the thesis whether conventional material process technologies can be replaced with the abrasive waterjet cutting technology under certain conditions, while maintaining the required quality of the machined surface and productivity. An analysis of the influence of the selected cutting parameters and an optimization of the model was performed on the specimens from the AISI 316L steel on the cutting depth of 25 mm. The results obtained by optimization showed that abrasive waterjet cutting can replace conventional technologies and achieve the required values of the machined surface.

Keywords: Abrasive waterjet cutting; optimisation; cutting parameters; centra lcomposite design; AISI 316L

1 INTRODUCTION

The major target of metal cutting is to ensure high productivity with the high quality of a product and low machining costs. What exerts the greatest influence on the choice of treatment are the type of material and the geometry of a specimen. Those two factors usually determine the way of processing, and after the selection of the process, it is necessary to determine the operating conditions. The surface finish produced by conventional machining is generally uniform. Therefore, the surface finish of the machined surface can simply be characterized by measuring the surface roughness of any point of the machined surface. The abrasive waterjet cutting technology (AWJC) represents a relatively new, emerging non-conventional way of cutting almost all sorts of materials and shapes.

Due to the numerous advantages such as the narrow kerf, no heat effect zone in the material, reduction of waste disposal costs, minimal force compared to other conventional machining methods and so on, abrasive waterjet cutting has been used in various industrial applications. Despite numerous advantages over many other ways of conventional processing, there are two major obstacles, which limit further application for industrial purposes: relatively high costs of machining and the formation of striation marks on the surface of the material on higher cutting depths.

2 RELATED AND PREVIOUS WORK

The topography characteristic of the surface generated by the abrasive waterjet cutting technology has been an aim of the research of many scientists since the early 1980s. Hashish and Kovacevic are considered to be the pioneers in the area of metal machining with AWJC. Based on the flow visualization study, Hashish has proposed a theory that surfaces created by the abrasive waterjet cutting technology (AWJC) can be divided into main two zones: the upper smooth zone where the primary irregularity on a machined surface is roughness and the lower rough zone that is characterized by wavy striations (as shown in Fig. 1). [1]

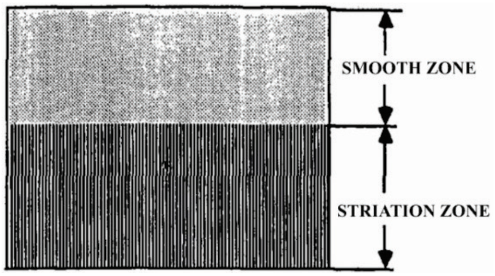


Figure 1 Division of the abrasive waterjet cut surface [1]

Based on Hashish's study, Tan has proposed a kinematics/geometry model of the cutting process in order to explain the striation forming mechanism. Souda, Matsui et al. reported that striation marks can be suppressed by adjusting the entrance angle of a water stream with multi pass cutting and with lower values of the jet traverse speed [1÷4].

There are other studies on waterjet generated surfaces that were aimed primarily at qualifying surface roughness as a function of the cutting parameters. In an experimental study for the abrasive waterjet cutting surfaces involving striations, the scientists Kim, Reuber and Hunt noticed that the values of surface roughness approximately increase with the increase of the cutting speed and cutting depth. Neusen et al. made a similar conclusion in the cutting of metal matrix composites. Kovacevic used a second-order mathematical model to characterize the surface roughness across the cut's depth as a function of several AWJ operation parameters. [1, 2,]

Striation marks represent a common phenomenon on the surfaces generated with beam-cutting technologies, such as waterjets, lasers or plasmas [4, 5, 6]. The formation of periodic wavy patterns (or striation marks) has drawn much attention in abrasive waterjet cutting on the higher cutting depth because it strongly affects the quality of the finished surface and the dimensional accuracy of the machined surface. [1]

An example of the surface created with abrasive waterjet cutting with a typical wavy structure in a lower zone of the specimen (cutting depth 25 mm) from AISI 316L steel is shown in Fig. 2.

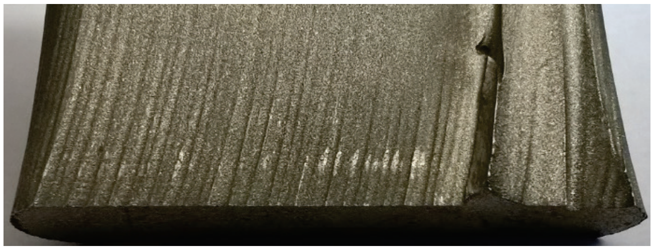


Figure 2 AISI 316L surface irregularities created by the AWJC technology

The mechanisms of forming striation marks on a surface of the material are not fully clarified and are still far from being qualitatively described. There are several different theories related to the striation marks forming mechanism, but generally, scientists agree that there are three categories with regard to the source of striations: as consequences of the machining system vibration, due to the dynamic behaviour of the waterjet and the dissipation of energy, and as a result of the characteristics inherent to the abrasive waterjet cutting (i.e. the process of material removal). [1]

3 EXPERIMENTAL SET-UP

In the experimental part of the paper, an influence of the selected cutting parameters was shown on the quality of surface roughness, or a mathematical model that will, depending on the input parameter, predict the quality-machined surface. The experiments were conducted on the TENKING 23020 abrasive waterjet cutting system with the ultra high-pressure pump capable of providing a pressure of water of 400 MPa. The examined material of specimens (dimension of specimens 40 × 30 × 10 mm) is the austenitic corrosion resistant steel X2CrNiMo17-12-2(AISI 316L) whose chemical composition is shown in Tab. 1.

Table 1 Chemical composition range for the AISI 316L stainless steel [7]

Grade		Cr	Mn	Si	P	S	Cr	Mo	Ni	N
AISI 316L	Min.	-	-	-	-	-	16.0	2.0	10.0	-
	Max.	0.03	2.0	0.75	0.045	0.03	18.0	3.0	14.0	0.1

In order to increase the cutting power of water stream, the Barton garnet MESH 120 abrasive particles were added in the mixing chamber of the waterjet cutter. Garnet abrasive offers the best combination of the cutting rate, consumable parts wear, availability, acquisition cost, and disposal cost. The most common grades used are #80 and #120. Fine grit abrasive particles (such as MESH 120) cut slower compared to MESH 80, but the finish on the machined surface is of more quality.

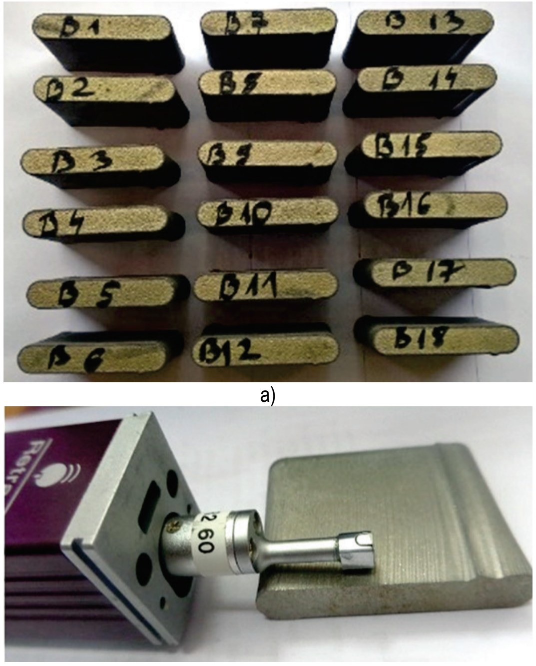
Three independent variables have been selected to analyze their influence on the roughness of the machined surface and they varied on two levels ($+\alpha$ and $-\alpha$). The variables include the jet traverse speed, pressure of water stream and flow rate of abrasive particles. The level and range of input variables used for the experimental design in the paper are listed in Tab. 2.

Table 2 Levels and ranges of input variables (cutting parameters) used for the experimental design

Levels of parameters	Pressure, MPa	Jet traverse speed, mm/min	Flow rate, kg/min
−1.682	300	22	0.3
−1	310	25	0.35
0	325	30	0.4
1	340	35	0.45
1.682	350	38	0.5

4 DESIGN OF EXPERIMENT (DOE)

After the cutting operation, the control and surface roughness measurement is carried out on the observed surface of the specimen. The surface roughness was measured with a portable surface roughness test Mitutoyo SJ 301 SurfTest on the cutting depth of 25 mm according to the standard ISO 4287:1997 (Figure 3b). In the mentioned cutting zone, it is pronounced that striations are forming on the surface of the material, and the attention of many researchers is focused on the research of the striation formation mechanism and improving the quality in the observed zone.



a)

b)

Figure 3 a) AISI 316L steel specimens used for experimental work, b) surface roughness measurement by the Mitutoyo SJ 301 Surf Test.

From all types of available parameters for describing the surface quality, *Ra* parameter was chosen, which defines the arithmetic mean deviation of the surface profile. The measurement is simple, standardized and generally applied [7].

Table 3 Values of surface roughness on the cutting depth of 25 mm

Number of runs	Process parameters			Response surface roughness *Ra*
	A: Pressure *p*	B: Jet traverse speed v_f	C: Flow rate m_a	
	MPa	mm/min	kg/min	µm
1	325	30	0.40	7.1
2	340	35	0.35	15.7
3	325	30	0.50	8.19
4	300	30	0.40	15.66
5	340	25	0.45	5.94
6	340	35	0.45	14.52
7	325	30	0.40	7.7
8	310	25	0.35	6.57
9	310	35	0.35	17.84
10	325	22	0.40	5.54
11	325	30	0.40	8.35
12	325	30	0.30	13.23
13	340	25	0.35	6.64
14	350	30	0.40	7.54
15	325	38	0.40	18.47
16	325	30	0.40	8.5
17	310	25	0.45	6.98
18	310	35	0.45	15.92

In order to obtain the independent and higher order effects on different process variables on the values of surface roughness, the experiment was performed by using the central composite design (CCD). The adequacy of the selected model for every level of cutting was tested by using the analysis of variance. [8]

The values of surface roughness for all levels were analyzed with a statistical software package Design Expert (version DX9, 9.0.6, Stat – Ease, Inc. Minneapolis 2014). The design of the experiment was 2^3 factorials with four central points, which requires 18 test runs (Fig. 3b). The design matrix (the number of experiments and the order of the run) with a surface roughness model as a response is shown in Tab. 3.

5 ANALYSIS OF VARIANCE (ANOVA)

The first step in the statistical analysis is to determine whether there is a need for the transformation of data. The range of values of surface roughness on the examined cutting depth is 5.54 ÷ 18.47 µm. Based on the response range of the data in the experiment, which is less than ten (3.334), the software suggests that there is no need for the transformation of data. The next step represents the selection of an adequate regression model for the observed cutting depth. The best model is the most fitted function to the experimental data. In this paper, checking the model adequacy is conducted with the analysis of variance (ANOVA) technique.

The model was tested in relation to mean square deviations, the deviations from the model and determination coefficients [8, 9].

The results obtained by ANOVA recommended that the quadratic regression model is statistically the best fit. The *P* – value for all zones obtained by the conducted statistical analysis showed that the value of models is lower than 0.05, which indicates that the models are statistically significant. With a backward elimination based on *p* – values, all insignificant terms are eliminated in order to adjust the fitted model. [9] The analysis of the variance for the regression model Ra_{25} is shown in Tab. 4.

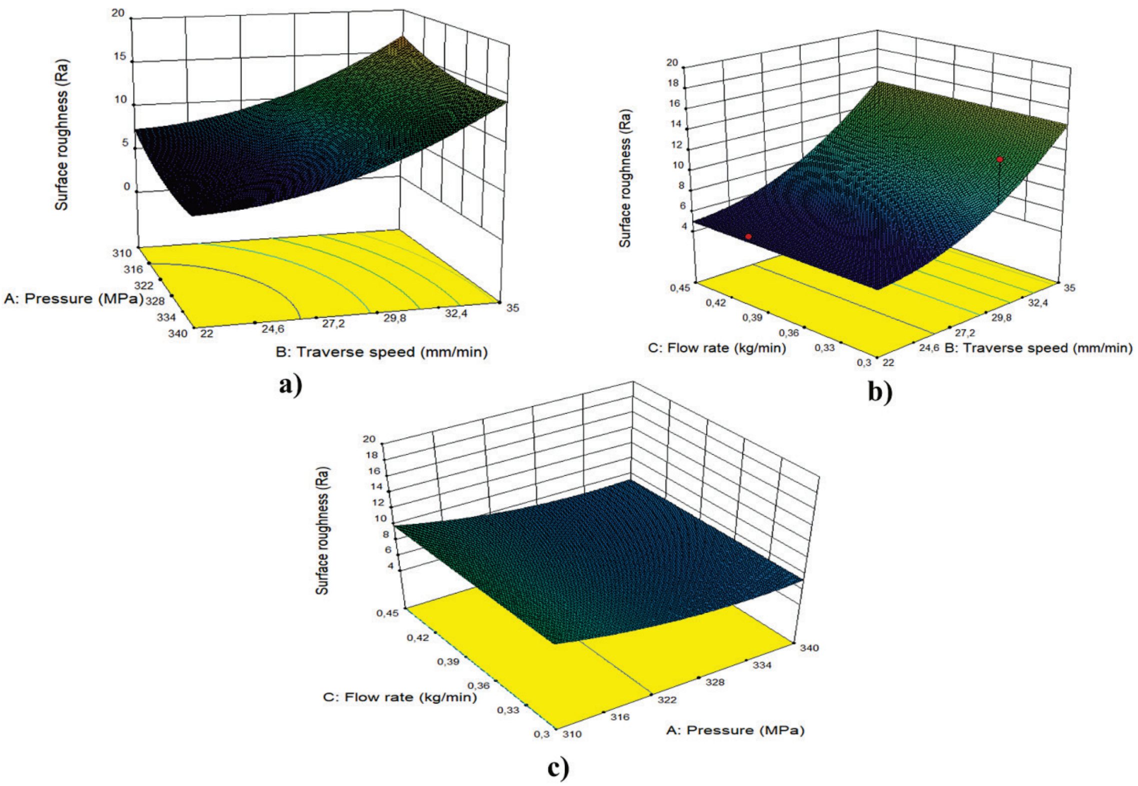
Table 4 Values of surface roughness on the cutting depth of 25 mm

Source	Sum of square	Degree of freedom	Mean square	*F*-value	*p*-value
Model	324.35	5	64.87	26.08	< 0.0001
A - pressure	24.02	1	24.02	9.66	0.0091
B – trav. speed	126.32	1	261.18	105.1	< 0.0001
C – flow rate	11.34	1	11.34	4.56	0.0540
A^2	13.61	1	13.61	5.47	0.0374
B^2	18.37	1	18.37	7.38	0.0187
Residual	29.85	12	2.49	-	-
Lack of fit	28.61	9	3.18	7.68	0.0603
Pure error	1.24	3	0.41	-	-
Total	354.19	17	-	-	-

From Tab. 4 it is visible that the *F* – value of the model amounts to 26.08, which implies that the selected model has a significant value. There is less than 0.1 % probability that the *F* - value is that high due to noise. Moreover, from the above-mentioned table it can be concluded that the factor B - jet traverse speed represents the most significant factor, and the *p*-value for the variable *F*-value (105.1) is less than the probability error type (< 0.01 %).

The influence of the pressure of water stream on the quality of the machined surface is also important: as the pressure of stream increases, the surface of the machined material becomes smoother. Due to an increase in jet pressure, the kinetic energy of the particles increases, which results in a smoother machined surface [11, 12, 13].

The mass flow rate of abrasive particles did not show prominent influence on the quality of the machined surface (i.e. not a significant cutting parameter), with the *value of F* = 4.56. Having in mind that even though the fact that with the addition of the abrasive particles' cutting power, the ability of the water stream increases, the quality of the machined surface decreases when an amount of abrasive particles in a stream increases. Abrasive particles collide with themselves in the water stream, and the result of that is a loss of kinetic energy and an uneven machined surface [13, 14]. Fig. 5 gives a graphical representation of the comparison of the predicted values and the data experimentally obtained (in other word the real values).



a) b) c)

Figure 4 Response surface of surface roughness vs. a) jet traverse speed and water pressure, b) jet traverse speed and flow rate, c) water pressure and flow rate

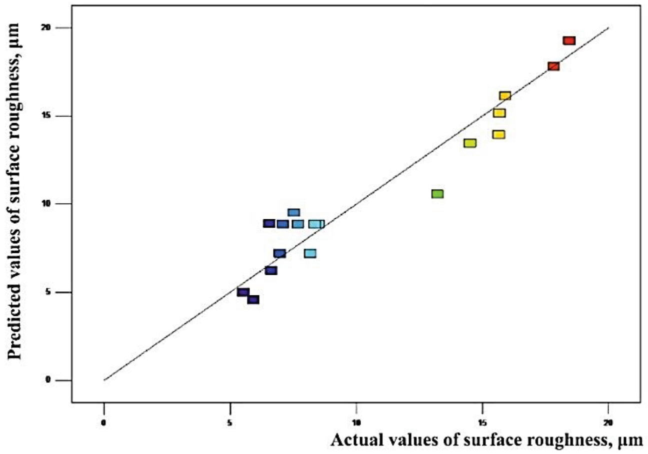


Figure 5 Values of the surface roughness *Ra* created by the model – predicted (Eq. (1)) vs. the actual values of surface roughness (Eq. (2))

The curve of the diagram is a straight line (i.e. Henry's line), as a proof that the data result from the normal distribution. All the effects that lie along the line are negligible, and there is no significant deviation from the line (i.e. there are no outliers). The plot appears satisfactory, so there is no reason to suspect that there are any problems with the validity of the conclusion.

6 REGRESSION ANALYSIS

The term regression analysis denotes a statistical modeling and an analysis method for mathematically modeling the relationship between thedependent and independent variables. The statistical analysis includes a correlation degree measurement between the selected variables and the estimation performance related to the independent variables. Additionally, the regression analysis compares the data obtained experimentally with the estimated data in order to understand the reliability of the regression model. In this paper, the jet traverse speed, waterjet pressure and the flow rate of abrasive particles are independent variables, and the values of surface roughness are estimated and dependent variable [9].

The mathematical model in terms of the coded (Eq. 1) and actual factors (Eq. 2) for an independent and dependent variables and the degree of the relations between the variables are as follows:

<u>The mathematical model in terms of coded factors</u>:

$$Ra_{25} = 8.07 - 1.33A + 4.80\,B - 1.26\,C + 1.03A^2 + 2.16B^2 \tag{1}$$

<u>The mathematical model in terms of factual factors</u>:

$$Ra_{25} = 545.19 - 3.0542A - 2.17056B - 16.83C + 4.56229 \cdot 10^{-3}\,A^2 + \ 0.051048\,B^2 \tag{2}$$

Values R^2 and $R^2_{\text{adj.}}$ are used in order to show the power of the relationship between the dependent and independent variables in the paper. Value R^2 is computed as 88.37 %, $R^2_{\text{adj.}}$ as 84.79 %. The obtained values of R show that the relationship among the data obtained from the mathematical model and the data obtained experimentally is very strong [9, 10].

7 OPTIMIZATION MODEL

According to the classification of the cut surface machined by the abrasive waterjet proposed by Hashish [1, 4], the cutting depth of 25 mm is defined as a deformation wear zone because of the pronounced striation marks on the surface of the material. Surface roughness in the observed zone is moving within the range of 5.54 ÷ 18.47 µm, thus there is a need for additional treatment due to the weak surface quality that causes the increase of machining costs.

During the machining of the above-mentioned steel on the classical milling machine, it is possible to achieve values of surface roughness in the range of 3.2 ÷ 6.34 µm. That range of surface values fulfills most of the exploitation requirements. Besides the cutting parameters, the economic feasibility of the process is taken into account (i.e. the maximum allowable cutting speed and minimum consumption of abrasive grains). During the process of optimization, it is necessary to take into account the costs that arise during the cutting. Considering the fact that abrasive grains have a great share in the total costs (approximately 55 ÷ 60 %), it is necessary to find a combination of cutting parameters that will ensure a minimum consumption of abrasive particles while maintaining the quality of the machined surface in the required range [13, 14].

The success of the conducted numerical optimization in the Design Expert is estimated through the objective function called desirability. The overall desirability (D) is a geometric (multiplicative) mean of all individual desirabilities (d_i) that range from 0 (least) to 1 (most) with the highest level of importance (5+):

$$D = (d_1 \times d_2 \times \dots d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\bar{n}} \tag{3}$$

where n is the number of responses.

For the case analyzed in paper, target optimization is chosen in the range of values of 5.54 ÷ 18.47 µm (Fig. 7), and the levels of the parameter for numerical optimization are shown in Tab. 6

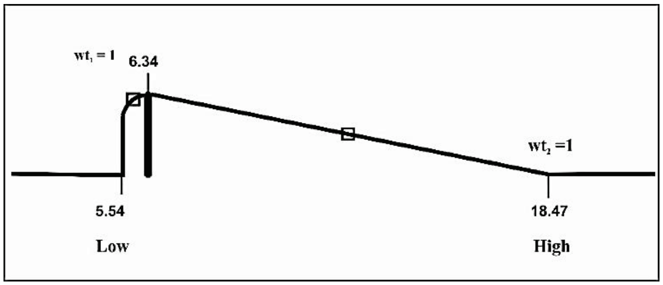


Figure 7 Desirability curve in the case when goal is the target

Table 6 Optimization of the Abrasive Waterjet Cutting parameters for the AISI 316L machining

Parameters	Low level	Center level	High level
Jet traverse speed, mm/min	22	28.50	35
Water pressure, MPa	310	325	340
Flow rate, kg/min	0.3	0.38	0.45

8 ESTIMATION AND VALIDATION OF EXPERIMENTAL RESULTS

Based on the set criteria, the software has created 100 potential combinations of parameters which are considered to be the optimal (i.e. desirability $d_i = 1$). In other words, it is possible to achieve the regression model which will be considered the optimal within required conditions, in 100 combinations according to the limitations of optimization.

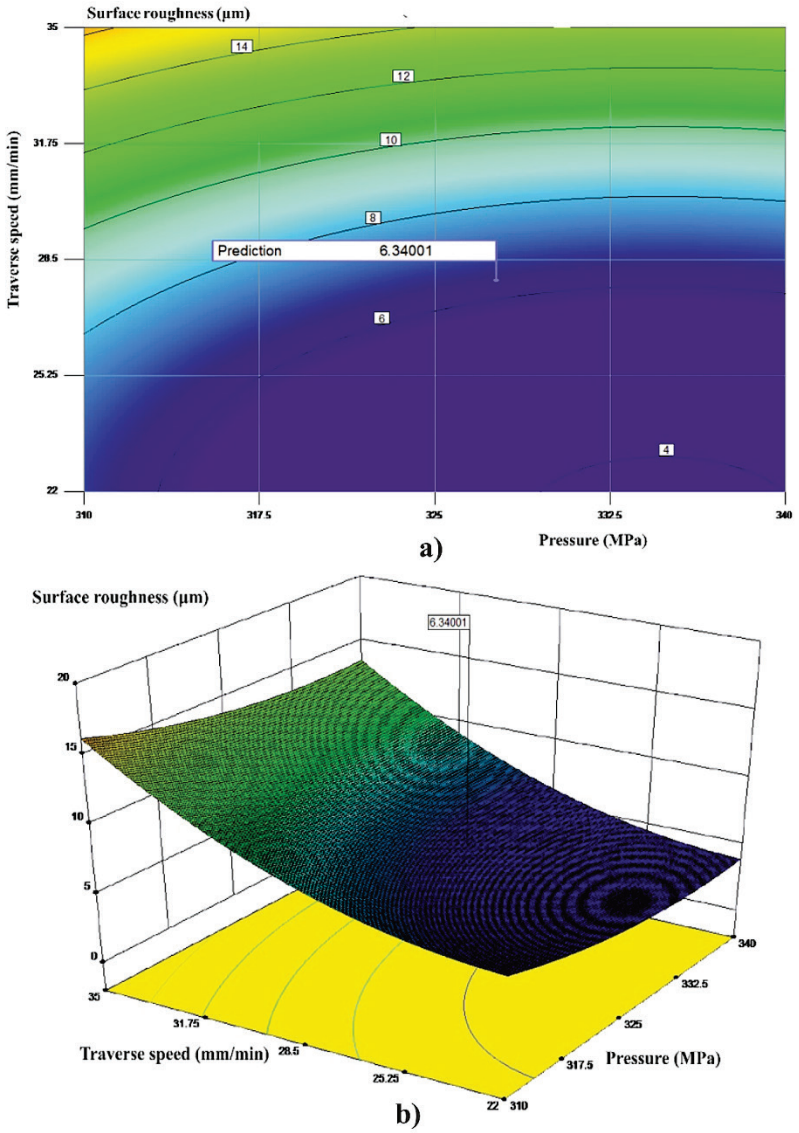
Table 6 Potential solutions for the numerical analysis of the regression model Ra_{25}

Number of runs	Process parameters			Values of surface roughness Ra	Desirability
	A: Pressure p	B: Jet traverse speed v_f	C: Flow rate m_a		
	MPa	mm/min	kg/min	µm	
1	327.763	27.283	0.416	6.340	1.000
2	332.345	26.979	0.394	6.340	1.000
3	327.425	25.176	0.354	6.340	1.000
4	325.993	26.520	0.398	6.340	1.000
5	325.832	26.580	0.401	6.340	1.000
6	326.737	26.415	0.391	6.340	1.000
7	326.744	26.864	0.406	6.340	1.000
8	323.243	26.561	0.414	6.340	1.000
9	323.955	26.573	0.410	6.340	1.000
10	318.781	22.297	0.365	6.34	1.0
⋮	⋮	⋮	⋮	⋮	⋮
98	321.624	27.246	0.448	6.34	1.0
99	328.591	25.900	0.369	6.34	1.0
100	334.597	22.848	0.301	6.34	1.0

The first solution generated by the software was selected as an optimal combination of the cutting parameters: v_f = 27.283 mm/min, p = 327.763 MPa and m_a = 0.416 kg/min. The results obtained by optimization also can be displayed in a graphical form. In order to determine the optimal levels of each variable for the required value of surface roughness, 3D and contour plots were constructed by plotting the response against each of the two selected variables (pressure of water stream and traverse jet speed), while the third variable (flow rate of abrasive particles) is maintained at a zero (fixed) level.

What is chosen as the optimal solution is the solution that suggests the smallest possible flow rate of abrasive particles to achieve the required values of surface roughness. The reason for this is the price of abrasive particles (app. 4.05 euros per kilo), which is the largest item in the share of the cutting costs. If the amount of abrasive particles is reduced to the minimal required amount, with an optimal combination of the main parameters (jet traverse speed and water pressure), the price of cutting with the abrasive jet will be lower, which represents another way of competing with conventional technologies.

The results of optimization (the optimal combination of parameters) can be displayed in graphic form by using the 3D and contour plot. The first 14 optimal combinations of parameters are shown in Fig. 8.



a)

b)

Figure 8 Graphical display of optimization for the analyzed cutting depth: a) 3D surface, b) contour

Graphical optimization is based on the overlapping of the two-dimensional responses of the obtained values. In the experimental space, when points with the same value of desirability are connected, the surface with optimal values is obtained (where values of desirability that are 1 or lower are acceptable). The response surface for *Ra* in terms of the waterjet pressure and jet traverse speed is shown in Fig. 8. From the above-mentioned figure, it can be concluded that the values of *Ra* increase with an increase of jet the traverse speed and pressure of water, while the value of the abrasive flow rate has a constant value (m_a = 0,4 kg/min). With the graphical display, the results of the numeric analysis are confirmed.

By comparing the results obtained by ANOVA (with the probability of 95 %) and optimization, it can be concluded that the quality of the machined surface obtained with abrasive waterjet cutting and with milling (as a representative of the conventional technology) can be compared.

9 CONCLUSION

The aim of this paper is to determine whether it is possible to compare the quality of machined surface created with an abrasive water jet (as a representative of the non-conventional technology) with conventional technology (in this case milling was chosen) which is currently dominating in the industry. The examination was conducted on specimens from the austenitic corrosion resistant steel AISI 316L.

In this paper, the data for the experiment were obtained by the central composite design (CCD) with three factors (jet traverse speed, the flow rate of abrasive particles and the pressure of the water stream) at two levels. The input variable is the surface roughness at a cutting depth of 25 mm.

Based on the analysis of variance on the selected cutting depth, it has been established that jet traverse speed, the pressure of the water stream and the interaction of those two factors are significant. With the increase of the cutting speed, the resulting cut has the smaller width and poor quality. In order to examine the hypothesis about the comparability of the surface roughness machined by abrasive waterjet cutting and milling, it was necessary to find the maximum cutting speed a with minimum consumption of abrasive grains that will ensure the value of surface roughness of 6.34 µm or less.

The results of optimization have shown that the abrasive waterjet cutting technology can compare and replace traditional technologies (such as milling). The highest cutting speed for achieving a required roughness of the surface is 27.283 mm/min, pressure is 327.763 MPa and the flow rate is 0.416 kg/min (Fig. 8). With that combination of parameters, the cost of cutting is reduced, and thw demand for the quality of thw-machined surface is successfully achieved.

Note: This research was presented at the International Conference MATRIB 2017 (29 June - 2 July 2017, Vela Luka, Croatia).

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