OPTIMIZATION OF CUTTING PROCESS OF AISI 316 L CORROSION RESISTANT STEEL WITH HYDRO ABRASIVE JET

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Modern technological development is characterized by discovering a large number of new and advanced materials for which the standard machining processing that currently prevails in industry from technical and economic point of view is often difficult to achieve. Due to the inability of fulfilling all the requirements of modern technology, application of non-conventional machining processes such as hydro abrasive cutting is more significant. The paper focuses on the verification of the thesis whether the standard operations such as milling could be replaced by non-conventional machining process of hydro abrasive cutting while maintaining the required quality of the processed surface. If the thesis is accepted, it is necessary to specify the maximum cutting depth to which to achieve the required quality of surface material machining is possible with minimal consumption of resources.

Keywords: analysis of variance; hydroabrasive waterjet cutting; process optimization; surface quality

Optimizacija procesa rezanja korozijski postojanog čelika AISI 316 L hidro abrazivnim mlazom

Suvremeni tehnološki razvoj karakterizira pronalazak velikog broja novih i naprednih materijala za koje je obrada standardnim postupcima koji trenutno prevladavaju u industriji s tehničkog i ekonomskog stajališta često teško izvodiva. Zbog nemogućnosti ispunjavanja svih zahtjeva suvremene tehnologije sve je značajnija primjena nekonvencionalnih postupaka obrade poput hidro abrazivnog rezanja. Članak se fokusira na provjeru teze mogu li se standardni postupci poput glodanja zamijeniti nekonvencionalnim postupkom hidro abrazivnog rezanja uz zadržavanje zahtijevane kvalitete obrađivane površine. Ukoliko se teza prihvaća, potrebno je odrediti maksimalnu dubinu rezanja do koje je moguće ostvariti traženu kvalitetu površine uz minimalni utrošak resursa.

Ključne riječi: analiza varijance; kvaliteta površine; optimizacija; rezanje hidro abrazivnim mlazom

1   Introduction

With more applications of hydro abrasive jet cutting technology there is a need to qualitatively and quantitatively describe cutting process in order to select and optimize the process parameters and predict the cutting performance. The mathematical models for the major cutting performance measures are therefore required [1]. Over the last decades, a great deal of research effort has been directed to develop such models. While most of the developed models are focused to estimate the depth of cut for different materials, some other models are also developed to express other cutting characteristics like material removal rate, the shape of kerf profile, kerf surface roughness and kerf width under certain cutting conditions. Chen et al. also [1, 2] investigated the influence of main variables on the depth of cut with an objective to find the optimum traverse speed. However, the optimum traverse speed may deteriorate other cutting performance measures such as machined surface quality. With an application of numerical analysis it is possible to determine the optimal cutting parameters where the traverse speed may produce maximum depth of cut and at the same time does not sacrifice surface quality.

2   Numerical optimization

Optimization in engineering terms represents a procedure of maximization or minimization of goal or goals within available resources, with the satisfaction of limitations that objectively exist [3]. It is assumed that the problem has a "surplus" of internal degrees of freedom, which are becoming variables of the optimization process. Unlike classical application of numerical methods in analysis, in the optimization each iteration involves analysis performing (system response simulation). Synthesis is not conducted by testing all potential solutions and then generating new solutions. Processes and procedures of optimization have an increasing importance and ever growing area of application. Today's logic in the development of products, services and process does not mean finding a solution that satisfies all the conditions, but finding a solution that satisfies all the conditions while minimizing the costs of all resources, or maximizing the objectives (so called solution excellence criteria). With enforcement of optimization, sequence of generated solutions leads to a way of better fulfilling of conditions, while at the same time fulfilling the limitations.

In that order, optimization is an iterative process regardless of the fact whether it is conducted in a classical way or supported by numerical methods [4, 5].

3   Definition of problem and setting the experimental conditions

In the experimental part of the work it was investigated whether in some conditions the technology of hydro abrasive jet cutting can replace conventional technology (in this case face milling and circumferential milling) and achieve the required quality of machined surface during the austenitic corrosion resistant steel X2CrNiMo 17 – 12 – 2 (AISI 316 L) cutting. Corrosion resistant steel belongs to the group of materials difficult to cut and process with conventional methods that are currently dominant in industry. During the processing of AISI 316 L steel on classical milling machine it is possible to achieve required quality of machined surface in the range of 3,2 ÷ 6,3 μm (Fig. 1). That value of surface

roughness fulfils most of the exploitation requirements. Besides cutting parameters, economic feasibility of the cutting process is taken into account, i.e. maximum cutting speed is required with minimal consumption of abrasive particles [6].
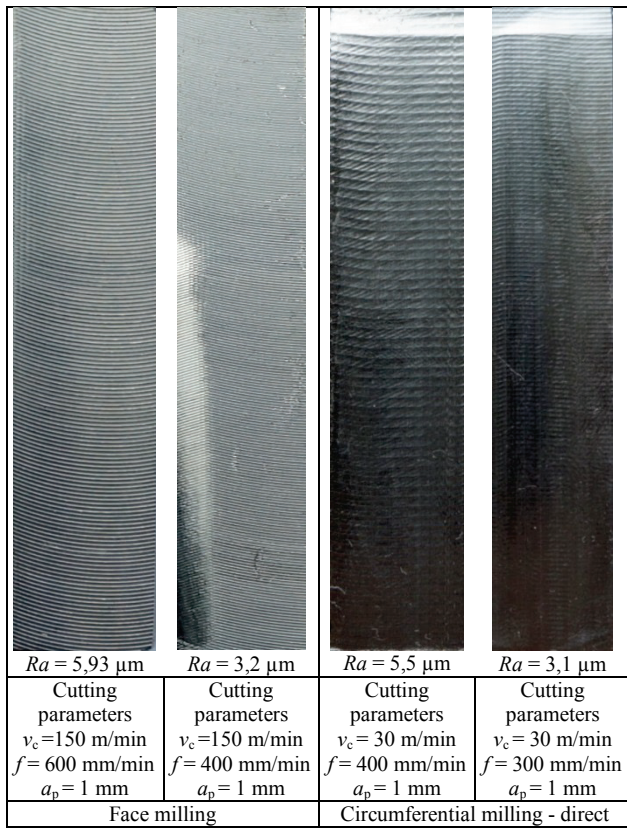

Ra = 5,93 μm	Ra = 3,2 μm	Ra = 5,5 μm	Ra = 3,1 μm
Cutting parameters v_c = 150 m/min f = 600 mm/min a_p = 1 mm	Cutting parameters v_c = 150 m/min f = 400 mm/min a_p = 1 mm	Cutting parameters v_c = 30 m/min f = 400 mm/min a_p = 1 mm	Cutting parameters v_c = 30 m/min f = 300 mm/min a_p = 1 mm
Face milling		Circumferential milling - direct	

Figure 1 Review of milled surface roughness results of AISI 316 L corrosion resistant steel [6]

Table 1 Process factors and their values by levels

Factors	Sign	Unit	CODED VALUES OF PARAMETERS				
			Low level (−1)	Center level (0)	High level (+1)	$-\alpha$ (−1,682)	$+\alpha$ (+1,682)
Traverse speed	V_f	mm/min	25	30	35	21,8	38,4
Cutting pressure	p	MPa	310	325	340	299	350
Abrasive mass flow	m_a	kg/min	0,35	0,4	0,45	0,32	0,49

In the experiment, specimens were cut with a Teen King 23020 hydro abrasive jet cutter of company Sigmat from Gromačnik, Slavonski Brod. For increasing the cutting parameters and higher productivity, particles of abrasive material Barton garnet *MESH* granulation 80 were added in water jet. Three main parameters of cutting were selected with the greatest influence on quality of the machined surface (traverse speed, pressure and mass flow rate) and they varied on 2 levels (+1,682 and −1,682). The range of process factors and their levels are shown in Tab. 1. Cutting parameters were chosen based on own practical experience and on cutting parameters calculator from waterjet machine for the chosen group material AISI and thickness of the material.

4 Design of experiment (DOE)

After the cutting operation, control and surface roughness measurements were carried out on the observed surface of specimen. Surface roughess was measured by portable surface roughness test Mitutoyo SJ 301 SurfTest on cutting depth of 25 mm according to the standard ISO 4287:1997 (Fig. 2). In the mentioned cutting zone striations forming on the surface of material is pronounced, and the attention of many researchers is focused on the research of striation formation mechanism and improving the quality in observed zone.

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, measurement is simple, standardized and generally applied [7].

Figure 2 Surface roughness measurement with portable surface roughness test Mitutoyo SJ 301 SurfTest

Table 2 Values of surface roughness on the cutting depth of 25 mm

Conventional order labels of performance	Order of random performance	Status label of the experiments	PROCESS FACTORS			Surface roughness at depth of 25mm / μm
			Pressure / MPa	Traverse speed / mm/min	Abrasive mass flow / kg/min	
1	5	5	310	25,00	0,35	7,92
2	11	11	340	25,00	0,35	7,02
3	10	10	310	35,00	0,35	13,87
4	14	14	340	35,00	0,35	12,97
5	2	2	310	25,00	0,45	6,44
6	3	3	340	25,00	0,45	6,34
7	16	16	310	35,00	0,45	13,46
8	1	1	340	35,00	0,45	9,19
9	12	12	300	30,00	0,40	10,75
10	15	15	350	30,00	0,40	7,6
11	17	17	325	21,60	0,40	4,93
12	13	13	325	38,40	0,40	14,77
13	7	7	325	30,00	0,32	12,57
14	9	9	325	30,00	0,48	6,78
15	18	18	325	30,00	0,40	7,89
16	6	6	325	30,00	0,40	7,40
17	4	4	325	30,00	0,40	7,80
18	8	8	325	30,00	0,40	7,00

According to the characteristics and physical limitations of the experiment, there are several designs of

experiment. Central - composite design provides a description of process while avoiding a large number of runs. In order to verify suitability of the chosen model, curvature of response surface and determine "pure" errors in experimental area, 3 more conditions were added to the central point, so the total number of runs needed for this experiment will be 18 (Tab. 2).

5 Statistical evaluation of model and regression diagnostic

The results of surface roughness measurement are generated with available software package for statistical analysis Design Expert 9. The suitability of the model is determined with F-test, and significance of model is determined with analysis of variance (ANOVA). With analysis of variance, besides creating a regression model, analysis of errors in experimental area will be conducted and potential non-linearity within the specified relations detected [8, 9].

First step in statistical analysis is to determine the type of transformation of the response surface. Based on obtained results, transformation is not required for this case. In the next step, based on the minimum sum of squared deviations program suggests the optimal model for analysed case. Analysis of variance showed that obtained cutting zone can be optimally described with the reduced quadratic model.

In order to eliminate the members of the model with negligible influence, reduction of the members is conducted with value Prob > F less than 0,05 (5 %). Analysis of variance (Tab. 3) shows that dominant cutting parameter with the greatest influence on quality of machined surface is traverse speed.

Table 3 Analysis of variance for regression model Ra_{25}

| Source of variation	Sum of square	Degree of freedom (dof)	Mean square	F - value	P - value Prob > F
Model	150,23	6	25,04	29,70	< 0,0001
A – Pressure	9,63	1	9,63	11,42	0,0061
B – Traverse speed	107,52	1	107,52	127,54	< 0,0001
C – Abrasive mass flow	18,95	1	18,95	22,48	0,0006
A^2	4,19	1	4,19	4,97	0,0475
B^2	8,39	1	8,39	9,95	0,0092
C^2	7,16	1	7,16	8,50	0,0141
Residuals	9,27	11	0,84	-	-
Lack of fit	8,77	8	1,10	6,58	0,0745
Pure error	0,50	3	0,17	-	-
Total	159,50	17	-	-	-

6 Obtained results during the experiment

After simplification of the process, final form of surface roughness prediction for regression model Ra_{25} is given with expression (1)

$$Ra_{25} = 366,04817 - 1,7191 \cdot p - 1,39330 \cdot v_f - 264,35629 \cdot m_a + 2,55872 \cdot E - 0,05 \cdot p^2 + 0,032574 \cdot v_f^2 + 0,032574 \cdot v_f + 300,99572 \cdot m_a^2 \qquad (1)$$

"Rough" deviation of certain points of real measured values of the observed property is determined with a diagnostic tool. Based on this display, it is possible to determine the optimum function.

In Fig. 3 plots of estimated variance for regression model Ra_{25} are shown three – dimensional with constant mass flow rate $m_a = 0,4$ kg/min. [8, 9]
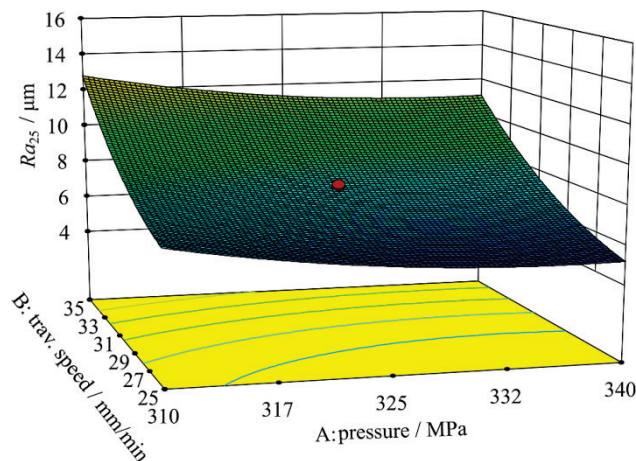
Figure 3 Plot of estimated variance for regression model Ra_{25} with constant mass flow rate $m_a = 0,4$ kg/min

From obtained plot it can be seen that traverse speed has a higher slope, ie. change of traverse speed will have greater impact on the quality of the machined surface in relation to the cutting pressure, and the higher the cutting depth the impact of cutting speed on the quality of the treated surface will be stronger. Mass flow, as a parameter of cutting has no significant impact on the quality of the machined surface.

In order to check the assumption that errors are approximately normally distributed with expectation 0 and constant variance, and determine additional conditions that will contribute to the quality of regression model, analysis of remains [1] is often applied in statistical analysis.
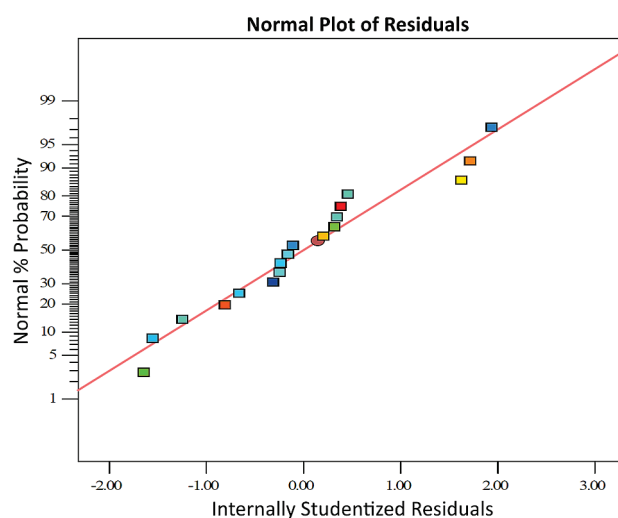
Figure 4 Normal plot of residuals for regression model Ra_{25}

For testing this assumption normal plot of residuals is used because it is one of the most effective and efficient ways to test the normality of remains (Fig. 4).

The remains are divided by the estimated standard deviation (which is calculated according to Student's t – distribution) along the line called Henry's line, sign of normal distribution. Fig. 4 shows that there is no major scattering of data in the experimental area, what is a sign that the selected model is described well, and it validates that transformation is not required.

By applying the statistical tool *Influence* it is necessary to check whether there is any data within the model that deviates significantly from the average and that value is called *Outlier*. Outliers are defined as extreme values of variable which have a disproportional influence on model (they control it), compared to the other states of experiment, which do not deviate from the average. The influence of each state of experiment on regression model is shown in Fig. 5.
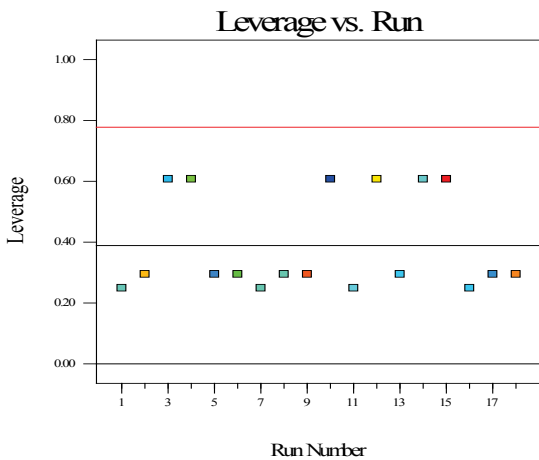

Figure 5 Influence of state of experiment on model

From Fig. 5 can be concluded that all states of experiment are moving within the range 0,00 ÷ 1,00, and that there are no outliers.

7 Optimization of model

Optimization of model is applied in searching for optimal solution from a set of available solutions. Software tools that have a statistical support, such as the Design Expert, allow optimization of model by defining the value of the parameters for achieving the desired results. The program finds optimal combination of 2 or more responses of observed variables in a way that first limits are chosen within the value of observed variables, and then algorithm for optimization runs. The success of the numerical optimization is evaluated through desirability. For the needs of the study, numerical optimization will be conducted in the cutting zone at the depth of 25 mm.

According to the classification proposed by Hashish [1], this zone is defined as a deformation wear zone because of pronounced striations on the surface of material produced after hydro abrasive jet cutting. Surface roughness in observed zone moves within the range 4,93 ÷ 14,77 μm, thus there is a need for additional treatment due to weak surface quality which causes the increase of machining costs. Statistical analysis has shown that traverse speed has a greater influence on the quality of cutting compared to pressure and mass flow rate, and it is

necessary to find the maximum possible traverse speed with a minimal mass flow rate of abrasive particles.

The range of values within which the optimization will be conducted is 4,93 μm (as a lower boundary) and 6,32 (as upper boundary and also target point) (Fig. 6).
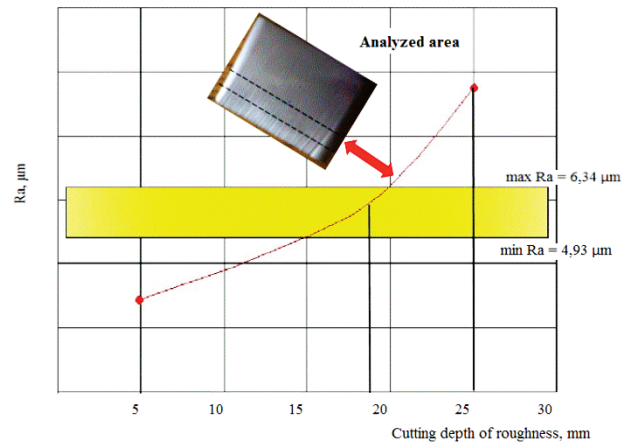

Figure 6 Area of optimization for regression model Ra_{25} [6]

Table 4 Potential solutions of numerical analysis for regression model Ra_{25}

Nr. of experiment	PROCESS FACTORS			Surface roughness at depth of 25 mm (μm)	Deserability
	Pressure (Mpa)	Traverse speed (mm/min)	Abrasive mass flow (kg/min)		
1	325,2	28,29	0,416	6,34	1
2	311,3	25,06	0,445	6,34	1
3	323,9	27,83	0,400	6,34	1
4	339,3	29,11	0,448	6,34	1
5	321,8	28,00	0,424	6,34	1
6	321,0	25,41	0,384	6,34	1
7	338,5	25,09	0,368	6,34	1
8	337,7	29,01	0,421	6,34	1
9	315,7	26,21	0,414	6,34	1
10	337,8	27,30	0,386	6,34	1
11	323,2	26,16	0,386	6,34	1
12	332,8	26,20	0,376	6,34	1
13	321,3	27,50	0,411	6,34	1
14	325,9	28,65	0,431	6,34	1
15	327,5	26,89	0,387	6,34	1
16	316,2	26,94	0,439	6,34	1
17	318,9	25,57	0,446	6,34	1
18	339,0	28,47	0,405	6,34	1
19	331,1	26,34	0,378	6,34	1
20	337,0	27,27	0,385	6,34	1
21	321,1	28,03	0,441	6,34	1
22	325,6	27,88	0,405	6,34	1
23	338,1	27,06	0,383	6,34	1
24	314,8	26,48	0,432	6,34	1
25	337,4	29,15	0,449	6,34	1
26	322,1	28,18	0,433	6,34	1
27	336,4	28,90	0,416	6,34	1
28	322,1	26,88	0,397	6,34	1
29	321,8	27,61	0,412	6,34	1

During the optimization process, it is necessary to take account of costs that arise during the cutting process. Considering that the abrasive has a relatively great share in total costs (approximately 60 %), it is necessary to find a combination of cutting parameters which will ensure minimal consumption of abrasive while maintaining the quality of surface in default value of *Ra* [6].

8 Results and discussion

Based on parameters, algorithm in the program suggests 29 potential solutions considered to have maximal desirability (or 1). That means it is possible to get optimal regression model with the required conditions in 29 possible combinations according to the limits of optimization (Tab. 4).

As the optimal solution, first choice recommended by the program is (v_f = 28,291 mm/min, p = 325,4 MPa and m_a = 0,416 kg/min).

Results of optimization also can be displayed graphically using the countor plot and 3D surface. Graphical optimization is a fast and simple method of optimization suitable for problems that involve up to 3 variables, based on principle of overlapping two-dimensional responses of observed variables within the boundaries.

The part of area within the boundaries that is common for all areas of response is considered to be optimal. Fig. 7 shows graphical optimization of problem with: a) contour and b) 3D surface.
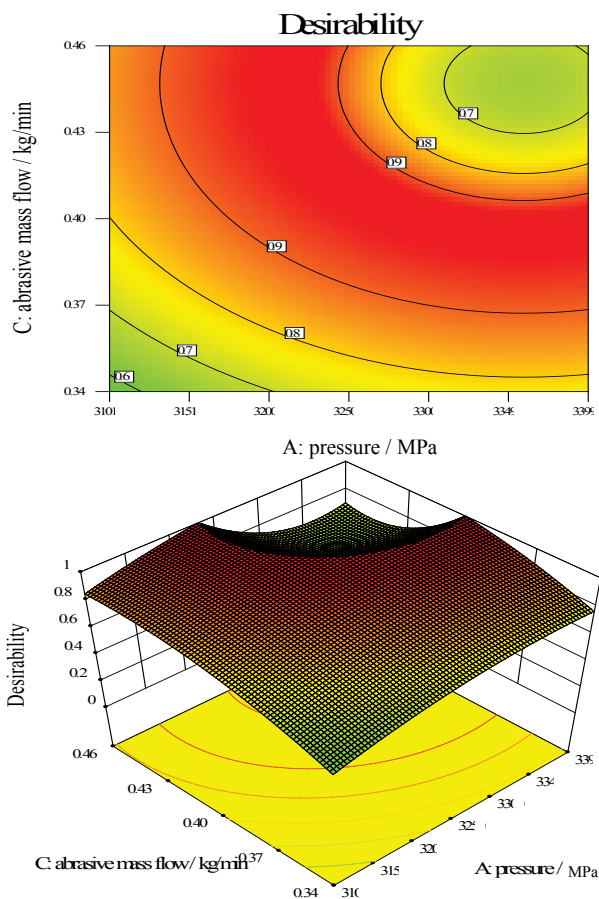

Figure 7 Graphical display of optimization: a) contour and b) 3D surface

With application of software LabVIEW calculation of cutting expenses was made to determine how much the change of individual cutting parameter will influence overall costs (Tab. 5). The largest items in the share of costs will be abrasive material (approximately 60 %) and electric energy (30,53 %), while the costs of water and consumable parts of the machine (orifice and focusing tube) are relatively low.

Table 5 Calculation of machining costs for achieving the required surface quality

Resources	Consuption of resources	Unit price, Kn	Share of costs, %
Abrasive	14,29 kg	30	59,18
Water	62,85 l	0,751	1,48
Electrical energy	11,904 kW·h	15,47	30,53
Focusing tube	0,007 pc	3,72	7,33
Orifice	0,00744 pc	0,744	1,46

Comparing the results obtained by the analysis of variance (with probability of 95 %) and optimization it can be concluded that the quality of machined surface with hydro abrasive jet and with conventional technology (milling) can be compared.

9 Conclusion

In this work the thesis about comparability of machined surface quality with hydro abrasive jet and milling was tested. Examining was conducted on specimens of austenitic corrosion resistant steel AISI 316 L with variation of 3 technological parameters of cutting (traverse speed, pressure and mass flow rate) on 2 levels.

Based on data obtained with measuring at the depth of 25 mm, statistical analysis was performed with software Design Expert 9. After analysis of variance, the following conclusions were drawn:

- Traverse speed has a greater influence on quality of machined surface compared to the other cutting parameters (pressure and mass flow rate) and their combination (A^2, B^2 and C^2), in the pressure range $310 \div 340$ MPa
- Further analysis revealed that residuals are normally distributed along Henry's line and the data from regression model are within the boundaries.

In order to examine the hypothesis about comparability of surface quality machined by hydro abrasive jet and milling, optimization was conducted. Results of optimization showed that the technology of hydro abrasive jet cutting can be compared with milling up to the cutting depth of 19,8 mm, because up to that depth the required surface roughness is achieved.

Decision support software such as LabVIEW allows finding the optimal solution that will satisfy the required criteria of quality while reducing machining costs.

Acknowledgement

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