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FACTOR ANALYSIS OF THE ABRASIVE WATERJET FACTORS AFFECTING THE SURFACE ROUGHNESS OF TITANIUM

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Preliminary notes

The paper focuses on experimental research and evaluation of the abrasive waterjet cutting technology process in order to evaluate the technology factors affecting the microgeometry (average roughness) of workpiece surface of titanium of 10 mm thickness using a full factorial design. The significance of four selected process factors – independent variables (traverse speed, abrasive mass flow rate, angle of attack, depth of cut) affecting the surface quality was evaluated by a two level full factorial design. The surface quality was evaluated by *Ra*, *Rq* and *Rz* surface roughness parameters. A multiple nonlinear regression equation obtained from ANOVA gives the level quality *Ra* as a function of the machining factors. A different significance of these factors has been found.

Keywords: *abrasive waterjet, surface roughness, titanium*

Faktorska analiza čimbenika abrazivnog mlaza vode koji utječu na hrapavost titanske površine

Prethodno priopćene

Članak se fokusira na eksperimentalno istraživanje i ocjenu tehnološkog procesa rezanja abrazivnim vodenim mlazom u cilju ocjene tehnoloških čimbenika koji utječu na mikro geometriju (prosječna hrapavost) titanske površine obratka debljine 10 mm koristeći puni faktorijelski plan. Značaj četiri odabrana faktora procesa - neovisne varijable (poprečna brzina, brzina masenog protoka abraziva, napadni kut, dubina reza) koje utječu na kvalitetu površine je ocijenjen pomoću dvorazinskog punog faktorijelskog plana. Kvaliteta površine je procijenjena pomoću *Ra*, *Rq* i *Rz* parametara hrapavosti površine. Jednadžba višestruke nelinearne regresije dobivena iz ANOVA daje razinu kvalitete *Ra* kao funkciju faktora obrade. Utvrđeno je drugačije značenje ovih faktora.

Ključne riječi: *abrazivni vodeni mlaz, hrapavost površine, titan*

1 Introduction
Uvod

The abrasive waterjet cutting process meets all the requirements of modern production, from an area of automation, economics, to environmental area. This technology has greatly altered the tooling and manufacturing industry, resulting in a dramatic improvement in accuracy, quality, and productivity. This abrasive waterjet cutting process is being currently used for many applications [3, 13]. The abrasive waterjet cutting technique is considered to be a flexible tool to process a wide range of materials without any time loss caused by a tool change. Abrasive machining is in most cases a very dynamic and stochastic process. Many scientific papers concerning the evaluation of the micro-geometrical features of abrasive waterjet cutting are available [8, 9, 10]. The objective is to determine the final surface quality as a function of the geometric characteristics of the abrasive waterjet tool and its factors which are divided into two basic groups; direct and indirect. To a group of indirect factors entering the cutting process belong: traverse speed; standoff distance, impact angle and number of passes. The factors affecting the cutting process (cutting factors) determine an impact of the created cutting tool on the workpiece material at the upper erosion base, where the erosion process begins. These factors create surface area as a trajectory of abrasive waterjet movement. Abrasive machining is a specific way of material machining due to the use of particles with more cutting edges, as the random oriented particles in a liquid phase. This random position and different shape of abrasive particles cause an irregular mechanism of material removal. The updated model contains two new factors; traverse direction and feeding direction of abrasives. The impact of these factors has not yet been exactly explained. It is assumed that these factors cause a difference in roughness values because of the feeding direction of solid phase, distribution of abrasive particle in the waterjet, and traverse direction. The need for improvements in surface quality has accelerated the process parameter optimization of the abrasive waterjet technology [5, 6]. Moreover, the process features change drastically with the machining factors entering the abrasive waterjet cutting process. The development of a mathematical model with the process factors (pressure, abrasive mass flow rate, traverse speed, diameter of nozzle, traverse direction) and output variables (surface profile parameter *Ra*) is a difficult task [9]. A statistically planned experiment as a method of designing the parameters at technological measurements are more effective tool when compared to the classic experiments [16, 23, 24].

2 Experimental set up
Eksperimentalna postavka

In order to investigate the influence of abrasive waterjet process factors on the average surface roughness, a full factorial design for four independent variables was designed. The full factorial analysis was used to obtain the combination of values for design optimization responding to a minimal number of experimental runs. Among the many process variables influencing the cutting results, there were selected four independent variables which were considered to be the factors within the experimental phase. The implicit-function representation is the following equation (1).

$$Ra = f(m_a, v, \varphi, h). \tag{1}$$

Four factors submitted for the analysis in the factorial design of each constituent at levels [–1; +1] are listed in Tab. 1. A 2^4 full factorial analysis was conducted leading to a total number of 16 runs. Two levels of factors (x_1, x_2, x_3, x_4) at level

Table *Hadamard matrix of design of experiments*
Tablica 1. *Hadamard matrica plana eksperimenata*

	Coded conditions				Real conditions			
	h / mm	m_a / g/min	v / mm/min	φ / °	h / mm	m_a / g/min	v / mm/min	φ / °
1.	-1	-1	-1	-1	1	300	100	0
2.	-1	-1	-1	+1	1	300	100	5
3.	-1	-1	+1	-1	1	300	300	0
4.	-1	-1	+1	+1	1	300	300	5
5.	-1	+1	-1	+1	1	400	100	5
6.	-1	+1	-1	-1	1	400	100	0
7.	-1	+1	+1	-1	1	400	300	0
8.	-1	+1	+1	+1	1	400	300	5
9.	+1	-1	-1	-1	10	300	100	0
10.	+1	-1	-1	+1	10	300	100	5
11.	+1	-1	+1	-1	10	300	300	0
12.	+1	-1	+1	+1	10	300	300	5
13.	+1	+1	-1	+1	10	400	100	5
14.	+1	+1	-1	-1	10	400	100	0
15.	+1	+1	+1	-1	10	400	300	0
16.	+1	+1	+1	+1	10	400	300	5

(–1 and 1) determine a matrix of 16-obsevations for dependent variable *Ra*. The behaviour of the presented system can be described by the nonlinear polynomial exponential equation (2), which includes all interaction terms regardless of their significance:

$$Ra = b_0 \cdot x_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + b_5 \cdot x_5, \quad (2)$$

where *Ra* is the average surface roughness parameter, x_1, x_2, x_3, x_4 are independent variables, b_0 is coefficient constant for offset term, b_1, b_2, b_3, b_4 are coefficient constant for effects, and b_{12}, b_{21}, b_{31},..., b_{1234} are coefficient constant for interactions effects. The obtained data from experiments were analyzed using Statistica 7.0 software and Matlab to estimate the dependent variable. For the experiments was used the adjustable precise cutting table from PTV Hostivice company. The water pressure was generated by the high-pressure intensifier pump with a maximum pressure of 415 MPa, power of 37 kW and water mass flow rate of 3,68 l/min. Titanium with a Young's modulus of 200 GPa was used as a target material. Each sample had a length of 35 mm, width of 8 mm, and height of 10 mm. Abrasive waterjet machining conditions were as follows: working pressure of 400 MPa, abrasive mass flow rate of 300 – 400 g/min, angle of attack of 0° – 5°, traverse speed of the cutting head of 100 – 300 mm/min. The Barton Garnet was used as abrasive material with MESH 80. Due to its resistance to corrosion titanium is considered to be a very attractive material. A surface roughness measuring device from the Mitutoyo Corporation – Suftest SJ 401 was used for surface roughness measurement. The surface roughness parameters (*Ra*, *Rq* and *Rz)* were measured in 20 depth traces with equidistant step of 0,5 mm.

3 Statistical evaluation and regression diagnostic
Statistička ocjena i regresijska dijagnostika

The results were analyzed using the analysis of variance statistical method as the appropriate to the experimental design (Fig. 1). The normality of experimental measured data was tested according to the Shapiro-Wilkson test criteria due to its good power properties when compared to a wide range of alternative tests. The Shapiro-Wilkson

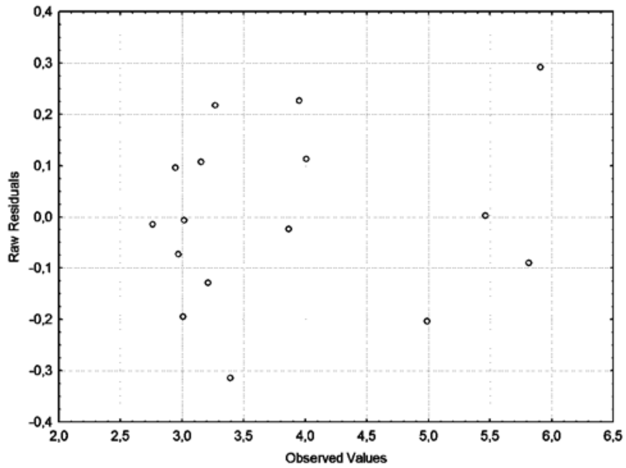

Figure 1 *Predicted vs. residual values*
Slika 1. *Predviđene naspram rezidualnim vrijednostima*

test has proved that all of 16 experiments (repeated measurements) have no greater value than the critical value $W_\alpha = 0{,}788$ for $n = 6$ and $\alpha = 0{,}05$. On the basis of this we can accept the null hypothesis about the normal distribution of measurements repeatability. The following equation shows a correlation matrix of the design variables eq. (3).

$$\mathbf{b} = \left[\mathbf{X}^{\mathrm{T}} \cdot \mathbf{X}\right]^{-1} \cdot \left[\mathbf{X}^{\mathrm{T}} \cdot \mathbf{Y}\right] = \begin{bmatrix} 3{,}858875 \\ 0{,}859500 \\ 0{,}005750 \\ 1{,}633250 \\ -0{,}077750 \end{bmatrix}. \quad (3)$$

The regression coefficients and equations obtained after the analysis of variance give the level of significance of the variable parameters tested according to Student's t-test. The critical value is

$$t_{1-\frac{\alpha}{2}}(f) = t_{0{,}975}(f = 11) = 2{,}2010.$$

The obtained regression coefficients with no statistical significance have been rejected from further evaluation.

Testing of model adequacy was done by Fisher-Snedecor; F-test, where testing criterion F = 6,80900 and critical value is

$$F_{1-\alpha}(f_1, f_2) = F_{0,95}(f_1 = 5, f_2 = 10) = 3,326.$$

Since

$$F > F_{1-\alpha}(f_1, f_2),$$

we can reject H_0 hypothesis, hence regression function describes the variability of measured values.

$$F = \frac{y^2_{x_1,x_2,x_3,x_4}}{1 - y^2_{x_1,x_2,x_3,x_4}} \cdot \frac{N - q - 1}{q} = 6,809. \tag{4}$$

Fig. 1 illustrates the residual values showing heteroscedasticity, a set of disordered values of the average roughness parameter. Fig. 2 shows a normal probability plot of the residual values. A reliability value being computed for Shapiro-Wilkson test of normality p is of 35128 and value of W criteria is W = 0,940185. According to inequality ($W_\alpha \geq W$), because W_α (N=16) = 0,88700 we can accept H_0 hypothesis about the residual values probability.

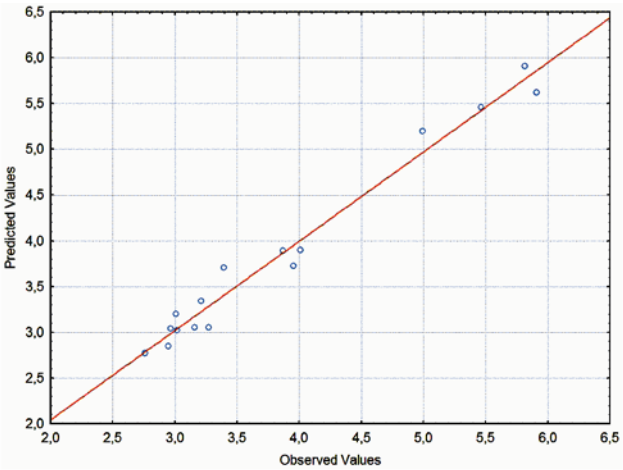

Figure 2 *Normal probability plot*
Slika 2. *Crtež normalne vjerojatnosti*

The regression equation obtained after the analysis of variance gives the level of the average roughness as a function of independent variables: abrasive mass flow rate m_a (g/min), traverse speed v (mm/min), material thickness h (mm), cutting head angle φ (°). All terms, with regard to their significance, are included in the following equation:

$$Ra = 3,8588 + 0,8595 \cdot h + 0,0057 \cdot m_a + 1,6332 \cdot v - \\ -0,077 \cdot \varphi + 0,88 \cdot h \cdot v. \tag{5}$$

According to the equation (5), factors x_1, x_2, and x_3 have a positive effect and factor x_4 has a negative effect. These results can be further interpreted in the Pareto Chart, which graphically displays the magnitudes of the effects from the results obtained. The effects are sorted in descending order from largest to smallest.

The chart shows that the material thickness is an important factor affecting the average roughness. The significance of the independent variables is interpreted in the following graph. Fig. 3 graphically displays the magnitudes of the effects. The most important factors affecting the average surface roughness parameter Ra (μm) are material thickness h and traverse speed v.

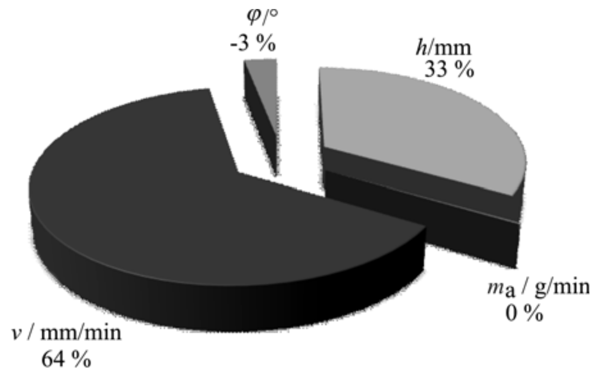

Figure 3 *Chart shows that depth was found to be the most significant*
Slika 3. *Grafikon prikazuje da je utvrđeno da je dubina najznačajnija*

The model was checked by several criteria. The fit of the model was expressed by the coefficient of determination R^2 = 0,97 indicating 97,59 % for the model of the variability. This value also indicates that only 2,41 % of the total variation is not explained by the model. This shows that the equation (5) is a suitable model to describe the average roughness parameter. As it can be seen from the plots of marginal means, the most important factor affecting the kerf width is the material thickness what is evident according to Fig. 4. The Fig. 4 shows plots of marginal means and confidential limits (95 %), traverse speed, angle of the cutting head, and abrasive mass flow rate. Marginal means plots show the predicted microgeometrical quality feature Ra as a function of independent variable – factors. It has been found that traverse speed v is significant with increasing depth of cut due to reduction of AWJ energy. Regarding angle of attack (5° red line), with interaction of abrasive mass flow rate it has been observed that values of surface profile parameter Ra rise with number of particles Fig. 4c at traverse speed of cutting head 100 and 300 mm. The values of significance abrasive mass flow rate they are rising sharply; it means that, for reaching low values of surface parameter roughness profile Ra, it is necessary to increase the amount of abrasive in the AWJ, Fig. 4d.

4 Conclusions
Zaključci

The problem being analyzed in this paper is focused on the study of abrasive waterjet cutting process in terms of the cutting quality of titanium. The experiments were planned according to Design of Experiment (DoE) as a full factorial design. This analysis points out that the variable independent factors affect the surface morphology in terms of microcutting quality. It has been found that the effects of selected factors are related to a different depth. The analysis by a full factorial design shows that the higher values of the average roughness are caused by an increase of the traverse speed. The thickness of the material, traverse speed and their mutual interactions has the most significant effect on the average roughness. By using a full factorial design it is possible to achieve greater depths of cut, a smoother cut, an optimization of the process with a significant impact on the final quality and process economics. It has been found that cutting head angle of attack has no important influence on surface roughness. That factor is significant for cutting of

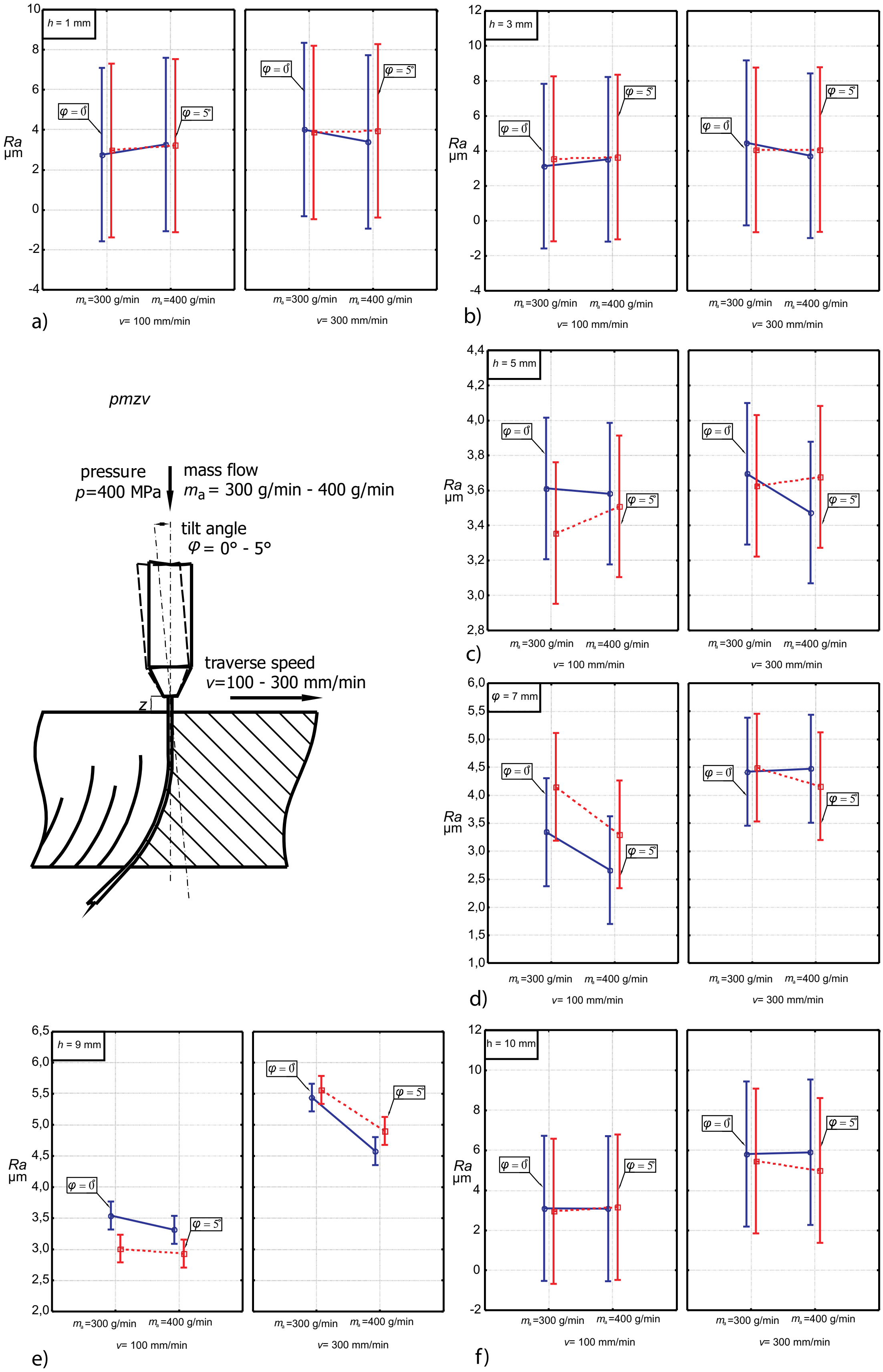

Figure 4 *Plots of marginal means for independent variables for depth trace a) h = 1, b) h = 3, c) h = 5, d) h = 7, e) h = 9, f) h = 10 mm*
Slika 4. *Crteži graničnih srednjih vrijednosti za neovisne varijable dubine traga a) h = 1, b) h = 3, c) h = 5, d) h = 7, e) h = 9, f) h = 10 mm*

materials thickness and reduce waviness zone at the bottom of the workpiece.

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5 References
Literatura

[1] Arola, D.; Ramulu, M. Material removal in abrasive waterjet machining of metals surface integrity and texture. Wear, 210, 6(1997), 50-8.

[2] Bitter, J. A study of erosion phenomena, part I. Wear, 6, (1963), 5-21.

[3] Botak, Z.; Kondic, Z.; Maderic, D. Waterjet Machining. Tehnicki Vjesnik-Technical Gazette. 16, 3(2009), 97-101.

[4] Gombar, M.; Hloch, S.; Radvanska, A. Traverse direction influence evaluation on average roughness at AWJ cutting. Annals of DAAAM for 2006 & Proceedings of the 17th International DAAAM Symposium - Intelligent manufacturing & automation: focus on mechatronics and robotics, 2006., 137-138.

[5] Hashish, M. Modelling study of metal cutting with abrasive waterjets. Transactions of the ASME, Journal of Engineering Material and Technology, 106, 1(1984), 88–100.

[6] Hashish, M. Optimization factors in abrasive waterjet machining. ASME J Eng Ind, 113, (1991), 9-37.

[7] Hlavacek, P. et al. Measurement of Fine Grain Copper Surface Texture Created by Abrasive Water Jet Cutting. Strojarstvo, 51, 4(2009), 273-279.

[8] Hloch, S. et al. Experimental study of surface topography created by abrasive waterjet cutting. Strojarstvo. 49, 4(2008), 303-309.

[9] Hloch, S.; Valíček, J.; Simkulet, V. Estimation of the smooth zone maximal depth at surfaces created by Abrasive Waterjet. International Journal of Surface Science and Engineering. 3, 4(2009), 347-359. DOI: 10.1504/IJSURFSE.2009.027420.

[10] Chen, F. L.; Siores, E. The effect of cutting jet variation on striation formation in abrasive water jet cutting. International Journal of Machine Tools & Manufacture. 41, (2001), 1479-1486.

[11] Kulekci, K. M. Processes and apparatus developments in industrial waterjet applications. International Journal of Machine Tools & Manufacture. 42, (2002), 1297-1306. DOI: 10.1016/S0890-6955(02)00069-X

[12] Kusnerova, M. et al. Derivation and Measurement of the Velocity Parameters of Hydrodynamics Oscillating System, Strojarstvo. 50, 6(2008), 375-379.

[13] Radvanska, A. et al. Technical Possibilities of Noise Reduction in Material Cutting by Abrasive Water-jet. Strojarstvo. 51, 4(2009), 347-354.

[14] Valiček, J. et al. An investigation of surfaces generated by abrasive waterjets using optical detection. Strojniski vestnik-Journal of mechanical engineering. 53, 4 (2007), 224-232.

[15] Valíček, J. et al. Experimental analysis of irregularities of metallic surfaces generated by abrasive waterjet. International Journal of Machine Tools and Manufacture. 47, 11(2007), 1786-1790. DOI:10.1016/j.ijmachtools.2007.01.004.

[16] Valíček, J.; Hloch, S.; Kozak, D. Surface geometric parameters proposal for the advanced control of abrasive waterjet technology. The International Journal of Advanced Manufacturing Technology. 41, 3-4(2009), 323-328. DOI: 10.1007/s00170-008-1489-2.

[17] Valíček, J.; Hloch, S. Optical measurement of surface and topographical parameters investigation created by abrasive waterjet. International Journal of Surface Science and Engineering. 3, 4(2009), 360-373. DOI: 10.1504/IJSURFSE.2009.027421.

[18] Valíček, J.; Hloch, S. Using the acoustic sound pressure level for quality prediction of surfaces created by abrasive waterjet. The International Journal of Advanced Manufacturing Technology. 48, 1-4(2010), 193-203. DOI: 10.1007/s00170-009-2277-3.

[19] Misik, L.; Hloch, S.; Vagaska, A. et al. Side milling factors analysis affecting the surface irregularities of high-grade steel E295. Tehnicki vjesnik-Technical Gazette, 15, 2(2008), 19-23.

[20] Harničárová, M.; Zajac, J.; Stoić, A. Comparison of different material cutting technologies in term of their impact on the cutting quality of structural steel, Tehnicki Vjesnik-Technical Gazette, 17, 3(2010), 371-376.

[21] Jurisevic, B.; Coray, P. S.; Heiniger, K. C.; Junkar, M. Tool Formation Process in Abrasive Water Jet Machining. MIT'2003 University of Ljubljana. 2003.

[22] Lebar, A.; Junkar, M. Simulation of abrasive water jet cutting process. Modelling Simul. Mater. Sci. Eng. 12, (2004), 1159–1170.

[23] Mason, R. L.; Gunst, R. F.; Hess, J. L. Statistical design and analysis of experiments. Second edition. Wiley-Interscience. A John Willey & Sons Publication, New Jersey, 2003., ISBN 0-471-37216-1.

[24] Montgomery, D. C. Design and analysis of experiments. 5th. edition, Hamilton Printing Company, 2001., ISBN 0-471-31649-0.

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