DESIGN OF EXPERIMENTS APPLIED ON ABRASIVE WATERJET FACTORS SENSITIVITY IDENTIFICATION

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ABSTRACT

The article gives an example of design of experiments (DoE) application on process factors evaluation of hydroabrasive waterjet cutting. The paper deals with macro geometrical cutting quality evaluation of process factors of abrasive waterjet cutting according to design of experiments. Full factorial design was used as a statistical method to study effects of independent factors: pressure p, abrasive mass flow rate m_A, traverse rate v and J/T abbreviation to impact to the taper λ as a dependent variable. Obtained regression equations after analysis of variance (ANOVA) and factor analysis give the level quality as a function of the process parameters. Different factor significance has been found, which generated surface profile under defined conditions by abrasive waterjet.

KEYWORDS factors, abrasive waterjet, design of experiments, taper

1 INTRODUCTION

Design of Experiments is a statistical technique used in technology systems operation, quality engineering, to identify significant or sensitive factors (independent variables) and levels their factor values that influence system performance and variability (dependent variables). This technique is especially useful when there is the need to understand the interactions and effects of several system variables and an absence of concrete information. Manufacturing engineers can use experimental designs to establish a cost-effective set of experiments to identify factors and levels that have the most and least impact on system performance.

In the real world, information is usually incomplete, time is short, funding is limited, and market pressure to deliver an operational and optimal solution in technology system production. These solutions have economic and operational costs associated with them. Experimental designs provide the manufacturing engineer with a methodology for collecting the data needed to evaluate the costs and benefits of various solutions of manufacturing technologies. One of the most evaluated technologies is abrasive waterjet cutting technology.

2 RELATED WORKS

The abrasive waterjet cutting technique is considered to be a flexible tool in the processing of a wide range of materials without wasting a time in tool changing and with minimal risk to occupational health and environment [1], [3], [9], [11], [17]. This technology nowadays represents cold precise, computerized controlled shape cutting without any strain. The work presented in this study investigates a macrogeometrical aspect of the cutting quality of the taper. At the top of the kerf, erosion at shallow impact angles controls the abrasive wear mode, while deformation wears by impacts at large angles takes place further down the kerf. Most scientific papers concerning evaluation macrogeometrical features of abrasive waterjet cutting are available [2], [3], [5], the object is to determine the final shape of the kerfs walls, which is a function of the geometric characteristic of the abrasive waterjet tool and its quality factors. The factor division is listed in the table below (Tab. 1).

Table 1 Abrasive waterjet process factors

	Type	Sign	Unit
Indirect	Pressure of the pump	p	[Pa]
	Jewel diameter	d_0	[mm]
	Focusing diameter	d_F	[mm]
	Length of mixing tube	l_F	[mm]
	Mass flow	m_A	[kg.min^{-1}]
	Diameter	d_p	[mm]
	Shape		
	Hardness	H_p	

Direct	Traverse rate	v	$[mm.s^{-1}]$
	Number of passes	n_p	
	Stand off	x	[mm]
	Angle of cutting	φ	[°]

Tool created through cutting factors, hits the workpiece the at upper erosion base, where erosion process begins. These factors create surface as area of trajectory working movement of abrasive waterjet. It is specific way of material machining because there are used particles with more edges; those cutting edges are made by abrasive particles that are random oriented in the liquid phase waterjet. The random position and different shape of abrasive particles causes irregular removal mechanism of material. Another specific of abrasive waterjet technology is that consist of three phases - liquid, solid and fluid (Fig. 1).

The general cut surface produced by abrasive water jet (AWJ) cutting consists of an upper smooth zone which is free of any striations and its primary surface irregularity is roughness, and a lower rough zone where the wavy striations are the dominant characteristic features (Fig. 1).

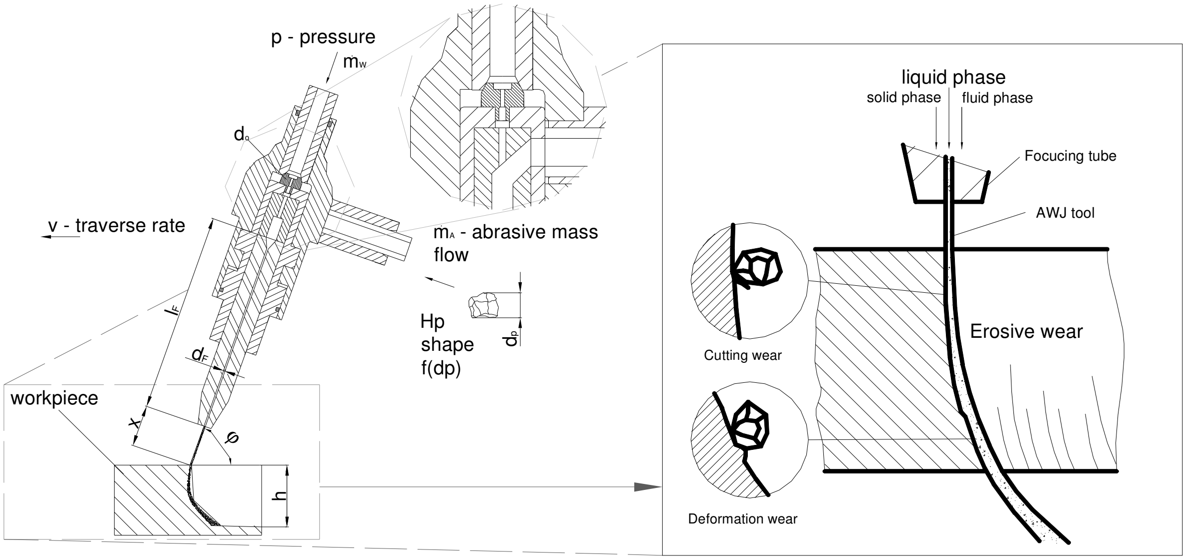

Figure 1 AWJ tool creation and impact to the target material

The taper geometry directly depends on the shape of the jet, which is not similar to shape of a fixed geometry tool. The tool quality depends on indirect factors (Fig. 2). In fact, due to hydrodynamic characteristics of the jet, is geometry significantly influenced by pressure, water orifice diameter, and abrasive factor and mixing factor. These factors influence the qualitative characteristics of the tool, the speed, diameter and kinetic energy of the stream. [5],[9],[11], [16].

Through cutting factors, created tool hits the workpiece the at upper erosion base, where erosion process begins. These facts confirm that abrasive waterjet cutting is a difficult process for classic experimental schemes. [6]

To evaluate the cutting process of abrasive waterjet, the influence of process factors (pressure, traverse speed, abrasive mass flow rate and J/T abbreviation) on the quality of abrasive waterjet cutting surfaces is analyzed by application of design of experiments. The analysis of variance is performed in order to identify which selected process factors and their interaction variables significantly influence the cutting quality of kerf and taper. [7]

In order to investigate the influence of abrasive waterjet process factors on macro geometrical cutting quality, full factorial design for four independent variables has been designed. Full factorial analysis was used to obtain the combination of values that can optimize the response within the region of the four dimensional observation spaces, which allows one to design a minimal number of experimental runs.

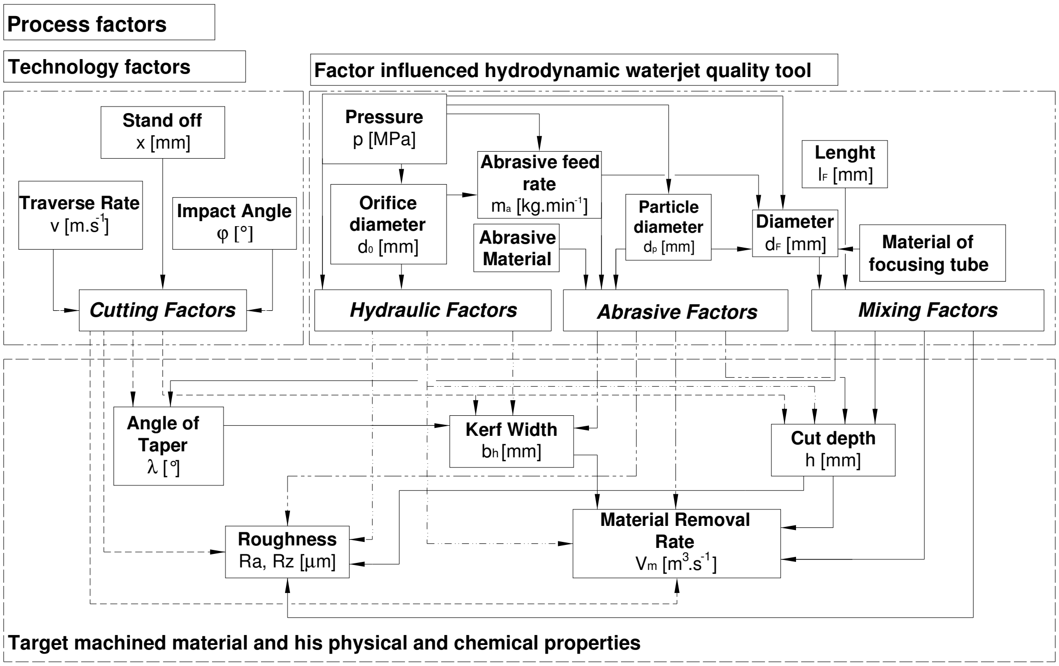

Figure 2 AWJ Process factors interactions and their influence to qualitative and quantitative characteristic of target material

Among the many process variables that influence the cutting results, four have been selected and considered as factors in the experimental phase. The variables are: pressure, J/T abbreviation, traverse speed, abrasive mass flow rate, which were submitted for the analysis in the design. The variable of each constituent at levels: –1, and +1 is given in Table 2. [4, 5, 6]

Table 2 Coded factors at defined levels

N	Factors		Factor level	
	Var.	Terminology and dimension	-1	+1
1	x_1	J/T abbreviation [mm]	0,1/1	0,14/1,2
2	x_2	Abrasive mass flow rate [g.min^{-1}]	300	500
3	x_3	Pressure [MPa]	200	350
4	x_4	Traverse rate [mm.min^{-1}]	70	120

The experimental cuts have been performed in a random sequence, in order to reduce the effect of any possible error. A 2^4 full factorial analysis has been used with 2 replicates at the center point, leading the total number of 16 experiments. Considering that the four levels of the x_1, x_2, x_2, x_4, and variables are -1 and 1, the designed matrix is 16-obsevations for dependent variable y_λ. [7] The graphical interpretations of DOE are illustrated in the figures 1,2. Specimens series A has been made with process parameter J/T at high level 0,14/1,2 (+1) and specimens series B with lowest level of J/T abbreviation. The smaller diameters of diamond orifice and focus tube produce water with higher speed of abrasive water jet. [5]

An observation has been realized in a random order. The behavior of the present system is described by the following equation (1), which includes all interaction terms regardless of their significance:

$$y_i = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + ... + b_{1234}x_1x_2x_3x_4$$

Where y_i is predicted response width in upper y_{ueb} and lower y_{leb} erosion base and taper y_λ and 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 are coefficient constant for linear effects and b_{12}, b_{21}, $b_{31}, \ldots, b_{1234}$ are coefficient constant for interactions effects. The model evaluates the effect of each independent variable to a response y_{ueb}, y_{leb}, y_λ. Design summary: (standard design): 2^4 Resolution R = FULL

- Number of factors (independent variables): 4
- Number of runs (standard experiment): 16
- Total number of runs in experiment: 16
- Number of blocks: 1
- Fractional replications: Full factorial

Figures 3, 4 illustrate the graphical interpretations of DOE. Specimens series A has been made with process factor J/T at high level 0,14/1,2 (+1) and specimens series B with lowest level of J/T abbreviation.

3.1 Experimental set up and measurement procedure

Abrasive machining conditions used in this study are listed in the table 4. According to experimental methodology of graphic presentation (Fig. 3) each cut has been replicated three times; yielding total of 48 cuts.

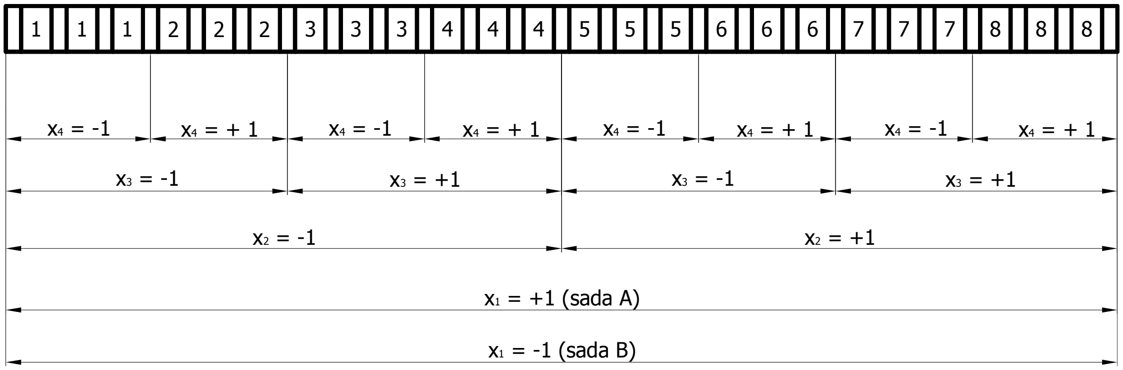

Fig. 3 Experimental methodology graphic illustration of specimens' series A and B

A two dimensional abrasive waterjet machine Wating, has been used in this work with following specification: work table x-axix 2000 mm, y-axix 3000 mm, z-axis discrete motion, with maximum traverse rate 250 $mm.s^{-1}$. The high-pressure intensifier pump was used the Ingersoll-Rand model with maximum pressure 380 MPa. As a cutting head an Autoline cutting head from Ingersoll-Rand head has been used.

Table 4 Set up of experiments

Variable factors	Values	***Constant factors***	Values
Pressure p [MPa]	200/350	*Standoff*	3 mm
Traverse rate v [mm.s^{-1}]	70/120	Abrasive material Barton Garnet Mesh 80	
J/T abbreviation	0,14/1,2; 0,1/1	Cutting head	Autoline^{TM}
Abrasive mass flow rate [g.min^{-1}]	200/500	Material thickness	10 mm

Target material: Stainless steel AISI 304 – Chemical Properties and Physical Aspects

% C max	% Mn max	% P max	% S max	% Si max	% Cr max	% Ni
0,07	2,0	0,045	0,03	1	18/20	8/10

Tensile Strength Rm [N.mm^{-2}]	Slip Limit Rp 0,2% [N.mm^{-2}]	Strength max. HRB	Structure
540/680	195	88	austenitic

System characteristics of Ingersoll Rand Streamline Pump

Intensifier type	Double effect	Water pressure (max)	380 MPa
Intensifier power	50 kW	Intensification ratio	20:1
Oil pressure (max)	20 MPa	Accumulator volume	2 l
Number of cuts: 96 (16 experimental conditions with 3 replications)		Number of measurements: 288	

4 RESULTS AND DISCUSSION

For simplified evaluation of measured characteristics and calculated the taper graphic execution have been done (Fig. 4, 5). Experimental graphic dependence describes the taper characteristics of 10 mm thick stainless steel. From the graph, it is evident the influence of J/T abbreviation process parameter. The smaller is the diameter of water orifice, the higher the speed of water. This improves the macrogeometrical quality characteristics of cutting surface.

The diameter of cutting tool is crucial. This phenomenon is connected with energetically potential of the stream. But these characteristics dramatically change depending on the depth (Fig.5), consequently on kinetic energy absorption by workpiece due to hydrodynamic friction of abrasive waterjet. Figure 5 shows the percentual proportion that was derived from regression coefficient of examined process parameters influence in upper erosion base and lower erosion base by factorial analysis.

There is also seen a cyclic increase and decrease of experimentally measured characteristics of samples series A and samples series B. Such trend of graphic representation is caused by traverse rate. Due to this influence of the factor the ideal circular shape of the tool is changing. Active area of the tool is deforming to the elliptic shape, and that causes reduction of the stream diameter, that is given by the minor axis size of ellipse.

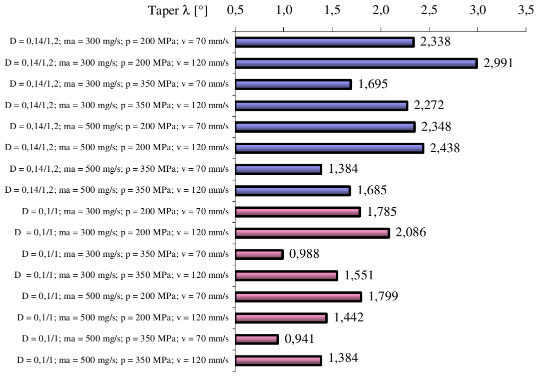

Fig. 4 The taper characteristic

The results were analyzed using the analysis of variance as fitting to the experimental design used. Experimental data have been tested according Cochran's test. The regression coefficients and equations obtained after analysis of variance gives the level of significance of variable parameters tested according to Student's t-test. Obtained regression coefficients that show no statistical significance have been rejected from the next evaluation of the process.

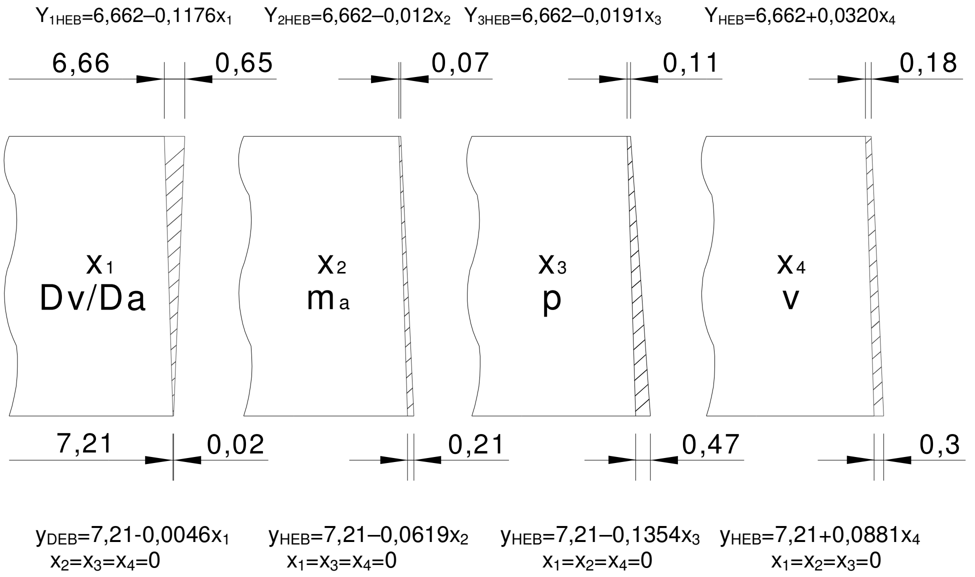

Fig.5 Abrasive waterjet factors Influence to y_{UEB}, yL_{EB}, y_λ

The model, expressed by following equation, was generated by multiple linear regressions of the data and is a function of the significant variables:

$$\bar{y}_\lambda = 1{,}82 + 0{,}3234x_1 - 0{,}1428x_2 - 0{,}333x_3 + 0{,}1607x_4 \quad (2)$$

Where: y_λ is the response, that is kerf of the surface and x_1, x_2, x_3, x_4 are coded values of the variables J/T abbreviation, abrasive mass flow rate, pressure and traverse rate. Regression model contains four linear terms. The model has been checked by several criteria. The fit of the model has been expressed by the coefficient of determination. R^2, which was found to be 0.9995 indicating that 99,95% of the variability in the response can be explained by the model. The value also indicated that only 0,05% of the total variation is not explained by the model. The significance of process factors is interpreted in the Pareto chart fig. 6. This shows that equation is suitable model for describing to describe the response of the taper. The value of adjusted determination coefficient adj = 0,9871 is very high to advocate for a high significance of the model. The significance of process parameters is interpreted in the Pareto chart fig. 6. An increase of the pressure, in general, improves surface quality. With pressure increase the abrasive increases water jet kinetic energy. [7]

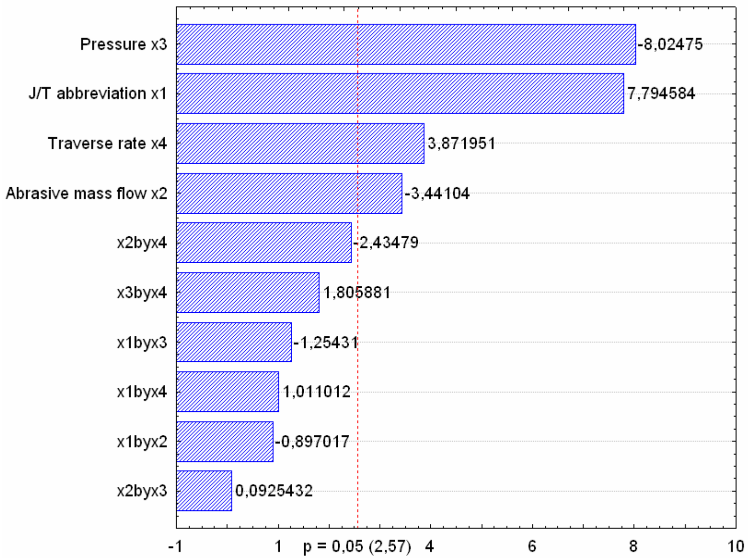

Fig. 6 Pareto charts of standardized effects for variable taper

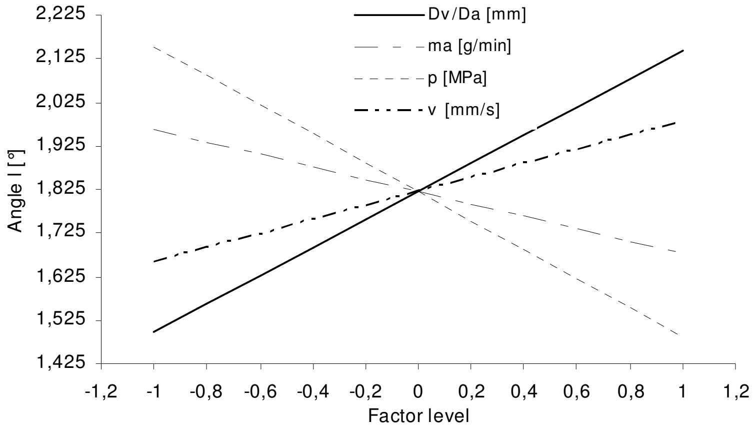

Fig. 7 Linear fits of factors influence to

From fluid mechanics in the hydroabrasive cutting process, the primary factor is the water stream velocity and that velocity strongly depends on pressure and diameter of the diamond orifice and diameter of the focusing tube. The second and the most significant factor is J/T abbreviation that relates with size and active length of cutting tool. The impact of J/T abbreviation is shown on Figure 7.

The important fact is that J/T abbreviation with level –1 (0,1/1) creates more coherent stream. Therefore the surface quality improves with higher pressure and smaller diameter because an abrasive water jet disposes with higher energy concentrated to smaller area of the workpiece. The Figure 4 illustrates fitted three-dimensional surface plot of abrasive mass flow rate and traverse rate process parameters.

With an increase in the abrasive-mass flow rate, the quality of surface - taper characteristics improves. But according to planned level conditions that factor there is range of abrasive mass flow rate from 300 $g.min^{-1}$ to 500 $g.min^{-1}$. From that mentioned reason high abrasive-mass flow rates influence to taper, is less significant. As the abrasive mass flow rate increases, speed of the abrasive water jet reduces. The higher the mass-flow rate, the higher the number of abrasive particles is that must share the kinetic energy of the water jet. It is assumed that at low values of the factor x_2, the particles do not collide one with another. They hit the material with a maximum velocity and maximum possible kinetic energy. The final result is that the abrasive mass flow rate has the less influence as hydrodynamics parameters, pressure and J/T abbreviation.

The traverse rate is more sensitive factor as abrasive mass flow rate. With an increasing speed of abrasive cutting head the taper increase. The smaller speed is, the longer abrasive waterjet remains at the upper erosion base location, and then the stream has the more time to erode the workpiece.

CONCLUSIONS

The quality parameter taper has been calculated according to measured experimental data the width of upper and lower erosion base. These data and calculated results have been analyzed using ANOVA, in order to identify the variables that significantly affect the relationship between the taper and process variables. The regressions equations obtained from analysis of variance gives the level quality as a function of different variables: pressure, traverse rate, abrasive feed rate and J/T abbreviation.

It has been observed that dominant parameters influencing macrogeometrical quality are hydrodynamic parameters - pressure and J/T abbreviation. These factors directly determine quality of the tool – high-speed waterjet. The effect of abrasive mass flow rate and feed rate are less noticeable.

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The authors would like to acknowledge the support of Scientific Grant Agency of the Ministry of Education of Slovak Republic, Commission of mechanical engineering, metallurgy and material engineering, for their contribution to project 1/1095/04 - Optimization of abrasive waterjet cutting technology process, by mathematical and experimental planning.

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