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THE QUALITY MODEL OF THE AWJ CUTTING PROCESS FOR ALUMINUM TYPE PA4 ALLOY

The article presents the quality model of the process of high-pressure abrasive waterjet cutting of aluminum alloy, type PA4, as well as the results of research that verified the accuracy of the determined dependence. The experimental works were performed on two experimental setups: machining AWJ center type RCT 32 by Resato company, as well as the prototype workstation constructed on the basis of plasma cut-off machine type TOPAZ-S by Eckert company. The geometric structure of the cut surfaces was measured using spatial profilometer Talysurf CLI 2000 equipped with a non-contact laser sensor. Nonlinear estimation module of Statistica program was used for qualitative development of the model of high-pressure abrasive aluminum alloy waterjet cutting process. The statistically elaborated dependence can be implemented in machine tool controllers designed for abrasive waterjet cutting of materials.

Key words: abrasive waterjet, materials cutting, model

1. INTRODUCTION

The scientific achievements of the last decades laid the foundations for the dynamic development of new technologies. An important case in this respect is the waterjet technology which makes use of concentrated energy streams in the form of high-pressure waterjet that often contains granular additives. Recent years have witnessed rapid development of this materials machining method, especially of the high-pressure abrasive waterjet cutting [3, 5].

This is connected with the technological growth that makes it possible to use high water pressures [6], as well as with the numerous advantages of this machining method, which include: no heat influence of the jet on the machined material, changing the tool is not necessary, low pressure force in the erosion area, the possibility of cutting a wide range of materials [1, 8, 9]. In view of this, the high-pressure abrasive waterjet, which is a universal technological tool, finds itself applicable in a wide range of machining processes.

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The basic parameters of the technological process that characterize material abrasive waterjet cutting are: the pressure of the waterjet, cutting head feed rate, abrasive consumption, diameter of the focusing nozzle and stand-off distance [10]. The knowledge of the machining conditions influence on the quality of the obtained cuts makes it possible to develop a model of the material cutting process that guarantees high quality of the cut surfaces [2].

This article presents the statistically elaborated model of the process of high-pressure abrasive waterjet cutting of aluminum alloy PA4, which forecasts the quality of the obtained cuts, expressed with the mean square deviation of the surface roughness.

2. RESEARCH METHODOLOGY

The research works were planned so as to determine the relationship between shaping the geometric structure of the cut surfaces (*Sq*) and the elementary machining parameters (water pressure *p*, cutting head feed rate v_f and the radius of curvature of the shape cut out with the high-pressure abrasive waterjet *r*) and the material thickness (*g*). The tests were performed using machine RCT 32, designed for high-pressure abrasive waterjet cutting of materials produced by Resato company (fig. 1).

Fig. 1. Abrasive-water jet cutting center type RCT 32

Hydraulic intensifier Power Jet PJE-4-4000, equipped with electric motor with the power of 37 kW (p_{max} = 380 MPa, Q_{max} = 3.8 dm^3/min) was used to produce the high-pressure water-jet. Cutting head type VJW1-2R-C60-ABR produced by Resato, equipped with water and focusing nozzle mounted in its body, was used in the tests. The cutting head feed rate was determined in the tests for each of the cut materials, in accordance with the default values attributed by Cadcraft GEMS R4 program.

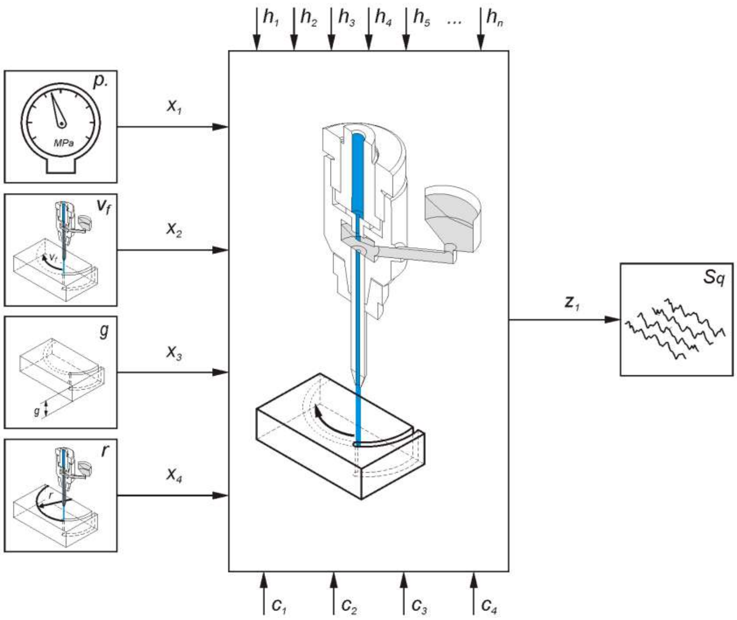

Fig. 2. The diagram of research model

The experiments were carried out using granate #80. It is an abrasive commonly used to create the waterjet in material cutting. The tests were carried out on aluminum type PA4 alloy. The main reason for using this material in the tests is the fact that it is often used in technical constructions. The graphic model form is presented in fig. 2.

The model elements were divided into four groups:

– input values:
  - x_1 – water pressure (p = 175–350 MPa),
  - x_2 – cutting head feed rate (v_f = 0.75–2.16 mm/s),
  - x_3 – material thickness (g = 20, 35 mm),
  - x_4 – cut trajectory radius of the head (r = 10, 20, 30, 40 mm),

– constant data:
  - c_1 – abrasive consumption (m_a = 3 g/s),
  - c_2 – water nozzle diameter (d_w = 0.25 mm),
  - c_3 – focusing nozzle diameter (d_o = 0.76 mm),
  - c_4 – stand-off distance (l = 3 mm),

– distorting values:
  h_1 – inaccuracy of the abrasive particles flow intensity,
  h_2 – inaccuracy of output data evaluation,
  h_3 – inaccuracy of cutting head positioning,
– output values:
  z_1 – mean square roughness deviation *Sq*.

After the experiments were finished, the geometric structure of the cut surfaces was mapped using spatial profilographometer Talysurf CLI 2000 by Taylor-Hobson. Non-contact laser sensor was used in the measurements that makes measuring in the unevenness range 169 nm-9.7 mm possible. The microtopography measurements were made in 401 passes with a step every 10 µm. In a single pass 801 points every 5 µm were registered with table speed v = 1 mm/s. Each measurement was carried out in a single-pass mode. The data, obtained during the measurements, underwent machining using specialist TalyMap Universal software. For each of the obtained microtopographies the value of the mean square deviation of the surface roughness was determined.

Non-linear estimation module of Statistica program was used to develop the model of aluminum alloy high-pressure abrasive waterjet cutting, thanks to which it is possible to approximate the experimental data with the regressive dependence indicated by the user and to determine with the maximum precision the values of coefficients of the suggested regression equation. The aforementioned module makes default use of the least squares sum method as the criterion (loss) function. This method, consists in minimizing the sum of squares of differences that occur between the observed values (experiment results) and the values calculated using the determined mathematic model [4].

Rosenbrock and quasi-Newton methods were used for estimation of the non-linear dependence. Such a combination of methods is recommended in a situation when there is no certainty as to the right input values of the estimation [7]. In this case the first method (Rosenbrock's) made it possible to determine the initial coefficient values which were then used in the quasi-Newton method.

3. QUALITATIVE MODEL OF CUT PROCESS

In order to determine the form of the qualitative model of curvilinear abrasive waterjet aluminum alloy cutting, a statistical analysis of the research results of the influence of the machining conditions (p, v_f, r, g) on the shaping of the cut surfaces was performed. Evaluation of the quality of the cut geometric structure was made using mean square roughness deviation *Sq*. This parameter is more sensitive to peaks and valleys then *Sa* (arithmetic average of absolute values), because the amplitudes are squared, which is a desirable feature in developing the model because of its accuracy.

The mathematical model that described the influence of water pressure p, cutting head feed rate v_f, cut trajectory radius of the head r and thickness of the cut material g on the quality of the area located in the bottom area of the cut aluminum type PA4 alloy, expressed with the mean square surface roughness deviation, is included in the form of the following formula:

$$Sq = 11 \cdot 14041 p^{-1,430} \cdot 39,6 v_f^{1,011} \cdot 668 r^{-0,231} \cdot 5270 g^{1,130}. \quad (1)$$

For the determined dependence the explained variance share, expressed using the determination coefficient and determined for the significance level $\alpha = 0.05$, is $R^2 = 0.925$. The obtained value confirms the proper matching of the model with the experimental data.

In order to confirm the relevance of the determined dependence, a statistical residuals, differences between the model values (determined using the model) and the experimentally determined values, test was performed. It was assumed in the regression analysis that the residuals random deviations were independent and were subject to normal distribution. This means that the suggested model may be deemed relevant for the experimental data only when the obtained residuals would exhibit tendencies confirming the assumptions that were made. The correctness of the assumption concerning normal residuals distribution was evaluated on the basis of the relative frequency of residuals (fig. 3a).

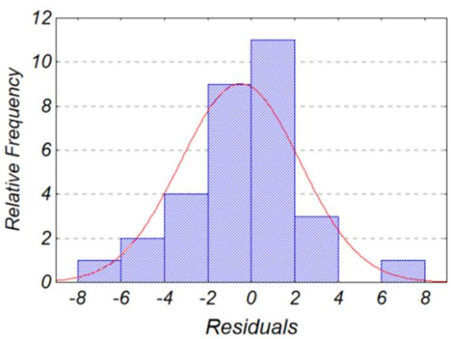

Fig. 3a. Relative frequency of residuals

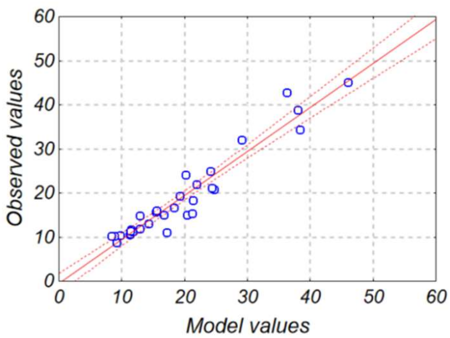

Fig. 3b. Scatterplot for observed vs model values

Even though no significant differences that would be indicative of discrepancy with the assumptions of the normal distribution were observed, an analytical check was performed with the Shapiro-Wilk normality test. The determined value of the test statistics $W = 0.965$ is higher than the test critical value ($W_{0.05;31} = 0.929$), determined from the level of significance $\alpha = 0.05$ and the size of the sample $N = 31$. The relatively high probability $p = 0.395$, exceeds the value of the assumed significance level α. On such a basis the analyzed residuals distribution may be treated as a normal distribution.

Taking into consideration the fact that the residuals undergo normal distribution, as proved before, it needs to be concluded that the determined model described with formula (1) is relevant for the research results. This is confirmed by the diagram illustrating scatterplot of the observed and model values (fig. 3b). Presented results do not reveal any specific oddities that would be indicative of irrelevance of the discussed dependence.

4. ANALYSIS OF ELABORATED MODEL CORRECTNESS

The target application of the elaborated model of high-pressure abrasive aluminum PA4 type alloy waterjet cutting process, anticipating the mean square deviation of the obtained cut surface roughness, is its usage in steering the prototype research workstation constructed on the basis of plasma cut-off machine type TOPAZ-S by ECKERT (fig. 4).

Fig. 4. Prototype research cut machining tool

Control tests were carried out to verify the accuracy of the determined model. When making the research conditions precise, it was assumed that the water pressure and the cut material thickness would be constant and have the respective values of p = 300 MPa and g = 20 mm. The changeability of the cut trajectory radius of the head r ranged from 10 to 30 mm. Next, using the statistically elaborated cutting process model, which determined the mean square roughness deviation Sq, the cutting head feed rate values were determined, which were necessary for obtaining the previously agreed cut surfaces quality (Sq = 10-13 µm). The thus determined machining parameter values (v_f) were introduced into NEC 2000 S controller. The obtained control test results are presented in fig. 5.

When analyzing the location of the obtained experiment results (points) in relation to the statistically elaborated model (surface) it may be concluded that the differences between the verification test results and the model values do not exceed 1.8 µm (14%). This relatively minor diversification makes it possible to conclude that the elaborated model is statistically relevant for the set of data collected in the research. Moreover, the same model which determines the influence of the machining conditions on the quality of the cut surfaces expressed with indicator Sq, can be successfully used for effective steering of the cutting process, carried out on the prototype research post.

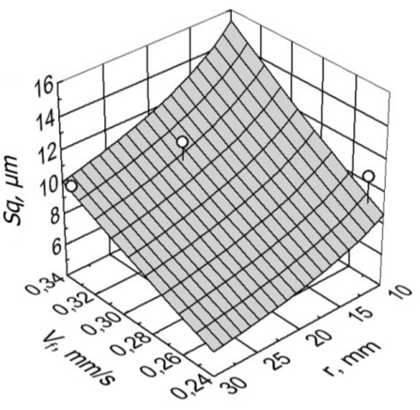

Fig. 5. Location of the test results with respect to the model surface

5. SUMMARY

As a result of the conducted experimental tests it was proved that there is a direct dependence between the elementary parameters of high-pressure abrasive material waterjet cutting process and the quality of the obtained cuts expressed by Sq parameter. Familiarity with the influence of the machining conditions on the geometric structure of the cut surfaces allowed to develop a model of high-pressure abrasive aluminum alloy waterjet cutting process.

The conducted verification tests proved that the determined dependence makes it possible to effectively steer the aluminum alloy cutting process, as far as the quality of the obtained surface is concerned. Moreover, the statistically elaborated dependence can be implemented in machine tool controllers designed for abrasive waterjet cutting of materials.

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JAKOŚCIOWY MODEL PROCESU CIĘCIA AWJ STOPU ALUMINIUM GATUNEK PA4

S t r e s z c z e n i e

W pracy zaprezentowano jakościowy model procesu cięcia stopu aluminium gat. PA4 wysokociśnieniową strugą wodno-ścierną oraz wyniki badań weryfikujących efektywność wyznaczonej zależności. Prace eksperymentalne wykonywano na dwóch stanowiskach badawczych: centrum obróbkowym AWJ typ RCT 32 firmy Resato oraz prototypowym stanowisku badawczym zbudowanym na bazie przecinarki plazmowej typ TOPAZ-S firmy Eckert. Strukturę geometryczną przeciętych powierzchni mierzono za pomocą profilometru przestrzennego Talysurf CLI 2000 wyposażonego w bezstykowy czujnik laserowy. Do opracowania jakościowego modelu procesu cięcia stopu aluminium wysokociśnieniową strugą wodno-ścierną zastosowano moduł Estymacja Nieliniowa programu STATISTICA. Opracowaną statystycznie zależność można zaimplementować w sterownikach obrabiarek, przeznaczonych do przecinania materiałów strugą wodno-ścierną.

Słowa kluczowe: struga wodno-ścierna, przecinanie materiałów, model