Qualitative analysis of AWJ factors affecting the surface roughness

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Abstract

The paper deals with experimental research and evaluation of abrasive waterjet cutting technology process by evaluation of technological factors, which influence the microgeometry (average roughness) of 10 mm thick stainless steel tooled workpiece surface through design of experiments. Significance of six chosen process factors – independent variables (traverse rate, abrasive mass flow rate, pressure, J/T abbreviation and feeding direction that influence the surface quality has been evaluated by factors experiment type 2⁶. The surface quality has been evaluated by static quality characteristic average roughness Ra. The multiple nonlinear regression equation obtained from ANOVA gives the level quality Ra as a function of the treatment factors. Different factor significance has been found, which generated surface profile under defined conditions by abrasive waterjet. The regression equations obtained from ANOVA and multiple linear regressions give the level quality Ra as a function of the treatment factors.

1 Introduction

Design of Experiments is a standard statistical technique used in quality engineering, manufacturing, and other industries to identify significant or sensitive factors (independent variables) and levels their factor values that influence system performance and variability. 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 current European conditions raising emphasis is posed to manufacturing processes quality with minimal environmental impact, connected with lower energetic and material consumption. Competition and scientific progress requires introduction of technologies that perform challenging claims of modern production in automation field, from economy, environmental and energy efficiency point of view. Abrasive waterjet cutting represents all of these claims.

Fig. 1. AWJ cutting process model; factors vs. parameters

2 Related and previous works

Abrasive waterjet machining belongs among complicated dynamical and stochastic processes with incomplete information about mechanism and side effects character. Their complicated appearance in large amount and parameters multiform determining process behaviour in large number of relations among parameters, and their interactions. [15] Their complicity incomplete knowledge functioning mechanisms and large amount of factors entering to the process complicate of mathematical model fitting by theoretical and analytical methods [12, 16]. Vice versa a mathematic-statistical method allows fitting of statistical models even from relative large amount input data. The nature of the mechanisms involved in the domain of AWJ machining is still not well understood but is essential for AWJ control improvement. In spite of great research effort and good knowledge in the field of progressive technologies there are number unexplained facts. One of them is influence of process factors on workpiece surface quality. [6, 10] The work presented in that study investigates a micro-geometrical aspect of the cutting quality of the average roughness. It is necessary to ensure asked quality characteristic of the cutting surface, which conditional to knowledge of the process function dependency between product quality parameters and abrasive waterjet manufacturing system factors [9]. Most scientific papers concerning to the evaluation of microgeometrical features of abrasive waterjet cutting are available [1, 2, 3, 4, 7, 11]. The object is to determine the final shape of the surface quality, which is a function of the geometric characteristics of the abrasive waterjet tool and its awj factors that are divided into two basic groups (fig.2); direct and indirect. Factors of indirect group influenced quality of the created tool where hydro-dynamic factors, mixing factors and abrasive factors belong. These factors influence the qualitative characteristics of the tool, the speed, diameter kinetic energy of the stream. Generated tool through these factors enters to the cutting technology process at material at the large number locality, by means of direct factors. There belongs traverse rate; stand off distance, impact angle and number of passes. Through cutting factors, created tool hits the workpiece the at upper erosion base (fig.1), where erosion process begins [11, 13].

In order to investigate the influence of abrasive waterjet process factors on average roughness Ra 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. Among the many process variables that influence the cutting results, four have been selected and considered as factors in the experimental phase. The variable of each constituent at levels: -1, and +1 is given in Table 1.

The experimental cuts have been performed in a random sequence, in order to reduce the effect of any possible error. A 2^6 full factorial analysis has been used with 3 replicates at the center point, leading the total number of 64 experiments. Considering that the four levels of the $x_1, x_2,$

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
5	x_5	Depth [mm]	1	9
6	x_6	Traverse direction	-180	180

Table 1. Coded independent variables at defined levels

x_3, x_4, x_5, x_6 and variables are -1 and 1, the designed matrix is 64-observations for dependent variable Ra. The graphical interpretations of factorial design is illustrated in the figure (2) Specimens series A has been made with independent variable – factor J/T at high level 0,14/1,2 (+1) and specimens series B with lowest level of J/T abbreviation. The behaviour of the present system can describe the nonlinear polynomial exponential equation (1), which includes all interaction terms regardless of their significance:

$$y = b_0x_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + \dots + b_{123456}x_1x_2x_3x_4x_5x_6 \quad (1)$$

Fig.2. Experimental methodology graphic illustration of specimens' series A and B

For investigation of the influence of the traverse rate the samples created for this purpose have been cut in two directions +180° and -180° (fig. 4). Traverse direction has been added to the experiment to explain the significance with connection of the selected factors.

2.1 Experimental set up

A two dimensional abrasive waterjet machine Wating, was used in this work with following specification: work table x-axis 2000 mm, y-axis 3000 mm, z-axis discrete motion, with maximum traverse rate of 250 mm.min⁻¹. The high-pressure intensifier pump was used the Ingersoll-Rand Streamline model with maximum pressure 380 MPa. As a cutting an Autoline cutting head from Ingersoll-Rand head has been used. The mechanical properties and chemical composition of the workpiece with austenitic composition is shown in table 2. The properties of each sample are: length 35 mm, width 8 mm, and height 10 mm. Abrasive machining conditions used in this study are listed in the table 2. The abrasive used in this experiment is Barton garnet, mesh 80, which is widely used for abrasive waterjet machining.

The stainless steel has been chosen as a target material upon these grounds: material is very attractive, because of its resistance to corrosion; it can provide significant value creation for the end user when considering all of the important attributes and how they help to bring reliability, performance, and safety to industry and the consumer. Fig. 4 shows the samples made according DoE (tab. 2, fig. 2).

Constant factors	Values	Variable factors	Values
Standoff	2 mm	Pressure p [MPa]	200/350
Abrasive material Barton Garnet Mesh 80		Traverse rate v [mm.min ⁻¹]	70/120
Cutting head Autoline™		J/T abbreviation	0,14/1,2 0,1/1
Impact angle φ	90°	Abrasive mass flow rate [g.min ⁻¹]	200/500
Target material: Stainless steel AISI 304		Material thickness h [mm]	1/9
C max 0.07%, Mn max 2.0%, P max 0.045%, S max 0.03% Si max 1%, Cr max 18/20%, Ni 10% Tensile Strength Rm 540/680 [N.mm ⁻²], Slip Limit Rp 0.2% 195 [N.mm ⁻²], HRB = 88			
System characteristics of 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

Table 2. Experimental set up

Fig. 3 Production of samples (B – series)

Fig. 4 Example samples of A and B series

2.2 Measurement procedure

A digital surftest Mitutoyo 301 has been used to calculate the average roughness with 0.01 μm precision of measurement. The measurement procedure consisted of measure variable dependent average roughness R_a in 1, and 9 mm with replicates of 6-times. The measurement dependent variables are shown on figure 4.

Fig. 5 Measurement procedure

Fig. 6 Example of created workpiece surface by abrasive waterjet

3 Statistical results

The quantitative description of the conditions effects on average roughness was performed. Response surface methodology is an empirical modelling technique used to evaluate the relationship between a set of controllable experimental factors and observed results. The results were analyzed using the analysis of variance as appropriate to the experimental design used. The normality of experimental measured data has been tested according Shapiro-Wilkson test criteria for its good power properties as compared to a wide range of alternative tests. Shapiro-Wilkson test proved that 64 values experiments is not greater than critical value $W\alpha = 0.788$ for $n = 6$ and $\alpha = 0.05$, respectively value of probability p is out of range, as preferred significance level α , we can accept the null hypothesis about normal distribution measurements repeatability. Figure 5 shows those residual values do not show heteroskedasticity – during of measurement of dependent variable average roughness variance of R_a

values has not been observed. Figure 6 shows the normal probability plot of residual values. Computed value obtained reliability for Shapiro-Wikson test of normality $p = 0.020032$ and value of W criteria $W = 0.95114$. According inequality $W_\alpha \geq W$, we can accept H_0 hypothesis about residual values probability.

Fig. 7: Normal probability plot

Fig. 8: Predicted vs. residual values

The regression equation obtained after analysis of variance gives the level of average roughness as a function of independent variables: J/T abbreviation, abrasive mass flow rate, pressure, traverse speed, traverse direction and material thickness. All terms regard their significance are included in the following equation:

$$\hat{R}_a = 10,06 + 1,97x_1 - 1,74x_2 - 4,35x_3 + 4,30x_4 + 11,03x_5 - 0,013x_6 \quad (2)$$

Where: y is the response, that is average roughness of the surface and $x_1, x_2, x_3, x_4, x_5, x_6$ are coded values of the variables J/T abbreviation, abrasive mass flow rate, pressure and traverse rate and the depth. The model has been checked by several criteria. The fit of the model has been expressed by the coefficient of determination $R^2 = 0,90234$ which was found to be for equation indicating that 90,23% for the model of the variability in the response can be explained by the models. The value also indicates that only 9,77% of the total variation is not explained by the model. This shows that equation is suitable model for describing to the response of the average roughness.

Fig. 9: Pareto charts shows that pressure as a controllable factor was found to be the most sufficient parameter that affects the average roughness

Fig. 9 graphically displays the influence magnitudes of the effects, which are sorted from largest to smallest, from the obtained results. The most important factors affecting the AISI 304 surface quality x_5 – material thick, x_3 – pressure, x_1 – J/T abbreviation, x_4 – traverse speed and two interactions.

The value of adjusted determination coefficient $adj = 0,8535$ is high to advocate for a high significance of the model. The significance of independent variables is interpreted in the Pareto chart of standardized effects for variable R_a (fig. 7). The following figure shows factors significance of treatment factors in % expression.

Fig. 10: Factors significance

As can be seen the most important factor is material thickness with significance 51,89%. The second factor affecting the quality of surface roughness of stainless steel is pressure 20,45%, third factor is traverse rate 20,20%, J/T abbreviation 9,27% and abrasive mass flow rate 8,17%. Traverse direction in that an experiment is not significant – has no diametric significance on surface quality of average roughness. But significance of that factor increase as the material hardness decrease. It has been observed at the factor designed experiment where the cast aluminium has been used as a target material. As can be seen from the picture 10 the percentual value of absolute value is higher than controllable factors; traverse rate, pressure, abrasive mass flow rate and J/T abbreviation, that indicates that there are associated factors that has a significance influence and has not been included and classified by factor analysis. For

exact explain of the model fig. 2 a new experiments will be provided. From present state of the art the two factors come in to account abrasive mesh and orifice stand off.

The following figures 11, 12, 13 show fitted surfaces of pressure, rate of speed, J/T abbreviation, and abrasive mass flow rate and depth. Three-dimensional surface plots showing predicted microgeometrical quality feature the Ra as a function of independent variable – factors. Figure 10 shows fitted surface of thickness material and traverse direction. Thickness of material is most important factor. x_1 factor in not controllable, but it is necessary to know the function in the relationship among the controllable factors. The second significant factor is traverse speed. The darker colour means higher values of surface roughness. The roughness numeric values increases as the traverse rate increase. This observation agrees with the results on stainless steel. With increasing depth average roughness strongly increases that is caused mainly by factors – traverse speed, abrasive mass flow rate and J/T abbreviation.

Fig. 11 Fitted surface of material thickness and traverse rate. Three-dimensional surface plot showing predicted average roughness as a function of material thickness [mm] and traverse rate [mm.min⁻¹]

Fig. 12 Fitted surface of material thickness and pressure. Three-dimensional surface plot showing predicted average roughness as a function of material thickness [mm] and pressure [MPa]

Observations proved influence of selected independent variables on surface roughness. Figures 8, 9, 10, 11 are graphical representation of factors change combination on average roughness measured in three various depths

Fig. 13 Fitted surface of material thickness and J/T abbreviation. Three-dimensional surface plot showing predicted average roughness as a function of material thickness [mm] and J/T abbreviation [mm]

for samples set A and B where is proven influence of factor x_1 (fig. 10). With increasing depth the number values of average roughness increases. The second significant factor is pressure which significantly affects the average roughness (fig. 11). The third significant factor is traverse rate that relates with size and active length of cutting tool. The influence of the traverse rate is shown on the figure 10. As can be seen from graphic interpretations average roughness shows week experimental dependence on change combinations of variable parameters in depth 1 mm. With increasing depth average roughness strongly increases that is caused mainly by factor x_3 , x_4 (pressure and traverse speed) (fig.8), (fig.9). The roughness significantly increases as the traverse rate increases. The importance of pressure and traverse rate and their significance with interaction material thickness confirm their importance at the cutting of hard machining materials. The impact of J/T abbreviation is shown on Figure 12. The important fact is that J/T abbreviation with level -1 (0,1/1) creates more coherent stream. The smaller diameters of diamond orifice and focus tube produce water with higher speed of abrasive water jet. 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. With an increase in the abrasive-mass flow rate, the quality of surface - Ra characteristics improves (fig. 11). 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 roughness, is less significant. As the abrasive mass flow rate increases, speed of the abrasive water jet reduces. The main reason is that 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 increase in the number of impacting particles at lower traverse rates contributes to the improved surface finish.

4 Conclusion

The problem analyzed in these pages is the study of abrasive water jet cutting in terms micro cutting quality. The quality parameter average roughness has been measured and evaluated according DoE. This analysis has pointed out that variable independent, pressure; abrasive mass flow rate, pressure, traverse rate and material thickness factor influence the morphology of cutting surface. It has been found that influence of process factors is variable related to different depth. Evaluation has been carried according to design of experiments. Full factorial design has been used as a statistical method to study effects of selected process factors. The pressure, abrasive mass flow rate, traverses rate, J/T abbreviation, material thickness, traverse direction as independent variable, has been evaluated their significance and their impact to the average roughness as a dependent variable. Obtained polynomial regression equation after analysis of variance gives the level quality as a function of the process factors. It has been found that pressure, and traverse rate are important with the depth. It has been observed that dominant factors influencing quality are pressure, traverse rate that directly determine quality of the tool – high-speed waterjet connected with thickness material and are most significant at the cutting of hard machining materials. According the experiment it has not been confirmed the significance of traverse direction at the cutting of hard machining materials. A new experiment in the future will be held with consideration of the mesh of solid phase and stand off, as object to reduce of significance absolute member in the model.

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