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APPLICATION OF MODELLING AND OPTIMIZATION METHODS IN ABRASIVE WATER JET MACHINING

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ABSTRACT
Abrasive water jet machining belongs to the non-conventional machining processes. Abrasive water jet machining as a tool used by water jet under high pressure with the addition of abrasive particles and represent of highly dynamic and stochastic machining process. The aim of this paper is to conduct the experimental research of process parameters influence on surface roughness of the machined parts, and to study the effects of selected process parameters on the surface roughness. The research was carried out for two different materials (stainless steel and aluminium alloy) using orthogonal experiment plan and factorial design. Based on the obtained experimental results are defined mathematical models of surface roughness using different approaches. The optimal values of process parameters, verified through confirmation tests, improve cutting quality.
Keywords: abrasive water jet machining, surface roughness, modeling, optimization

1. INTRODUCTION
Manufacturing industry is becoming ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. These trends have placed a premium on the use of new and advanced technologies for quickly turning raw materials into usable goods; with no time being required for tooling. Waterjet (WJM) and abrasive water jet machining (AWJM) technology has been found to be one of the most recent developed and fastest growing advanced non-traditional machining processes used in industry for material processing with the distinct advantages of no thermal distortion, high machining versatility, high flexibility and small cutting forces [1]. It is used in a wide range of industries from automotive and aerospace to medical and the food industries. Current applications include stripping and cutting of fish, cutting of car carpets, removal of coatings from engine components, to cutting of composite fuselages for aircraft construction. The impact of the water alone is enough to machine a material, however, with the addition of abrasive, the material removal rate in the process is several orders of magnitude higher [2]. However, AWJM has some limitations and drawbacks. It may generate loud noise and a messy working environment. It may also create tapered edges on the kerf, especially when cutting at high traverse rates [3]. AWJM is complicated dynamical and stochastic process with incomplete information about mechanism and side effects character. Its complicated appearance in large amount and parameters multiform determining process behaviour in large number of relations among parameters, and their interactions. Their complicacy its incomplete knowledge functioning mechanisms and large amount of factors entering to the process [4].

2. METHODOLOGY

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. The work presented in this paper investigates a microgeometrical aspect of the cutting quality under two surface roughness parameters *Ra* and *Rz*. To evaluate the cutting process of AWJM, there are several process parameters among which water pressure, abrasive flow rate, traverse rate, stand-of distance, material thickness and type of material have great importance on the quality of AWJ cutting surface (Fig. 1.). The objective of the design of experiments is to derive conclusions based on the measured surface roughness, in which manner certain machining parameters affect surface roughness of the workpiece, examined for various materials of different thickness. In order to obtain mathematical models (regression modelling) and optimal machining parameters (Taguchi approach) for certain materials, it was necessary to conduct the experiments, and obtain the most favourable machining parameters in real conditions, which result in minimum surface roughness as response characteristics of AWJM.

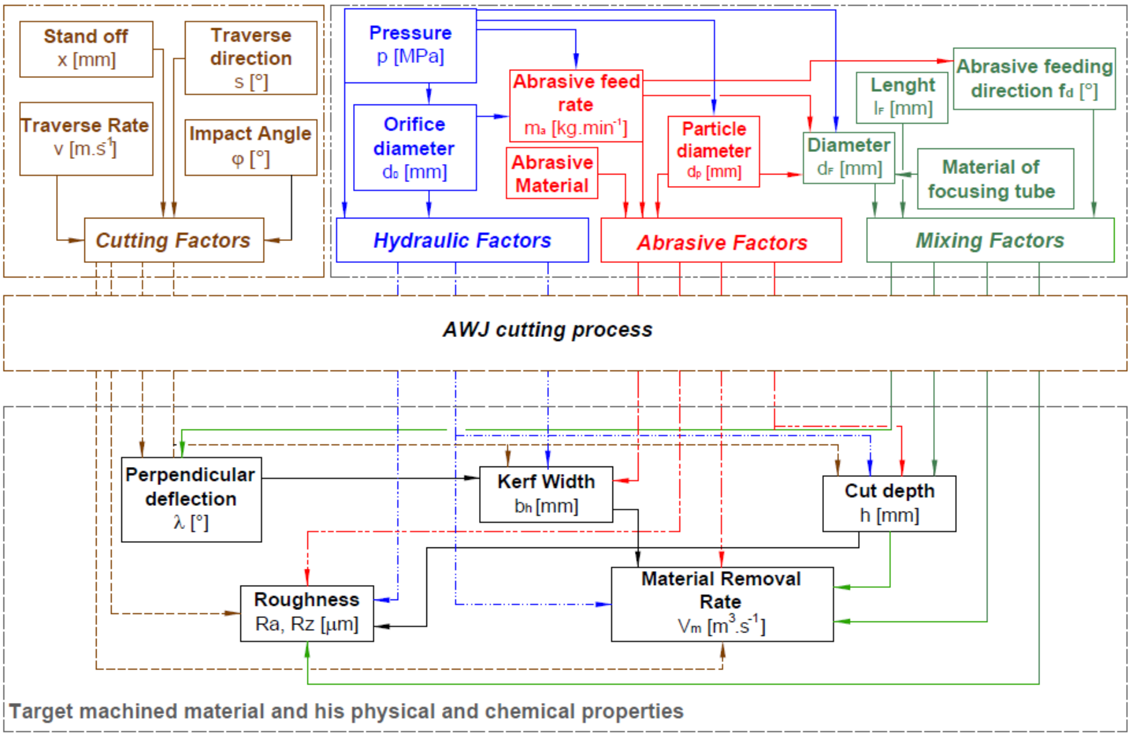

Figure 1. AWJM process model, factors vs. response parameters [4]

3. CONDITIONS OF EXPERIMENTS

Experimental investigation was conducted on the NC3015 machine, Water Jet Sweden (Figure 1). High pressure pump Streamline SL-IV 50 is a product of Ingersoll Rand, 37 kW, of maximum pressure of 410 MPa. Measuring of surface roughness was conducted on the machine type T1000 basic, by manufacturer Hommel-Tech. Measuring of surface roughness of the workpiece shall be conducted for two surface roughness parameters; *Rz* maximum height of roughness profile, *Ra* arithmetical mean deviation of roughness profile. Sample materials are the following: stainless steel (EN 10088-3), aluminium (EN AW-5083). The abrasive used in the experiment is Garnet 80. In the experimenting process, specific conditions were set on the machine and shall not be changed during the experiment. The water nozzle (orifice) is sapphire, and the diameter of the nozzle equals 0,254 mm. The abrasive water nozzle is made of carbide, 0,76 mm in diameter. The cutting angle of 90°, i.e. abrasive water nozzle is vertical in relation to the machining surface [5].

3.1. Design of experiments

Samples of dimensions 100 x 20 mm were cut out of the boards of greater dimensions, which were used for measuring of surface roughness. After the machining of samples, surface roughness of each sample was measured. Measuring was conducted in three places per each sample, at the beginning, in the middle and at the end of the cut. Finally, average value of surface roughness parameters was calculated from the obtained results. Figures for various parameters in relation to the measured surface roughness values were designed based on data obtained in this way. Changeable machining parameters which will be set on the machine in order to derive conclusions referring to how they affect quality of the machined surface are the following. Material type is a parameter of the experiment which shows the quality of the machined surface for various materials. The following changeable parameter is abrasive flow rate, i.e. its impact on the surface quality for two materials. An important changeable parameter is also stand-of distance. Water pressure will change on two levels, and water flow rate will also be changed for each change of the pressure. Traverse rate, i.e. cutting speed is a parameter which varies on three levels. It may be considered a crucial parameter for machining productivity. The desired machining quality and optimally set parameters will provide the greatest cutting speed for certain surface quality, which will achieve maximum possible productivity. The experiment is conducted by specific methodology, i.e. by using the Taguchi's experiment plan (Table 1 and 2) [6] and [7].

Table 1. Levels of independent AWJM process parameters

Symbol	*Parameters/Levels*	*1*	*2*
A	*type of material*	*stainless steel*	*aluminum*
B	*abrasive flow rate (g/min)*	*220*	*350*
C	*stand-of distance (mm)*	*2*	*4*
D	*water pressure (MPa)*	*220*	*330*
E	*traverse rate (mm/min)*	*100*	*300*
F	*sample thickness (mm)*	*2*	*4*

Table 2. Two-level orthogonal array, L_8 (2^7), with experimental results (average) and calculated signal-to-noise (S/N) ratios according to Taguchi method

No.	*Parameters*						*Surface roughness parameters*		*S/N ratio*	
	A	*B*	*C*	*D*	*E*	*F*	*Ra (µm)*	*Rz (µm)*	*Ra*	*Rz*
1	*stainless steel*	*220*	*2*	*220*	*100*	*2*	*3,968*	*25,197*	*-11,984*	*-28,046*
2	*stainless steel*	*220*	*2*	*330*	*300*	*4*	*4,886*	*30,133*	*-13,826*	*-29,633*
3	*stainless steel*	*350*	*4*	*220*	*100*	*4*	*3,521*	*21,050*	*-10,938*	*-26,475*
4	*stainless steel*	*350*	*4*	*330*	*300*	*2*	*4,119*	*24,620*	*-12,295*	*-27,85*
5	*aluminium*	*220*	*4*	*220*	*300*	*2*	*7,015*	*40,713*	*-16,944*	*-32,264*
6	*aluminium*	*220*	*4*	*330*	*100*	*4*	*5,142*	*33,130*	*-14,239*	*-30,444*
7	*aluminium*	*350*	*2*	*220*	*300*	*4*	*5,272*	*30,310*	*-14,447*	*-29,639*
8	*aluminum*	*350*	*2*	*330*	*100*	*2*	*4,268*	*26,523*	*-12,646*	*-28,501*

4. REGRESSION MODELLING

Multiple regression is used as a model formulation procedure to investigate how control parameters affect the response characteristics of an experiment (*Ra, Rz*) and lead to the development of first-order prediction models [3,4,6]. The first-order prediction model for *Ra* surface roughness is given by:

$$Ra = 4{,}456 - 0{,}00467 \cdot B + 0{,}00379 \cdot E + 0{,}08 \cdot F \quad \text{(stainless steel)} \quad (1)$$

Also, the first-order prediction model for *Rz* surface roughness is given by:

$$Rz = 30{,}561 - 0{,}0375 \cdot B + 0{,}0212 \cdot E + 0{,}341 \cdot F \quad \text{(stainless steel)} \quad (2)$$

Therefore, the models obtained in the present work could be used to predict the surface roughness characteristics of AWJM process.

5. TAGUCHI APPROACH

Optimization based on Taguchi approach [7], [8], [9] and [10] is used to achieve more efficient cutting parameters. Parameter design is the key step in the Taguchi approach to achieve high quality without increasing cost. To solve this problem Taguchi approach uses a special design of orthogonal arrays where the experimental results are transformed into the S/N ratio as the measure of the quality characteristic deviating from the desired value. Table 1 shows that the experimental plan has two levels and an appropriate Taguchi orthogonal array with notation L_8 (2^7) was chosen (Table 2.). The right side of the Table 2 includes the average results (each trial has 3 samples), of the measured arithmetic average surface roughness (*Ra*) and maximum peak-to-valley roughness height (*Rz*), as well as the calculated signal-to-noise (*S/N*) ratio, respectively. The *S/N* ratio, as the yardstick for analysis of experimental results. The *S/N* ratio is in relation to the smaller-is-better quality characteristics, what means minimization of output parameter to achieve the desired optimal or near optimal solution, what in the particular case means minimization of arithmetic average roughness to achieve the desired surface roughness. Optimal cutting parameters and their influences on the surface roughness were analyzed. According to the analysis of variance the most influence on the surface roughness has the type of material with 42,7% and 43,37% of contribution for *Ra* and *Rz*, respectively. Influence of abrasive flow rate and traverse rate are also considerable between 34% and 19% of contribution for *Ra* and *Rz*. In this case study there are no significant influences of the stand-of distance, water pressure and thickness (small variation) on *Ra* and *Rz*. The optimal parameters levels of AWJM process and optimal values of the surface roughness parameters obtained with Taguchi approach, were verified with the confirmation tests, shown in Table 3.

Table 3. The comparison of the obtained optimal results for Ra and Rz with confirmation tests

	Taguchi approach – optimal results	*Confirmation tests*
Parameters levels	*A1B2C1D2E1F2*	
Ra (μm)	*3,185*	*3,295*
Parameters levels	*A1B2C1D1E1F2*	
Rz (μm)	*20,098*	*20,603*

6. CONCLUSIONS

In this paper has been presented application of modelling (regression modelling) and optimization technique (Taguchi approach) to obtain mathematical models of response characteristics and to find optimal parameters of AWJM process. The modelling and optimization technique presented here has great potentiality to improve initial process parameters or in study case the achievement of the desired surface roughness at AWJM process, with high accuracy which was verified by confirmation tests.

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