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Paper

PERFORMANCE OPTIMIZATION OF ABRASIVE WATERJET TECHNOLOGY IN GRANITE CUTTING

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ABSTRACT

Waterjet technology is based around the use of a very high velocity jet of water, commonly with abrasive particles entrained into it, for applications such as cutting, drilling and milling of materials. The technology has been begun to use for years in the machining and/or processing of natural stones, in particular, granite for especially decorative cutting purposes. In this paper, the performance optimization of abrasive waterjet technology in granite cutting was investigated through design of experiment techniques. Design of experiments was based on Taguchi $L_{16}(4^4*2^1)$ orthogonal array providing a decrease of the necessary number of experiments to a conventional full factorial design. The output parameters were evaluated by using the statistical method of signal-to-noise ratio for determination of the effects of each parameter on the cutting process.

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1. INTRODUCTION

Recent trends in constructional and ornamental industry have increased the use of granite in both internal and external flooring owing to the outstanding features such as resistance to environmental effects, aesthetic view and hardness. With the growing use of granites as constructional and ornamental materials, there is an increasing demand on the new machining and processing technologies to improve productivity and reduce costs. On the other hand; machining of granites requires the need for better understanding of cutting processes regarding accuracy and efficiency. Additionally, due to the anisotropic and heterogeneous nature of granites, their machining behavior differs in many aspects from metal machining (Karakurt et al., 2011).

Abrasive waterjet (AWJ) technology is one of the non-conventional processes used extensively in various industries. It has unique features such as minimal stresses on the workpiece, high machining versatility and flexibility for especially shape cutting. There are numerous associated parameters and factors of AWJ process that can influence the output parameters or cutting performance. Up to present, a great deal of studies has been carried out for better understanding of the cutting processes in AWJ machining applications in different materials. Azmir et al. (2007) found that the traverse speed was the most significant factor on the surface roughness of the composites in the machining of Kevlar reinforced phenolic composite by AWJ. Singh et al. (2008) concluded that the aluminum was being smeared while brass showed clear evidence of abrasion as a mechanism of material removal in AWJ machining. Wang (2007) determined that nozzle oscillation at small angles can improve the depth of cut by as much as 82 % if the cutting parameters are correctly selected in abrasive waterjet cutting of alumina ceramics. It was stated that the depth of the upper smooth zone in nozzle oscillation cutting can be increased by more than 30 % as compared with that without oscillation in abrasive waterjet cutting of ductile materials (Lemma et al., 2002; Xu and Wand, 2004). Aydin et al. (2011) found that the surface roughness of the granites was considerably affected by the grain size and its boundaries with surrounding grains in machining of granite by AWJ. The traverse speed and standoff distance were found to be the most important parameters affecting the kerf angle of the granite cut by AWJ (Aydin et al., 2010).

In this paper, performance optimization of AWJ in granite cutting was carried out on the basis of statistically design of experiment method (DOE). The output parameters were cut depth and surface roughness. This paper also carries an importance in terms of the applicability of DOE in cutting of granite by AWJ.

2. EXPERIMENTAL STUDY

2.1. Material and Method

In the present study, pre-dimensioned granite of 3 cm thickness, 20 cm length and 10 cm width was used for the experiments and it was equidistantly cut through its length (Fig.1.) by an AWJ. The main properties of the sample are given in Table 1. The garnet consisting of chemically 36 % FeO, 33 % SiO_2, 20 % Al_2O_3, 4 % MgO, 3 % TiO_2, 2 % CaO and 2 % MnO_2 was used as an abrasive. Surface roughness measurements of the cut surfaces of the granite were made using a stylus-type profilometer, Mitutoyo Surftest SJ-301. Due to the data variability, four measurements on each cut were made and the average was taken as the final reading for the surface roughness and cut depth.

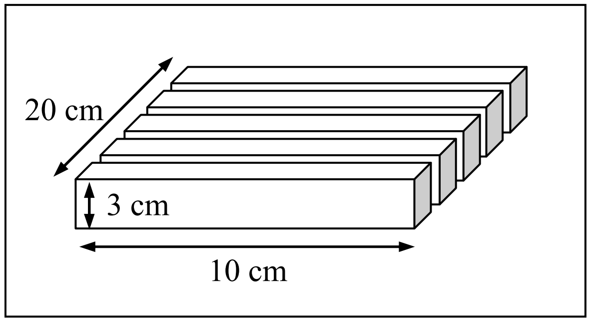

Figure 1. A schematic illustration of the granite after cutting

Table 1. Main properties and mineralogical compositions of the granite

Features		**Carmen Red**
Physical and Mechanical	Mean grain size (mm)	15.1
	Water absorption (%)	0.24
	Specific bulk density (KN/m^3)	26.4
	Uniaxial compressive strength (MPa)	105
	Flexural strength (MPa)	13
Mineralogical Composition (%)	Alkali feldspar	47
	Quartz	37
	Plagioclase	10
	Biotite	5
	Other	1

Design of Experiments

Statistically designed experimental methods are widely used for controlling the effects of parameters in many processes. Their usage decreases the number of experiments, time, costs and material resources. Furthermore, the analysis performed on the results is easily realized and the experimental errors are minimized. Statistical methods measure the effects of change in operating variables and their mutual interactions on the process (Mahapatra and Patnaik, 2009). Experimental design using Taguchi's method provides a simple, efficient and systematic approach for an optimal design of experiments to assess the performance, quality and cost (Davim, 2003). In the study, five machining parameters were selected as control factors as shown in Table 2. The parameters and their levels were selected primarily based on the literature review of some studies on rock and/or rocklike materials. Based on the Taguchi's method DOE, an $L_{16}(4^4 * 2^1)$ orthogonal arrays table with 16 rows (corresponding to the number of experiments) was selected for conducting the experiments. All machining procedures were carried out using a single-pass cutting. Some of the machining parameters including impact angle (90^o), nozzle diameter and length of the nozzle were kept constant during the experiments.

Table 2. Machining parameters and their levels considered for the experimentation

Symbol	Machining Parameters	Units	Level 1	Level 2	Level 3	Level 4
T	Traverse speed	mm/min	100	150	200	250
M	Abrasive flow rate	gr/min	150	200	250	300
D	Standoff distance	mm	2	4	6	8
P	Water pressure	MPa	200	250	300	350
S	Abrasive size	mesh	80	120		

In the Taguchi method, the signal to noise (S/N) ratio is expressed as a log transformation of the mean squared deviation as the measure for analysis of experimental results (Azmir et al., 2009). It is named as loss function and the S/N ratio shows the deviations between the experimental value and the desired value. Usually, there are three S/N ratios available, depending on the type of characteristics. One is the lower-the better, other is the higher-the better, and the last one is the nominal-the better. In abrasive waterjet cutting, the lower surface roughness and the higher cut depth are an indication of better performance. Therefore, the lower-the better (LB) and the higher-the better (HB) were selected for the surface roughness and cut depth of the granite. The S/N ratios for each type of characteristics can be calculated as follow;

The higher-the better:

$$\text{S/N ratio} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

The nominal-the better:

$$\text{S/N ratio} = 10\log\left(\frac{\bar{y}}{s_y^2}\right) \tag{2}$$

The lower-the better:

$$\text{S/N ratio} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{3}$$

where $\bar{y}$ is the average of the observed data, s_y^2 is the variance of y, n is the number of observation, and y is the observed data. Regardless of the category of the performance characteristics, the greater S/N ratio means the better performance characteristics. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio (Hasçalık and Çaydaş, 2008).

3. RESULTS and DISCUSSON

A compilation result of the experiments together with the experimental layout and the corresponding S/N ratios by Eq. (1 and 3) are given in Table 3. The optimum condition represents the combination of machining parameter levels that is expected to produce the best performance. The average S/N ratio for each factor level shows the possible effects of the various factors on the quality characteristics of output parameters of the granite. In Taguchi analysis, the greater S/N ratio means the better performance characteristics.

Table 3. Experimental layout and results for $L_{16}(4^4 * 2^1)$ orthogonal array including S/N ratios

Exp. No.	Factors					Responses (results)		S/N ratios	
	T	M	D	P	S	Surface Roughness (µm)	Cut depth (mm)	Surface Roughness (µm)	Cut depth (mm)
1	1	1	1	1	1	6.44	27.21	-16.1777	28.6946
2	1	2	2	2	1	5.50	29.94	-14.8072	29.5250
3	1	3	3	3	2	5.63	25.68	-15.0102	28.1919
4	1	4	4	4	2	5.97	23.81	-15.5195	27.5352
5	2	1	2	3	2	6.08	16.47	-15.6781	24.3339
6	2	2	1	4	2	6.46	19.01	-16.2047	25.5796
7	2	3	4	1	1	5.75	24.76	-15.1934	27.8750
8	2	4	3	2	1	5.82	27.76	-15.2985	28.8684
9	3	1	3	4	1	6.35	12.61	-16.0555	22.0143
10	3	2	4	3	1	6.24	21.49	-15.9037	26.6447
11	3	3	1	2	2	6.13	14.42	-15.7492	23.1793
12	3	4	2	1	2	6.14	14.61	-15.7633	23.2930
13	4	1	4	2	2	5.48	11.69	-14.7756	21.3563
14	4	2	3	1	2	5.35	12.34	-14.5670	21.8263
15	4	3	2	4	1	6.00	18.64	-15.5630	25.4089
16	4	4	1	3	1	6.39	18.59	-16.1100	25.3856

Therefore, based on the average S/N ratio for each factor level shown in Fig.2, the optimal machining performance for the surface roughness was achieved at the fourth level for the traverse speed, the second level for the abrasive flow rate, the third level for the standoff distance, the second level for the water pressure and fine-grained abrasive (120 mesh). The optimum parametric combination for the surface roughness of the granite is T4, M2, D3, P2 and fine-grained abrasive.

As illustrated in Fig. 3, depending on the average S/N ratio for each factor level for the cut depth of the granite, the optimal machining performance was achieved at the first level of the traverse speed, the fourth level of the abrasive flow rate and coarse-grained abrasive. Additionally, it can be concluded that the machining parameters, the standoff distance and water pressure didn’t have discernible effect on the cut depth. The optimum parametric combination for the cut depth of the granite is T1, M4 and coarse-grained abrasive. The standoff distance and water pressure was excluded, since it does not have discernible effect on the cut depth.

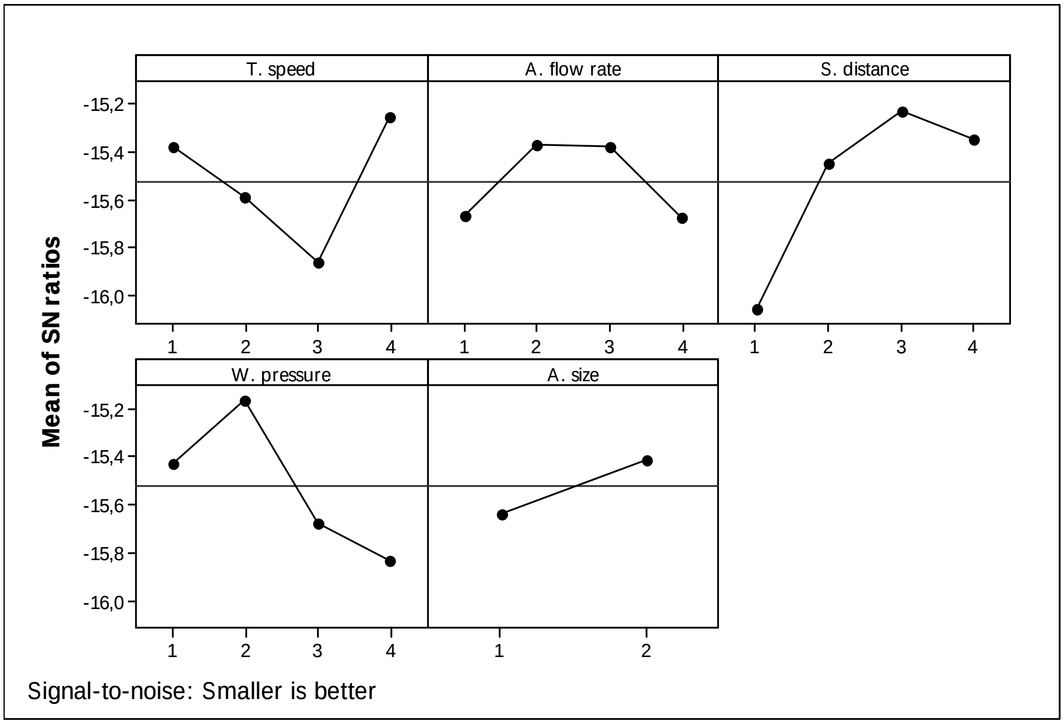

Figure 2. Main effects plot (data means) for S/N ratio for the surface roughness of the granite (produced through MINITAB statistical software)

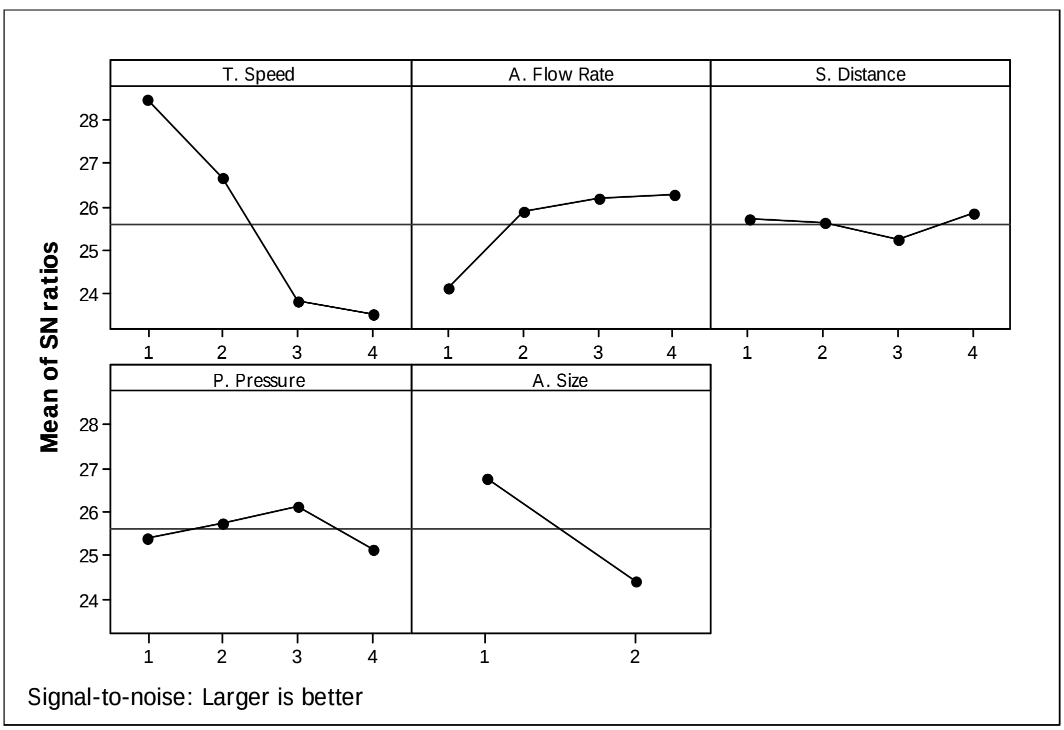

Figure 3. Main effects plot (data means) for S/N ratio for the cut depth of the granite (produced through MINITAB statistical software)

4. CONCLUSIONS

Depending on the experimental results aiming at performance optimization of AWJ in granite, following conclusions could be drawn;

i. Based on the average S/N ratios, it can be stated that the traverse speed, standoff distance, abrasive size and water pressure have a discernible effect on the surface roughness of the granite. The abrasive flow rate has also effect on the surface roughness, but effect of this machining parameter can be omitted.

ii. The machining parameters, the traverse speed, abrasive flow rate and abrasive size were found to be the most significant factors on the cut depth of the granite. On the other hand; it can be concluded that other machining parameters were found to be insignificant on the cut depth.

iii. When considering the DOE techniques, it was determined that the Taguchi's approach can be applied for the experimental studies of rock (e.g granite) machined by AWJ in order to reduce costs, time and improve productivity with less number of experiments.

5. ACKNOWLEGDEMENTS

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