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ASSESMENT OF THE SURFACE QUALITY OF THE GRANITE CUT BY ABRASIVE WATERJET

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Abstract

Abrasive waterjet (AWJ) cutting has been increasingly used in various industries due to its considerable advantages over the conventional cutting technologies. Although many studies have been carried out to fully understand the cutting performances of the AWJ for a variety of materials, the studies focused on the rock machinability by abrasive waterjet in terms of cut surface quality are required. In this study, cut surface quality of a granite cut by an abrasive waterjet is experimentally analyzed. The cutting performances are assessed in terms of the cutting wear zone and surface roughness. The experimental studies are conducted on the basis of Taguchi's orthogonal array. Effect of the process parameters is presented as mean responses in detail. Additionally, analysis of variance (ANOVA) is used to evaluate data obtained statistically. Major significant process factors affecting the cutting wear zone and surface roughness are determined. As a result of the study, it is determined that the highly effective parameters on the cutting wear zone are the traverse speed and the abrasive size respectively. Similarly, the water pressure, the traverse speed and the standoff distance are found as highly effective process parameters on the surface roughness of the granite.

Keywords: Abrasive waterjet, Granite, Surface quality, Anova

1. Introduction

The world natural stone production, in particular marble and granites, has gradually increased recently. The stone products are more and more used for outside and inside flooring, outside and inside covering, home and urban furnishing, civil building and sacred art [1]. This growing request of stone products has made evident the need of optimised cutting methods able to increase the machining and processing efficiency by minimising the production time and of course costs. Thus, the growing interest of natural stone has stimulated the study of innovative manufacturing processes.

Among the innovative manufacturing processes which have shown their suitability in stone machining, abrasive waterjet (awj) cutting may satisfy the demand of non-thermal, high productivity, flexible cutting and low cutting force. In abrasive waterjet machining, various machining parameters such as abrasive size, water pressure, standoff distance, abrasive flow rate and traverse speed can be adjusted to influence the cutting performances such as depth of cut and surface quality of the cut material [2]. However, the quality of the cutting surfaces is limiting the applicability of the technology [3]. Whilst, the technology of high-speed jet machining itself is well defined, the studies of abrasive waterjet (AWJ) parameters on the quality of produced cuts are still required.

Different approaches can be found in the existing literature studying the relationship among parameters and cutting efficiency of the AWJ. One of the earlier studies was carried out). Ojmertz [4] noticed that low traverse speeds resulted in an irregular surface morphology of the milled area with lower surface roughness values. Surface irregularities in particular in the form of striations were studied by Lemma et al, [5] and Hloch et al [6]. Hashish [7] conducted a visualisation investigation of the AWJ cutting process using a high-speed photography of the material removal process in a plexiglass sample. It was suggested that striations were the inherent characteristic feature to the AWJ cutting process. In a study by Chen et al. [8] it was

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proposed that striations are formed by the variation of the distribution of particle kinetic energy with respect to the cut surface. Contrary to findings, it was stated by Chao and Geskin [9], the striation formation occurred on the cut surfaces was a result of external disturbances, such as machine vibrations. Babu and Krishnaiah [10,11]investigated the influence of process parameters on depth of cut, surface roughness and kerf width of the granite using orthogonal array and analysis of variance approach in AWJ cutting. Similar study was carried out for the composites by Ramulu and Arola [12] These attempts gave rise to various response equations developed for predicting the output parameters.

The present work reports an experimental study on the influence of the AWJ cutting variables on the surface roughness and cutting wear zone of the granite. In the first part of this work, the influence of some controllable process variables on the surface roughness and cutting wear zone is analysed in detail. Then, the data obtained are evaluated statistically using the analysis of variance (ANOVA) to determine significant process parameters affecting the surface roughness and cutting wear zone of the granite.

2. Materials and Method

In the experiments, pre-dimensioned granite specimen of 30 mm thickness, 20 mm length and 10 mm width was cut by a KMT international waterjet cutter driven a “Model SL-V 50 HP” intensifier pumping system with operating pressure of up to 380 MPa. The motion of the nozzle is controlled by a computer as shown in Fig. 1 [13]. The main properties of the specimen are given in Table 1. Abrasive type used in the study is garnet and it consists of chemically 36 % FeO, 33 % SiO_2, 20 % Al_2O_3, 4 % MgO, 3 % TiO_2, 2 % CaO and 2 % MnO_2. Additionally, the main characteristics of the abrasive waterjet cutter are given in Table 2.

Table 1. Main properties and mineralogical compositions of the granite

	Features	*Baltic Brown*
Physical and Mechanical	Grain size (mm)	0.6-20
	Water absorption (%)	0.22
	Specific bulk density (KN/m^3)	26.8
	Uniaxial compressive strength (MPa)	194
	Flexural strength (MPa)	12.7
Mineralogical Composition (%)	Alkali feldspar	57
	Quartz	21
	Plagioclase	15
	Biotite	3
	Other	4

Table 2. Main properties of the abrasive waterjet cutter

Machine model	SL-V 50 HP (KMT)
Energy consumption (kwh)	40
Abrasive consumption (gr/min)	100–400
Nozzle diameter (mm)	1.1
Nozzle length (mm)	75
Water consumption (lt/m)	3.8

Surface roughness is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost. It describes the geometry and surface textures of the machined parts [14,15]. In general, the surfaces produced by abrasive water jet (AWJ) cutting consist of a cutting wear zone where the primary surface irregularity is roughness, and a deformation wear zone that is characterised by wavy striations [16]

There are several ways to describe surface roughness, such as the roughness average (*R*a), the root-mean-square (rms) roughness (*R*q) and the maximum peak-to-valley roughness (*R*max), etc. Ra is defined as the arithmetic value of the profile from centreline along the sampling length [17]

Surface roughness measurements of the cut surfaces of the granite specimen were made using a stylus-type profilometer, Mitutoyo Surftest SJ-301 whose principals are schematically described in Fig. 2. Eight measurements for each specimen on each cut were made at the cutting wear zone of the cut surface and the average was taken as the final reading for both the surface roughness (Ra) and cutting wear zone.

2.1. Design of the Experiments

Design of experiments (DOE) is the process of planning the experiments considering the process parameters at different levels. 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 [18]. Statistically designed experiments are conducted more efficiently as they consider multiple factors simultaneously and they can detect important interactions with minimum number of experiments unlike traditional experimentation which considers only one factor at a time while keeping the other parameters constant [19]. For example, one need to conduct 3^5 (243) experiments when five factors, each varied at three levels are considered. In the present work, four factors varied at four levels and one factor varied at two levels are considered. The range of different process parameters and factor levels used for this study are shown in Table 3.

Table 3. Process parameters and their levels considered for 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		

An orthogonal array of $L_{16}(4^4 * 2^1)$ was found to be appropriate. A total of 16 runs were tested in this experimental investigation. The experiments were conducted in the order shown in Table 4. A statistical ANOVA test was also performed to decide process factors significantly affecting the process responses.

Table 4. Experimental layout for $L_{16}(4^4 * 2^1)$ orthogonal array

Experiment	*Factors*				
number	T	M	D	P	S
1	1	1	1	1	1
2	1	2	2	2	1
3	1	3	3	3	2
4	1	4	4	4	2
5	2	1	2	3	2
6	2	2	1	4	2
7	2	3	4	1	1
8	2	4	3	2	1
9	3	1	3	4	1

10	3	2	4	3	1
11	3	3	1	2	2
12	3	4	2	1	2
13	4	1	4	2	2
14	4	2	3	1	2
15	4	3	2	4	1
16	4	4	1	3	1

3. Results And Discussion

The effects of different process parameters such as the traverse speed (*T*), the abrasive flow rate (*M*), the standoff distance (*D*), the waterjet pressure (*P*) and the abrasive size (*S*) on the surface roughness and cutting wear zone are presented in terms of mean responses.

3.1. Effect of the Traverse Speed

The typical effect of traverse speed on the surface roughness and cutting wear zone is plotted in Fig. 3. It shows that the cutting wear zone decreased with an increase in traverse speed, whereas an increase in traverse speed resulted in increasing of the surface roughness. It can also be noted that the rate of decrease for the cutting wear zone decreased as the traverse speed increases. Similarly, the rate of increase for the surface roughness decreased as the traverse speed increases.

Generally, as the nozzle travels at a high speed, there will be fewer particles that strike the target material and, this means that there are fewer particles involved in the erosion action in the cutting wear mode, resulting in a decrease in cutting wear zone and increases in the surface roughness. And, also less number of impacts and cutting edges will be available per unit area that results in rougher surfaces as the traverse speed increases.

3.2. Effect of the Abrasive Flow Rate

Figure 4 illustrates the effect of the abrasive flow rate on the cutting wear zone and the surface roughness. It can be seen that the cutting wear zone increased marginally with an increase in the abrasive flow rate. It can be also observed that the surface roughness showed a decrease until the third level of the abrasive flow rate, and then increased. This is attributed to the fact that an increase in abrasive flow rate results in more particles impinging on the cutting surface and increasing the cutting wear zone. However, it is noticed that the relationship between the cutting wear zone and abrasive flow rate was not linearly occurred. Similar observation was taken place in the surface roughness. This may be due to the increased particle fragmentation and interference as the abrasive flow rate increases, which reduces the cutting efficiency of individual particles [20,21].

3.3. Effect of the Standoff Distance

The surface roughness and cutting wear zone variation with standoff distance is shown in Fig. 5. It can be noticed from the figure that cutting wear zone exhibited an initial increase with an increase in the standoff distance and then a slow decrease with the further increase in the standoff distance. Accordingly, an increase of standoff distance resulted in a constant increase in the surface roughness.

Basically, an increase in standoff distance causes a broader scanning scope of the abrasive waterjet [22]. Thus, more overlapping action may occur that affect the surface roughness positively by correcting the irregularities of the previous cutting. On the other hand, As stated by Liu [21], the turbulent jet existing from the nozzle is gradually stabilized as the jet continues to flow. This phenomenon may change the particle impact angle favourable for cutting wear zone. Therefore, a slight increase in the standoff distance may increase the cutting wear zone.

3.4. Effect of the Water Pressure

As shown in Fig. 6, the cutting wear zone increased slightly with an increase of water pressure until a critical pressure. However, further increase in the water pressure caused a decrease in the cutting wear zone. Accordingly, the surface roughness exhibited an initial increase with an increase in the water pressure and then a slow decrease with the further increase in the water pressure.

Increasing of the cutting wear zone with the increase of the water pressure may be associated with the high energy offered by high water pressure to the jet for high particle velocity. On the other hand, due to the high energy the particle fragmentation and particle interference can be occurred. This may be the reason for the decreasing of the cutting wear zone, and so does the surface roughness with further increase in the water pressure.

3.5. Effect of the Abrasive Size

The experimental data plotted in Fig.7, illustrate the variation of the cutting wear zone and surface roughness with respect to the abrasive size. As plotted in the figure, both the cutting wear zone and surface roughness decreased when finer abrasive size was used. Small particle abrasives remove particle in a smaller amount, so both the surface roughness and cutting wear zone decrease with a decrease in the particle sizes. Moreover, the results of the abrasive size on the surface roughness and cutting wear zone are consistent with the studies in the existing literature. As stated by Zeng and Kim [23], coarser abrasives can cut the materials more rapidly than finer abrasives owing to their heavies and inertia. In the study of Külekçi and Akkurt [24], it was reported that although deeper cutting wear zone could be obtained by coarser abrasives, the cut surfaces may be rougher.

3.6. Analysis of Variance (ANOVA)

In the analysis of variance (ANOVA), *F* ratio was used to determine significant process factors. *F* ratio is a tool to see which process factor has a significant effect on the surface roughness and cutting wear zone of the granite. An F ratio is calculated from the experimental results and then compared to the critical value. If the F ratio calculated is larger than the F critical value, it is an indication that the statistical test is significant at the confidence level selected. If not, it indicates that the statistical test is not significant at the confidence level. In addition, larger F ratio value indicates that there is a big considerable on the performance characteristic due to the variation of the process parameters [25,26].

This analysis is carried out for the confidence level of 95 %. Table 5 shows the result of ANOVA for machining outputs, respectively.

Table 5. Results of analysis of variance (ANOVA) for the surface roughness and cutting wear zone of the granite

Output	*Source*	*Degree of freedom*	*Sum of squares*	*Mean square*	*F ratio*	*Contribution (%)*
Surface Roughness	T	3	0.753	0.251	4.80	17.13
	M	3	0.561	0.187	2.83	12.77
	D	3	1.310	0.436	6.61	29.79
	P	3	1.451	0.483	7.32	33.00
	S	1	0.189	0.189	2.86	4.30
	Error	2	0.132	0.066		3.01
	Total	15	4.398			100
Cutting Wear	T	3	77.343	25.781	23.11	61.02
	M	3	8.871	2.957	2.65	6.99

D	3	9.082	3.027	2.71	7.16
P	3	6.107	2.036	1.83	4.82
S	1	23.136	23.136	20.74	18.25
Error	2	2.231	1.115		1.76
Total	15	126.770			100

From the F-statistic table 5 % level of significance, it was found that the machining P (the water pressure) is the most significant factor influencing the assessment of the surface roughness of the granite, followed by control factors D (the standoff distance) and T (the traverse speed). Control factors M (the abrasive flow rate) and S (the abrasive size) were found to be insignificant since they failed the test of significance of 5 %. Similarly, the most significant factors affecting the assessment of the cutting wear zone of the granite were found as the traverse speed (T) and the abrasive size (S) respectively. The other machining parameters were found to be insignificant.

The last column of the above table indicates the percentage of each factor contribution (*P*) on the total variation, thus exhibiting the degree of influence on the result [27]. It is important to observe the *P*-values in the table. Therefore, from the last column of the table above, the factor D (33.00 %) showed a high significant effect. It was followed by standoff distance (29.79 %) and the traverse speed (17.13 %) for the surface roughness. On the other hand, the factor T (61.02 %) showed a high significant effect on the cutting wear zone of the granite, followed by the factor S (18.25 %).

4. Conclusions

The following conclusions could be drawn from the results of the surface roughness and cutting wear zone of the granite, machined by abrasive waterjet

i. Lower traverse speed levels resulted in deeper cutting wear zones and lower surface roughnesses on the granite.

ii. The cutting wear zone increased marginally with an increase in the abrasive flow rate, whereas the surface roughness showed a decrease until a critical level of the abrasive flow rate, and then increased with further increase in the abrasive flow rate.

iii. An increase of standoff distance resulted in a constant increase in both the cutting wear zone and surface roughness. However, with the further increase in the standoff distance, the surface roughness tended to increase slightly while the cutting wear zone showed a decreasing tendency.

iv. The cutting wear zone and the surface roughness of the granite showed a similar behaviour with increasing water pressure. Both output parameters increased slightly with an increase of water pressure until a critical pressure. With further increase in the water pressure caused a slowly decrease in the cutting wear zone and surface roughness. Moreover, deeper cutting wear zone was obtained by coarser abrasives, whilst lower surface roughness was obtained by finer abrasives.

v. Based on the analysis of variance (ANOVA) results, the highly effective parameters on the surface roughness were determined as the water pressure, the traverse speed and the standoff distance respectively. Accordingly, the traverse speed and the abrasive size were determined as highly effective parameters on the cutting wear zone the granite.

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