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A Machinability Study of Granite Using Abrasive Waterjet Cutting Technology

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ABSTRACT

Abrasive waterjet (AWJ) machining is one of the non-traditional machining processes which have been used extensively in various industries. It offers some advantages like narrow kerf width, reduced waste material and flexibility to machining process in different shapes. In this study, abrasive waterjet machining of the granite was experimentally investigated for various process parameters in terms of the cut depth and kerf width. The design philosophy of Taguchi was followed to conduct experiments. Analysis of variance was used to evaluate data obtained statistically. Major significant process factors affecting the cut depth and kerf width were determined. Additionally, effects of the process parameters on the cut depth and kerf width were presented by mean responses in detail. As a result of the study, it was determined that the highly effective parameters on the cut depth were the traverse speed, the abrasive flow rate and the abrasive size, although all the process parameters were found to be highly effective on the kerf width of the granite.

Key Words: *Abrasive waterjet, Granite, Cut depth, Kerf width, Anova.*

1. INTRODUCTION

Natural stones, in particular granite and marble, are widely used as structural material owing to their excellent resistance to environmental influences and attractive decorative properties. The consumption of natural stones as a construction material is continuously increasing [1]. From the recent trend of introducing natural products to living space, stone products are also currently in great demand for the interior walls of buildings [2].

Machining and processing of natural stones by using conventional techniques such as diamond saws, have a wide field of application in stone industry [3]. With the growing use of natural stones as a construction material, there is an increasing demand on the new machining and processing technologies to improve productivity and reduce costs.

As an advanced manufacturing technology, abrasive waterjet (AWJ) machining has been increasingly accepted by industry for machining and processing various materials due to its distinct advantages over the other cutting technologies, such as no thermal damages and high versatility to cut different materials [4].

In recent years, a large amount of research effort has been made to understand the process and improve its cutting performance such as the depth of cut and surface finish for various materials [5]. One of the earliest studies was

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♠Corresponding author, e-mail: karakurt@ktu.edu.tr carried out by Bortolussi et al [6]. They used granite samples for their experimental studies and investigated the effect of process parameters on rock cutting. It was found that entraining of abrasive particles increase the cutting capability of waterjets and increases of waterjet pressure allow to obtain deeper depths of cut. Miranda and Quintino [7] experimentally studied the effect of material properties on cutting performances using calcareous stones. Liu and Chen [8] conducted an experimental study to define the effects of process parameters on cutting mechanisms and performances of granite. Hashish [9,10,11] has introduced cutting models in order to correlate the depth of cut with the process parameters and the properties of the target material. In his comprehensive study of the material removal mechanisms under the impacts of an ultrahigh pressure AWJ, Hashish reported that cutting wear and deformation wear were the primary material removal modes in the AWJ cutting process. Zeng and Kim [12] developed an abrasive waterjet kerf cutting model for brittle materials. Although many researchers are still dealing with water jetting technology from all over the world, machining performance, including depth of cut and cut quality, is a major technological challenge to the AWJ machining technology. This challenge becomes more intensified as the technology is more widely used in industry. Therefore, the present paper is aimed at investigating the abrasive waterjet machining of the granites. The target parameters are cut depths and kerf widths that are inherent to AWJ.

2.EXPERIMENTAL STUDY

2.1.Material and Procedure

In the experiments, pre-dimensioned granite specimen of 3 cm thickness, 20 cm length and 10 cm width (Figure 1.) was used. The main properties of the specimen are given in Table 1.

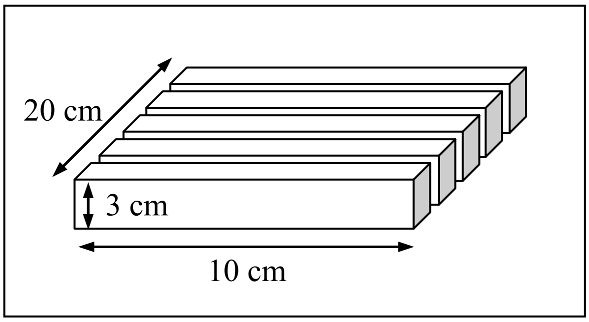

Figure 1. A schematic illustration of the granite specimen after cutting.

Eight measurements for cut depth and four measurements for kerf width on each cut were carried out and the average was taken as the final reading for the cut depth and kerf width. 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.

Table 1. Main properties and mineralogical compositions of the specimen.

Features		**Rosa Minho**
Physical and Mechanical	Mean grain size (mm)	13.16
	Water absorption (%)	0.30
	Specific bulk density (KN/m^3)	27.2
	Uniaxial compressive strength (MPa)	110
	Flexural strength (MPa)	15.3
Mineralogical Composition (%)	Alkali feldspar	54
	Quartz	29
	Plagioclase	10
	Biotite	5
	Other	2

2.2.Experimental Set-up

The pre-dimensioned granite specimen was cut by a KMT international waterjet cutter, driven by 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 Figure 2. The main characteristics of the abrasive waterjet cutter are given in Table 2.

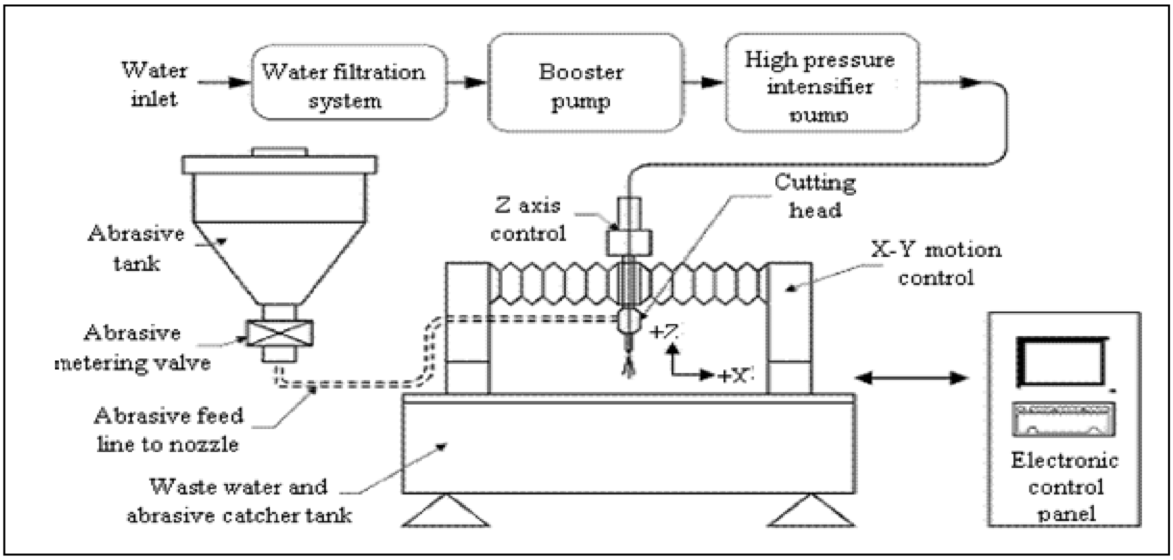

Figure 2. A schematic illustration of the experimental set-up [modified from 13].

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

2.3.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 [14,15]. 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. For example, one needs 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 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		

An orthogonal array of $L_{16}(4^4 * 2^1)$ was found to be appropriate. A total of 16 runs were undertaken in this experimental investigation. The experiments were conducted as 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 number	Factors				
	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

Analysis of the cutting performance of the abrasive waterjet cutting of the granite is characterized with the cut depth and kerf width of the target material. The cut depth and kerf width are two major characteristics of in abrasive waterjet cutting applications. While the cut depth represents the capacity of the jet to penetrate into the material, kerf width is a description of the width of the cut produced by abrasive waterjet cutting and it is important in terms of the amount of the material lost. To this end, 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 depth of cut and kerf width are presented in detail below in terms of mean of means responses.

3.1. Effect of the Traverse Speed

The relationship between traverse speed, cut depth and kerf width is plotted in Figure 3. It shows that the cut depth and kerf width decreased approximately linearly with the increasing traverse speed, although the cut depth exhibited a stable trend with further increase to beyond 200 mm/min.

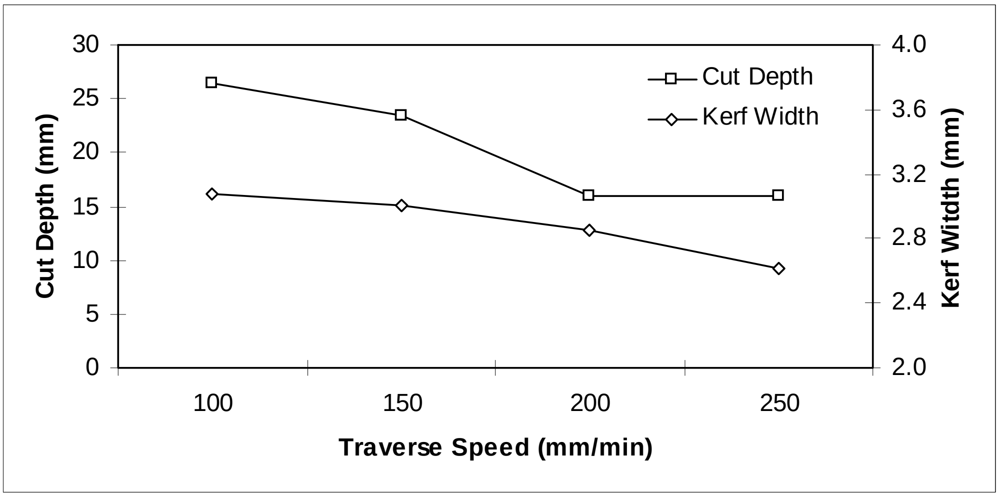

Figure 3. Effect of the traverse speed on the cut depth and kerf width of the granite.

In general, an increase in the traverse speed leads to a decrease in the cut depth and kerf width. In other words, decreasing the depth of cut with an increase in the traverse speed may be explained with the shorter exposure time for a certain point on the cutting line on the target material (granite) and reducing the particle interference. A faster traverse speed also allows less overlapping cutting action and fewer particles to impinge on the material, resulting in reduced cut depth and a narrow kerf width. However, as stated by Hashish [9], in particular, the relationship between the cut depth and traverse speed is quite complex. Thus, the decreasing of the cut depth with the increasing traverse speed may not be always occurred linearly.

3.2. Effect of the Abrasive Flow Rate

The influence of the abrasive flow rate on the depth of cut and kerf width is shown in Figure 4. It is evident that the cut depth increased slightly with an increase in abrasive flow rate. In other words, the rate of increase decreased as abrasive flow rate increases. It can be also noted that the kerf width increased until a critical value (250 gr/min) and then exhibited a marginal decrease with further increase in abrasive flow rate, which is in agreement with earlier investigation [16,17,18].

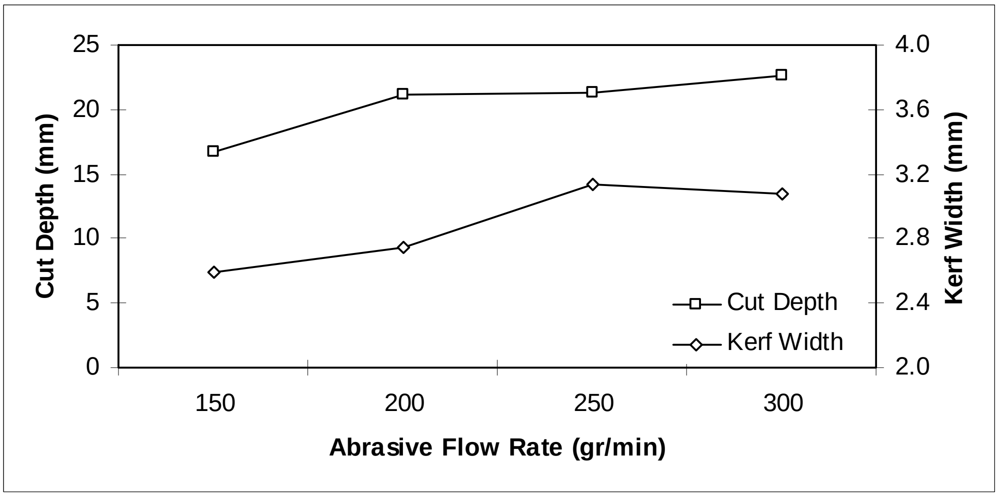

Figure 4. Effect of the abrasive flow rate on the cut depth and kerf width of the granite.

As stated by Wang and Guo [19], it is apparent that more particles tend to remove more materials and increase the cut depth. And also, a higher abrasive flow rate provides more particles to strike on the target material and opens a wider kerf width. However, not all the abrasive particles in the jet will strike the target material or at least not remove the material in the same efficiency. This is due to the interference between particles which reduces the particle energy as well as the effectiveness of individual particles in cutting the material. An increase in the number of particles in the jet, will increase the probability of particle interference. Thus the overall cutting performance in terms of the cut depth does not increase linearly with abrasive mass flow rate, in addition to the kerf width. Moreover, as performed by Hashish [20], the more particles in the jet, the more effect to remove the more material. However, there must be a critical value for the optimum performance characteristics such as the cut depth, the kerf width.

3.3. Effect of the Standoff Distance

The effect of standoff distance on the cut depth and kerf width is illustrated in Figure 5. It shows that an increase in standoff distance is associated with a decrease in the cut depth, whereas an increase proportionally in the kerf width. The phenomenon of the increasing kerf width may be explained by jet divergence and droplets flown away from the jet stream.

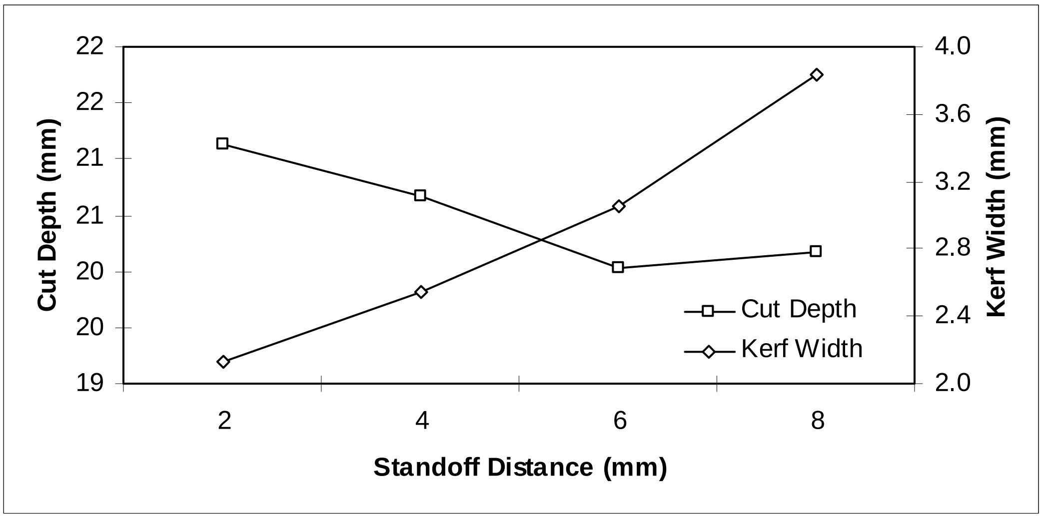

Figure 5. Effect of the standoff distance on the cut depth and kerf width of the granite.

Basically, standoff distance does not have a discernible effect on the cut depth, in particular, small range of standoff distance (e.g. 2,4 mm) considered [21]. With the small variation of the standoff distance, the jet energy does not dissipate significantly so that the influence of this variable on the depth of cut is not discernable. However, as the range of standoff distance considered in this study reflected that the selection of this parameter is also important for the target material tested.

3.4. Effect of the Water Pressure

Figure 6 shows the effect of the water pressure on the cut depth and kerf width of the granite tested. It can bee observed that the cut depth and kerf width increased with an increase in water pressure. However, the increasing rate of the cut depth and kerf width with water pressure reduced as the water pressure further increases, as shown in the Figure. Increasing of the cut depth with an increase of the waterjet is attributed to the fact that abrasive particles gain high velocity and energy when water pressure is high. Therefore, high energy particles can remove more material, so that the cut depth increases. Findings of this study are in line with those obtained by earlier investigations [21,22]. As identified by Hashish [23], there may be a critical water pressure, beyond this critical pressure; the positive effect of water pressure on the cut dept reduces because of the increased particle fragmentation and interference at high water pressure levels which reduces the cutting efficiency.

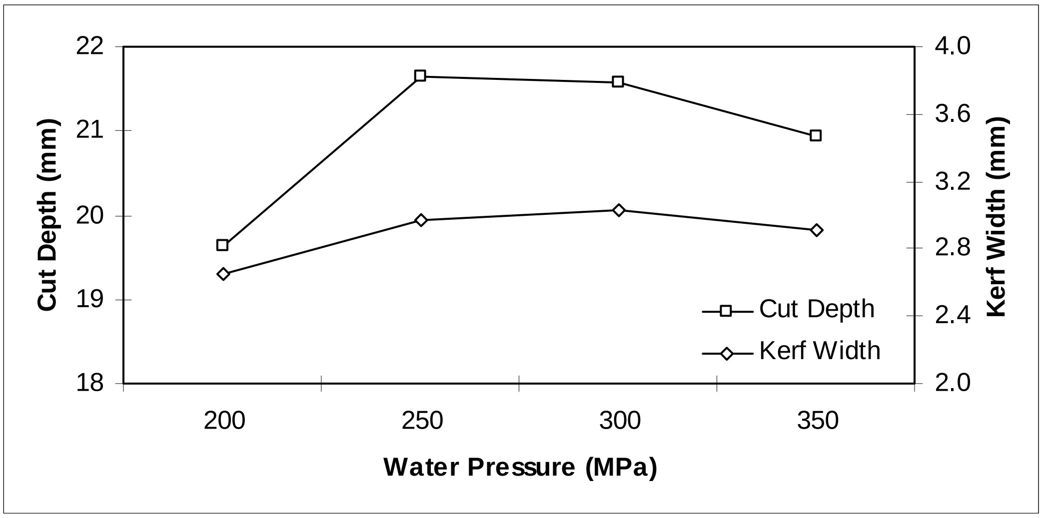

Figure 6. Effect of the water pressure on the cut depth and kerf width of the granite.

3.5. Effect of the Abrasive Size

The effect of the abrasive size on the cut depth and kerf width is plotted in Figure 7. As shown, higher cut depth was obtained by the coarse abrasive size than finer abrasive size did. On the other hand, the kerf width of the granite was narrower with the coarse abrasive size.

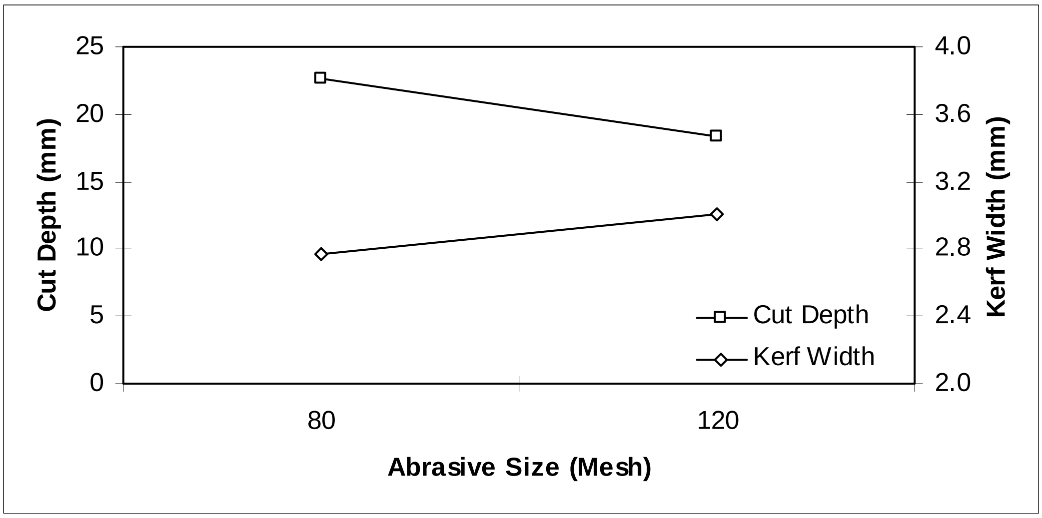

Figure 7. Effect of the abrasive size on the cut depth and kerf width of the granite.

In the existing literature few studies have concentrated on the investigation of effect of the abrasive size on the cutting performances of the abrasive waterjet such as cut depth [12,24] . As pointed out in the literature, the smaller abrasive particles loose rapidly their kinetic energy then coarser abrasive size. In other words, the coarser particles have more energy to cut material when they reach at the material, thus they cut the material rapidly. And, deeper cut depth could be obtained by the coarse abrasive particle. Additionally, the difference between the coarse particle and fine particle is the shape factor. The coarse particle has more velocity gain then the fine particle, therefore, the cut depth may increase for using the coarse particle.

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 depths of cut of specimens. 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 considerable change on the performance characteristic due to the variation of the process parameters [25,26].

Table 5. Results of analysis of variance (ANOVA) for the cut depth and kerf width.

	Source	D. of freedom	Sum of squares	Mean square	F ratio	Contribution (%)
Cut Depth	T	3	344.102	114.701	20.41	64.31
	M	3	79.461	26.487	4.71	14.85
	D	3	4.03	1.346	0.24	0.75
	P	3	22.764	7.588	1.35	4.25
	S	1	73.488	73.488	13.08	13.73
	Error	2	11.239	5.620		2.11
	Total	15	535.093			100
Kerf Width	T	3	0.501	0.167	7.19	5.99
	M	3	0.803	0.267	11.52	9.61
	D	3	6.465	2.155	92.65	77.27
	P	3	0.323	0.107	4.64	3.87
	S	1	0.225	0.225	9.70	2.70
	Error	2	0.046	0.023		0.56
	Total	15	8.367			100

This analysis is carried out for the confidence level of 95 %. Table 5 shows the results of ANOVA for machining outputs, respectively. From the F-table 5 % level of significance, it was found that the machining factor T (traverse speed) is the most significant factor influencing the assessment of the cut depth of the Rosa Minho, followed by control factors S (the abrasive size) and M (the abrasive flow rate). Others (the water pressure and the standoff distance) were found to be insignificant since they failed from the test of significant. Table 5 shows also the significant machining factors influencing the kerf width of the Rosa Minho. Accordingly, all the machining factors were found to be significant that affect the assessment of the kerf width of the granite. However, the level of significance varies with respect to the F ratio in the Table. The most significant factor is the standoff distance (D), followed by the abrasive flow rate, the abrasive size, the traverse speed and the water pressure respectively.

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.

From the analysis of ANOVA, the factor T (64.31 %) showed a high significant effect on the cut depth. It was followed by the abrasive flow rate (14.85 %) and the abrasive size (13.73 %). Similarly, the factors exhibiting the degree of influence on the kerf width are ranged as standoff distance (77.27 %), abrasive flow rate (9.61 %), traverse speed (5.99 %), water pressure (3.81 %) and abrasive size (2.70 %) respectively.

4.CONCLUSIONS

Conclusions, on the basis of experimental results presented in this paper, can be summarized as follows;

i. Increasing of the traverse speed resulted in decrease both in the cut depth and kerf width of the granite. This decrease was occurred more evenly in the kerf width.

ii. The cut depth and kerf width of the Rosa Minho increased with an increase in the abrasive flow rate. However, further increase in the abrasive low rate resulted in marginally increases both in the cut depth and kerf width of the Rosa Minho.

iii. An increase in standoff distance caused a decrease in the cut depth, whereas an increase proportionally in the kerf width.

iv. The cut depth and kerf width increased generally with an increase in water pressure. However, the increasing rate of the cut depth and kerf width with water pressure reduced as the water pressure further increases. Both the cut depth and kerf width showed a decreasing trend at the highest level of the water pressure.

v. Based on the analysis of variance (ANOVA) results, the highly effective parameters on the cut depth were determined as the traverse speed, the abrasive flow rate and the abrasive size respectively. Similarly, the standoff distance, the abrasive flow rate, the traverse speed, the water pressure and the abrasive size were determined as highly effective parameters on the kerf width of the granite.

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