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Analysis of Kerf Taper Angle in Abrasive Water Jet Cutting of Makrana White Marble

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***Abstract* - Abrasive water jet cutting (AWJ) process is used to experimental investigations parameters on kerf taper angles of makrana white marble. Marble is having a wide application in domestic, commercial and industrial construction so there is a need to investigate the AWJ cutting of marble. Three different process parameters were undertaken for this study; water pressure, nozzle transverse speed and abrasive flow rate. Experiments were conducted in varying these parameters for the cutting of marble. The design philosophy of Taguchi was followed to conduct the experiments. Analysis of variance (ANOVA) was used to evaluate the data obtained to determine the major significant process factors statistically affecting the kerf taper angle. The results revealed that the nozzle transverse speed was the most significant factor affecting on the kerf taper angle.**

***Keywords:* Abrasive water jet machining, Kerf taper angle, Taguchi method, ANOVA.**

I. Introduction

Abrasive Water Jet machining (AWJM) was first developed in 1974 to clean metal prior to surface treatment of the metal. The addition of abrasives to the water jet enhanced the material removal rate and produced cutting speeds between 51 and 460 mm/min. Generally, AWJM cuts 10 times faster than the conventional machining methods of composite materials. The cutting power is obtained by means of a transformation of a hydrostatic energy (400MPa) into a jet of a sufficient kinetic energy (nearly 1000 m/s) to disintegrate the material. The required energy for cutting materials is obtained by pressurizing water to ultrahigh pressure and forming an intense cutting stream by focusing high-speed water through a small orifice [1]. In Water jet cutting the material removal process can be described as a supersonic process [2]. AWJ cutting has been claimed to have various distinct advantages over the other cutting technologies, such as no thermal distortion on the work piece, high machining versatility to cut virtually any material, high flexibility to cut in any direction and small cutting forces [3, 4, 5].

Kerf geometry is a characteristic of major interest in abrasive water jet cutting. It has a wider entry and its width decrease as the jet cut into the material, by this kerf is produced [4]. This is supported by finding of Wang. *et al*. [6]. Kerf taper is defined as a half of the kerf width variation per millimeter of depth of cut (or penetration).

The aim of the present work is to optimize the process parameter of water jet cutting of marble to analysis the kerf taper angle. Now days, marble is widely used in commercial and industrial purpose. Traditionally marble is cut using diamond wire/saw cutter. Diamond wire cutting (DWC) is the process of using wire of various diameters and lengths, impregnated with diamond dust of various sizes to cut through materials. Because of the hardness of diamonds, this cutting technique can cut through almost any material that is softer than the diamond abrasive. During traditionally cutting of marble the various problems were observed [7] like time consuming process, dust and noise nuisance, material wasted while cutting of slots, not suitable in loose and crack strata and jamming of hammer and bit.

Because of the present problems encountered in conventional cutting of marble, attempts can be made for cutting of marble using nontraditional machine process such as EDM, WEDM, ultrasonic , Water jet, Abrasive Water Jet, laser beam machining etc. Problem with EDM, WEDM, is that work piece need to be conductive, while marble is an insulator, so these cannot be applied. Ultrasonic machining is a slow and time consuming process.

So in the present study, attempt can be made to find out machining characteristic of marble using water jet cutting. The advantages of this technology for mechanical processing of marbles are: Precise shape cutting can be achieved with a good surface finish. AWJ cut kerf width is much smaller than that produced by traditional sawing technologies.AWJ cutting systems can be easily integrated with existing CAD/ CAM systems, thereby greatly optimizing the cutting of intricate profile. The system produces no dust fumes etc. thereby significantly improving working conditions and environment.

There are various parameters which are affecting the AWJM as shown in Fig.1. [8, 9, 10]. In the present study water pressure, nozzle transverse speed and abrasive flow rate are chosen for Analysis the kerf taper angle.

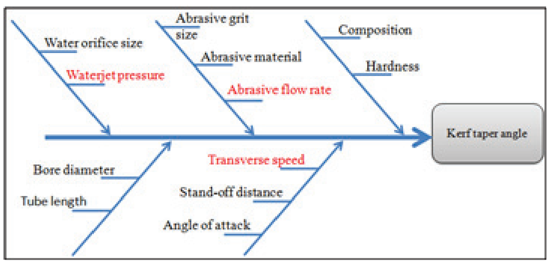

Fig. 1 Fish bone diagram for affecting the process parameters on AWJM

II. Experimental Work

A.Material and Dimensions

The material used for present study is Makrana white Marble. The marble is a brittle material and has the various applications as a building/construction material. The dimensions of these Makrana white marble were 80mm × 80mm × 15mm. The Chemical composition, Mechanical and physical properties of Makrana white Marble are shown in Table I & II.

Table I Chemical Composition Makrana White Marble

Elements	Weight %
Lime (CaO)	38-42%
Silica (SiO_2)	20-25%
Alumina (Al_2O_3)	2-4%
Other Oxides like Na, Mg	1.5 to 2.5%
Loss On Ignition (LOI)	30-32%

Table II Mechanical and Physical Properties of Makrana White Marble

Hardness	3 to 4 on Moh's Scale
Density	2.5 to 2.65 Kg/m^3
Compressive Strength	1800 to 2100 Kg/cm^2
Water Absorption	Less than 1%
Porosity	Quite low
Weather Impact	Resistant

B. Equipment

The equipment used for machining the samples was OMAX 80160 jet machining centre as shown in Fig. 2. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table with dimension of 6170 mm x 3405 mm. Diamond orifice was used to transform the high-pressure water into a collimated jet, with a tungsten carbide nozzle to form an abrasive water jet.

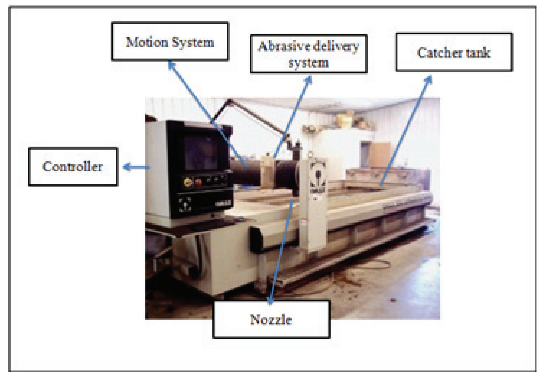

Fig. 2 Pictorial view of OMAX 80160 jet machining centre

C. Experimental Design

Large number of process variables are there, which are effecting the cutting performance of AWJM as shown in Fig.1, out of them only three parameters are selected as control factor in the present study as shown in Table III.

Table III The Levels of Parameters Used in Cutting of Marble

AWJ cutting Parameter	Units	Symbol	Level		
			1	2	3
Water pressure	MPa	A	200	270	340
Nozzle Transverse speed	mm/min	B	50	75	100
Abrasive flow rate	g/min	C	200	300	400

The parameters and their levels are selected based on the pilot study and the literature review. Rest of the parameter kept as constant which are shown in table IV. The parameters and levels were selected primarily based on the literature review of some studies that had been documented on AWJ machining on graphite/epoxy laminates [11], Kevlar composite [12], ceramic materials [13], structural metal alloys [14], metallic coated sheet steels [15], fibre-reinforced plastics [16] and Cast iron [17]. The preliminary experiments were carried out to find out the minimum value of water pressure as well as abrasive flow rate at which through cutting can take place. In the present study these come out to be 200 MPa & 200 g/min respectively. Experiments were also conducted to find out maximum value of velocity for the through cut. It comes out to be 100mm/min at threshold levels of other two input variables for through cutting.

Table IV Constant Parameters and Their Values

Sr. No	Constant parameters name	Values
1	Orifice diameter (Diamond)	0.3556 mm
2	Nozzle diameter/mixing tube diameter (Tungsten carbide)	0.7620 mm
3	Nozzle length	101.65 mm
4	Abrasive type	Garnet
5	Abrasive size (grit no)	80 mesh size
6	Carrier medium	Water
7	Standoff distance (SOD)	1 mm

Since there are three process parameters each with three levels in this cutting of marble experiment. There are various strategies that ensure an appropriate choice of runs. One of the strategies is the Taguchi's orthogonal scheme. The approach is to determine which factors in a Design of Experiments can dramatically reduce the number of trials required to gather the necessary data. An orthogonal array (OA) selector can assist in determining how many trials are necessary and the factor levels for each parameter in each trial. An L_9 orthogonal was selected for the experimentation. The standard L_9 orthogonal array (OA) has been shown in Table V.

D. Experimentation

Based on the process factors and their levels, a standard OA's of L_9 was found to be appropriate for the experimental layout. In total 9 runs were undertaken in this experimental investigation. Three experiments were conducted three times at the same setting to get appropriate S/N ratio. All the specimens were cut out with full penetration over a length of 40 mm as shown in Fig. 3.

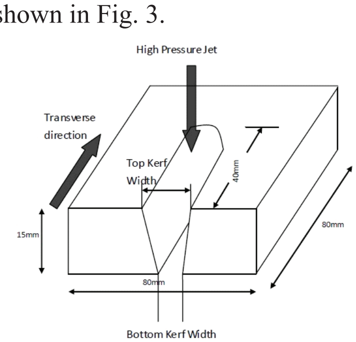

Fig. 3 Illustration of AWJ cutting

Study has been made for optimizing the process parameter cutting of marble including the output response parameter i.e. kerf taper angle.

E. Data Acquisition

"SX 45" stereo zoom microscope is used to measure the top and bottom kerf width. Three measurements were taken for each response and, the average is used for the measurement of kerf taper angle. It was anticipated that in AWJ contouring the two kerf walls might not be symmetrical due to the jet tail back effect. Thus the kerf taper and smooth depth of cut was obtained on each of the kerf walls [4]. The kerf taper was obtained by measuring the kerf wall inclination ($W_t - W_b$) from the top kerf edge as shown in Fig. 4. The kerf taper angle is calculated from equation 1.

$$\theta = tan^{-1}\left(\frac{W_t - W_b}{2t}\right) \qquad (1)$$

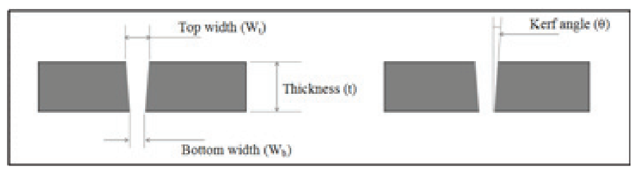

Fig. 4 Schematics of kerf geometry

Where: θ = kerf taper angle, W_t = top kerf width, W_b = bottom kerf width, t = thickness of workpiece.

The kerf geometry, which is produced by the cutting of marble as shown in Fig. 5. Table V is also shows the calculated data of the kerf taper angle respective the design of experiment by Taguchi approach.

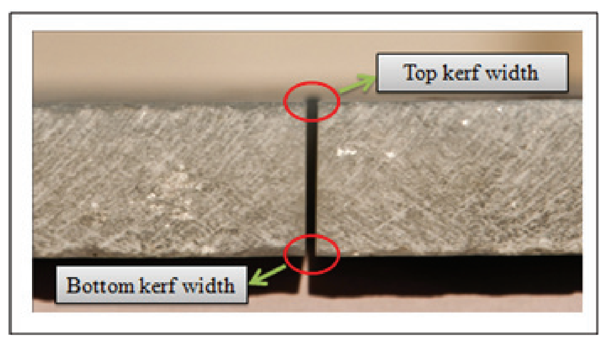

Fig. 5 Kerf profile produced by cutting of marble

III RESULT AND DISCUSSION

A. *Effect Of Control Factors*

Analysis of the results obtained has been performed according to the standard procedure recommended by Taguchi. The analysis of response data is done by software "MINITAB 16" specifically used for the design of experiment applications. In order to identify the process parameters that are significant in affecting on the kerf tapper angle, an ANOVA (analysis of Variance) has been carried out. ANOVA is computational technique that helps to estimate the rela tive contributions of each control factor, is found to be a very helpful DOE tool.

ANOVA was carried out to analyses the effect of process parameters on the kerf taper angle and to distinguish the most significant parameters in the generation of kerf taper angle.

TABLE V L_9 ORTHOGONAL ARRAYS FOR THE EXPERIMENTAL DESIGN AND DATA SUMMARY FOR KERF TAPER ANGLE

Experiment No.	Parameters			Kerf taper angle (degree)		
	Water pressure (MPa)	Nozzle transverse speed (mm/min)	Abrasive flow rate (g/min)	Trial		
				1	2	3
1	200	50	200	0.323	0.324	0.324
2	200	75	300	0.344	0.344	0.345
3	200	100	400	0.354	0.363	0.366
4	270	50	300	0.329	0.320	0.329
5	270	75	400	0.344	0.343	0.344
6	270	100	200	0.362	0.366	0.363
7	340	50	400	0.329	0.329	0.320
8	340	75	200	0.347	0.347	0.348
9	340	100	300	0.382	0.380	0.380

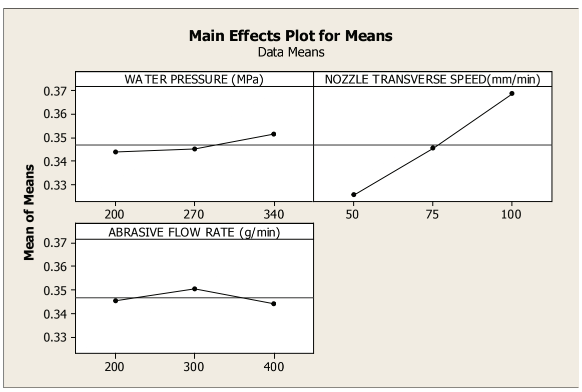

Fig. 6 Effect of process parameters on Kerf taper angle

The effect of process parameters on kerf taper angle as shown in Fig. 6.

It is found that from the Fig. 6 that the kerf taper angle slightly increased with increased the water pressure from level A_1 to level A_3. Because the outer rim of the diverged jet still has sufficient energy to cut material and due to the diverged jet energy, larger kerf angles may be obtained at higher water pressure. This is the consistent with the earlier finding of Wang, Jun [18]. Kerf taper angle was found to increase with increasing traverse speed from level B_1 to level B_3; this is because of the widening of the kerf lower part by the jet decreases as the traverse speed increases. Cutting at a low traverse speed is, therefore, associated with small kerf angles. This is the agreement with the findings of Azmira *et al*. [19]. Although a decrease in traverse speed will practically increase the production time, lower speed is always favorable in achieving small kerf angles. The experimental results shown in Fig. 6, reveal that the kerf taper angle exhibits a slight increase with the abrasive flow rate from level C_1 to level C_2 and then declined from level C_2 to level C_3, although the influence is not as significant as that of other process parameters.

B. Statistical Analysis for Kerf Taper Angle

The output of the analysis about the effect of process parameters on the kerf taper angle is calculated from the pooled analysis of variance table. It is observed that nozzle traverse speed is the primary variables that have a significant effect on the kerf taper angle. Among the primary variables, nozzle traverse speed plays a more important role in affecting the kerf taper angle, followed by water pressure. Tabulated F ratio values for this analysis 19.37 whereas the F ratio values from the polled analysis table of water pressure is 1.83 and for nozzle transverse speed is 47.41. So that nozzle transverse speed is the significant factor because its F ratio is more than the tabulated F value. Factor nozzle transverse speed has 92.505 % contribution for the variation in top kerf width while water pressure has 3.584 % contribution. So it is observed for factor nozzle transverse speed is most significant for this analysis.

C. Conformation Test

At the optimum settings the confirmation experiments are performed for various responses on kerf taper angle confirmation test was used to predict and verify the improvement in the qual ity characteristics for machining of makrana white marble with respect to the chosen initial parameter setting. Predicted mean value with optimum setting i.e. $A_1\ B_1C_2$ of kerf taper angle was 0.322°. Actual value produced by optimum setting by the conformation test was 0.334°. So the total percentage error produced with optimum level of setting is 3.59%.

IV. Conclusions

On the basis of experimental results, calculation of S/N ratio, analysis of variance (ANOVA), F-test values and confirmation test results the following conclusions can be drawn for effective machining of makrana white marble by AWJM process as follows:

1. The preliminary experiments were carried out to find out the minimum value of water pressure as well as abrasive flow rate at which through cutting can take place. In the present study these come out to be 200 MPa & 200 g/min respectively. Experiments were also conducted to find out maximum value of velocity for the through cut and it comes out to be 100mm/min at threshold levels of other two input variables for through cutting.

2. Out of all the selected parameters only nozzle transverse speed was significantly affecting the kerf taper angle with a percentage contribution of 92.505%. Water pressure can be termed as less significant for kerf taper angle with a percent contribution of 3.584 %. It was found that abrasive flow rate was providing very less contribution hence it was pooled out. It has been concluded from the results that input parameter settings of nozzle transverse speed at 50 mm/min (level B_1), water pressure at 200 MPa (level A_1), and abrasive flow rate at 300 g/min (level C_2) have given the optimum results for kerf taper angle; when Makrana white marble was machined with AWJM.

3. Predicted mean value with optimum setting i.e. $A_1\ B_1C_2$ of kerf taper angle was 0.322°. Actual value produced by optimum setting by the conformation test was 0.334°. So the total percentage error produced with optimum level of setting is 3.59%.

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