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Minimization of kerf taper angle and kerf width using Taguchi's method in abrasive water jet machining of marble

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Abstract

Abrasive water jet cutting is a non-traditional machining method that offers a productive alternative to conventional techniques. It uses a fine jet of ultra high pressure water and abrasive slurry to cut the target material by means of erosion. This paper attempts to investigate kerf characteristics in abrasive water jet machining of marble which is having wide applications in domestic, commercial and industrial construction work. Three different process parameters were undertaken for this study; water pressure, nozzle transverse speed and abrasive flow rate. Experiments were conducted according to Taguchi's design of experiments. Analysis of variance (ANOVA) was used to evaluate the data obtained to determine the major significant process factors statistically affecting the kerf characteristics. The results revealed that the nozzle transverse speed was the most significant factor affecting the top kerf width, the kerf taper angle.

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Keywords: Abrasive water jet machining, Marble, Taguchi ANOVA

1. Introduction

Marble is a rock resulting from metamorphism of sedimentary carbonate rocks which causes variable re-crystallization of the original carbonate mineral grains. The resulting marble rock is typically composed of an interlocking mosaic of carbonate crystals. Marble has numerous applications for structural and decorative purposes. It is utilized for outdoor sculpture, external walls, floor covering, decoration, stairs, and pavements, statuary, table tops, and novelties [Kearey and Philip, 2001]. 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

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almost any material that is softer than the diamond abrasive. A diamond blade grinds, rather than cuts, through material. Blades typically have rectangular teeth (segments) which contain diamond crystals embedded throughout the segment for grinding through very hard materials. During traditionally cutting of marble a number problems was observed such as time consuming process, dust and noise nuisance, material wastage while cutting of slots, not suitable in loose and crack strata and jamming of hammer and bit [Hasan et al., 2008; Cinar, 2007].

Because of the present problems encountered in conventional cutting of marble, attempts can be made for cutting of marble using non traditional machining process such as Ultrasonic machining , Water jet machining (WJM), Abrasive Water Jet machining (AWJM), Laser beam machining (LBM) etc. Ultrasonic machining can be applied to non conductive as well as brittle materials, but it is a slow and time consuming process, tool wear rate is very high even greater than the metal removal rates expected from the process [Garg, 2012]. LBM can also be used; however, height of the work piece is a major constraint [Garg, 2013]. Thus, studies can be directed towards machining of marble using Abrasive Water Jet Machining.

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 cutting speeds obtained in the range of 51 to 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. The use of the AWJ cutting is based on the principle of erosion of the material by the impact of jets. Each of the two components of the jet, i.e. the water and the abrasive material has a specific purpose. The primary purpose of the abrasive material within the jet stream is to provide the erosive forces. However the water jet also accelerates the abrasive material to a speed such that the impact and change in momentum of the abrasive material can perform its function [Jankovic et al., 2011]. Each hard abrasive particle acts like a single point cutting tool. The abrasive particle-laden water jet impinges onto the surface of the work piece and material is removed by an erosion process. Abrasive water jet (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 [Wang and Guo, 2003]. There is no heat buildup with abrasive Water jet cutting; so no fire hazard, thus making the process safe. There is no radiation emission or danger from flying slag or chip particles. Airborne dust is virtually eliminated. Moreover, the noise levels are tolerable ranging range from 85 to 95 dB [Palleda, 2007].

AWJM is successfully applied in the past for cutting of wide variety of materials ranging from conventional steels to ceramic materials. The intensity and the efficiency of the cutting process depend on several AWJM process parameters such as traverse rate, stand off distance, angle of impact etc [Hashish et al., 1983]. Many investigations have been conducted to understand the effects of the process variables on the cutting performance measures, such as the top kerf width, kerf taper and surface roughness. Kerf geometry is a characteristic of major interest in abrasive waterjet cutting. As shown in Figure 1, AWJ will generally open a tapered slot with the top kerf w_t being wider than the bottom kerf w_b, kerf taper or kerf taper angle normally θ being used to represent this characteristic.

2. Literature Review

A number of researchers have investigated parametric influence of AWJM on a wide variety of materials. Literature reported that the kerf taper angle decrease with increase in the water pressure [Shanmugam et al., 2009; Khan et al., 2007]. Wang and Jun (1999) witnessed an opposite trend in of kerf taper angle with respect to the water pressure when cutting polymer matrix composite because the outer rim of the diverged jet still had sufficient energy to cut this relatively soft material. Literature reveals that kerf taper angle increase with an increase the nozzle transverse speed [Shunmugam et al., 2009, Wang and Wong, 1999]. Wang and Jun (1999) found that kerf taper angle decreases with increase in the nozzle transverse speed, this may be due to the different types of materials processed, the different pressure and speed ranges selected, as well as different ratios of jet energy used to the energy required to cut the materials. An increase in standoff distance (distance of the nozzle tip from the work surface) leads to an increase in kerf taper angle [Shunmugam et al., 2009; Khan et al., 2007; Wang and Wong, 1999]. It has been reported from the experimental investigation on ceramic material, that abrasive mass flow rate does not have significant effect on the kerf taper angle. This is because of the fact that abrasive mass flow rate affects the top and bottom kerf width in a similar scale or magnitude [Chen et al., 1996]. Similarly Shunmugam *et al.* (2009) observed that with an increase in the abrasive mass flow rate the kerf taper angle seems to decrease insignificantly. Generally standoff distance, transverse speed and a water pressure have the more effect on the kerf taper angle than the abrasive flow rate. A combination of high water pressure, low transverse speed and a small standoff distance generate more parallel kerf.

It is found that the top kerf width (w_t in figure1) slightly increase with increase the water pressure [Shanmugam et al., 2009; Wang and Jun, 1999; Wang and Wong, 1999; Chen et al., 1996]. These investigations reveal that a higher water pressure produce a wider slot as a jet with greater kinetic energy impinges onto the target material. While Kantha and Krishnaiah (2006) did not find any relationship between water pressure and top kerf width. It has been reported that the top kerf width is inversely proportional to the nozzle transverse speed because a slower pass allows more abrasive particle to impact on the target and open a wider slot [Wang and Jun, 1999; Wang and Wong, 1999]. This is also supported by Hascalik *et al.* (2007). However Chen *et al.* (1996) found that nozzle transverse speed has little effect on the top kerf width on the cutting of brittle material.

Thus, literature review reveals that AWJM is applied to a wide variety of materials and the potential of AWJM in cutting of marble is still remain unexplored. Moreover, conflicting results are obtained for parametric influence of AWJM on kerf characteristics for wide variety of materials owing to their different compositions and material properties. It becomes imperative to study the effect of process parameters in AWJM of most commonly used Makrana marble. Present work attempts to do this by investigating the effect of AWJM process parameters on top kerf width and kerf taper angle. Further, optimization of process parameters is also performed for minimum values of top kerf width and kerf taper angle.

3. Experimental set up and selection of process parameters

The equipment used for machining the samples is OMAX 80160 jet machining centre as shown in Figure 2. A plate of Makrana marble having size 80mm × 80mm × 15mm is chosen as the work piece. Table 1 indicates the important properties of Makrana marble (material chosen for experimentation).

As discussed in the literature review, a large number of variables are involved in the AWJM and virtually all these variables affect the cutting results. Therefore only those parameters are selected which shows a considerable influence on objectives of the study i.e. kerf taper angle and top kerf width. These parameters are nozzle traverse speed, water pressure and abrasive mass flow rate. The rest of the parameters are kept constant which are given in Table 2.

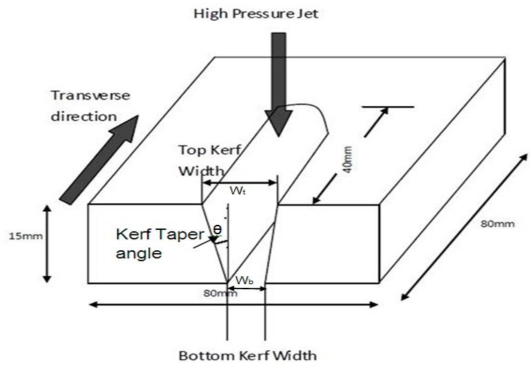

Fig. 1. Kerf geometry of an AWJ cut

Fig. 2. OMAX 80160 Jet Machining Centre

Table 1: Mechanical and Physical Properties of Makrana Marble

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

Table 2: Constant Parameters and Their Values

Constant Parameters	Orifice diameter (Diamond)	Nozzle diameter/mixing tube diameter	Nozzle length	Abrasive type	Abrasive size (grit no)	Standoff distance (SOD)
Value	0.3556 mm	0.7620 mm	101.65 mm	Garnet	80 mesh size	1 mm

To achieve a thorough cut it was required that the combinations of the process variables give the jet enough energy to penetrate through the specimens. Screening experiments are performed to limit the range of process parameters at which cutting through the full thickness of the work piece can be performed. The minimum value of water pressure as well as abrasive flow rate at which through cutting can take place come out to be 200 MPa and 200 g/min respectively. Experiments were also conducted to find out maximum value of nozzle traverse speed for the through cut. It comes out to be 100 mm/min at threshold levels of other two input variables for through cutting. The higher levels of water pressure and abrasive flow rate and lower level of nozzle traverse speed are selected at the threshold levels permitted by the machine tool as input. Table 3 indicates variable process parameters and their levels selected.

4. Design of experiments and experimentation

For experimentation, a full factor experimental design could have been used, there would be a total of 81 runs and it would be too expensive to do. The solution is to use only a fraction of the runs specified by the full factorial design. There are various strategies that ensure an appropriate choice of runs. One of the strategies is the Taguchi's orthogonal scheme. This approach can drastically reduce the number of trials required to gather the necessary data. A L_9 orthogonal was selected for the experimentation which takes into account three factors at their three levels as shown in table 3. In total, 9 runs were undertaken in this experimental investigation. These experiments were conducted three times at the same setting to get appropriate S/N ratios. All the specimens were cut with full penetration over a length of 40 mm as shown in Figure 1.

In order to quantitatively evaluate experimental results, a measurement of the kerf characteristics such as top kerf width and kerf taper angle was made. The measurement of kerf taper, top kerf width and depth of cut was carried out from the end of the kerf prior to separating the specimens to measure the smooth depth of cut. 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. The kerf taper was obtained by measuring the kerf wall inclination (W_t – W_b) from the top kerf edge as shown in Figure 1. The taper angle is calculated by the following relation. Table 4 presents the design matrix as well as data about the observations.

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

Where W_t is the top kerf width, W_b is the bottom kerf width and 't' is the thickness of the work piece

Table 3: Variable Parameters and Their Levels

Parameters	Level 1	Level 2	Level 3
Water pressure (M Pa)	200	270	340
Nozzle Transverse speed (mm/min)	50	75	100
Abrasive flow rate (g/min)	200	300	400

Table 4: Data summary for top and bottom kerf width

Experiment No.	Parameters			Top kerf width (mm)			Bottom kerf width (mm)		
	Water Pressure (MPa)	Nozzle Transverse Speed (mm/min)	Abrasive Flow Rate (g/min)	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	200	50	200	0.83	0.83	0.82	0.66	0.66	0.65
2	200	75	300	0.80	0.80	0.80	0.61	0.61	0.61
3	200	100	400	0.76	0.77	0.76	0.57	0.57	0.56
4	270	50	300	0.84	0.84	0.83	0.66	0.67	0.65
5	270	75	400	0.81	0.81	0.82	0.62	0.63	0.63
6	270	100	200	0.77	0.78	0.79	0.58	0.58	0.59
7	340	50	400	0.82	0.81	0.81	0.64	0.63	0.64
8	340	75	200	0.79	0.78	0.78	0.60	0.59	0.59
9	340	100	300	0.77	0.76	0.77	0.56	0.56	0.57

5. Results and Discussion

After conducting the experiments with different settings of input parameters i.e. water pressure, nozzle transverse speed and abrasive flow rate, the values of output parameter i.e. top kerf width, kerf taper angle are recorded and these are plotted as per Taguchi's design of experiments methodology. The 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. The detailed description of the analysis is given as under in this section.

5.1 Statistical analysis of the significance of process parameters

In order to identify the process parameters that are significant in affecting the top kerf width and kerf taper angle, an analysis of variance (ANOVA) has been carried out. ANOVA is a computational technique that helps to estimate the relative contributions of each control factor. It uses a mathematical technique known as the sum of squares to quantitatively examine the deviation of the control factor response average from the overall experimental mean response, which is referred to as the variation between the control factors. ANOVA provides insight into the main effects, as well as interaction effects of factors.

5.1.1 Effect of process parameter on the top kerf width

For a good analysis, three tests must be verified i.e. normal distributed plot, residual versus fits and constant variance test. Figure 3 gives the residual plots for mean. This normal probability plot shows the normal distribution of residuals. It shows that the residual fall on a straight line which implies that errors are normally distributed. Versus fits shows that the residuals are randomly distributed and these do not follow a pattern. The versus order is having a constant variance. These three test conditions are satisfied which clearly indicate that the reliability of the observations is up to the mark and obeys 95 % confidence interval.

To analyze the effect of process parameters on the top kerf width, ANOVA is carried out to distinguish the most significant parameters in the generation of top kerf width. The effect of process parameters on top kerf width is shown in Figure 4. It can be noticed that the top kerf width appear to increase with the water pressure from level 1 to level 2. This is expected as higher water pressure results in greater jet kinetic energy and opens a wider slot on the work piece. It is interesting to note that water pressure exhibits a reduced effect on the top kerf width when it is increased from level 2 to level 3. This is due to fact that abrasive water jets become less effective at pressures above a threshold value depending on the other process parameters. This is the consistent with the earlier findings of Wang and Wong (1999).

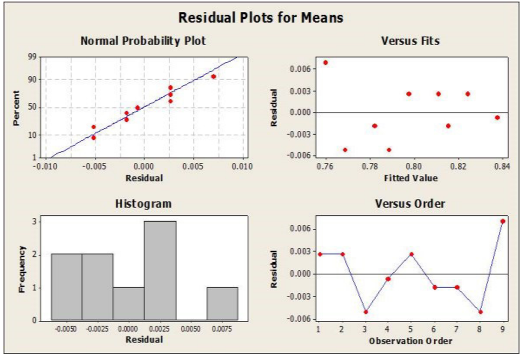

Fig. 3. Residuals Plot Analysis for Top Kerf Width

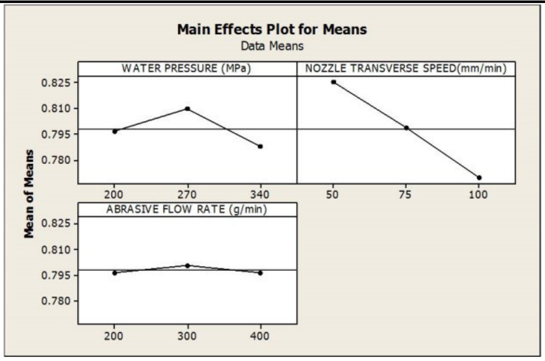

Fig. 4. Effect of Process Parameters on Top Kerf Width

It is observed from figure that traverse speed exhibits a negative effect on the top kerf width. The negative effect of traverse speed on the kerf width is due to the fact that a faster passing of abrasive water jet allows fewer particles to strike on the target material and hence generates a narrower slot. The effect of abrasive flow rate on the top kerf width exhibits that an increase in abrasive flow rate from level 1 to level 3 effects top kerf width non-significantly.

To identify the significant process parameters for top kerf width statistical analysis is carried out using Minitab - 16 software. The pooled analysis of means for top kerf width is given in Table 5 and pooled response is shown in Table 6. It is found that nozzle transverse speed be the primary variable effecting the top kerf width. Water pressure has the less effect on the top kerf width and abrasive flow rate has been pooled out. Table 5 shows that the tabulated F ratio values for this analysis 19.37 and calculated F ratio of water pressure is 21.47 (13.619 % contribution) and for nozzle transverse speed is 70.79 (84.004 % contribution). All these statistics are more than the tabulated values; so these factors are significant. Thus, it is concluded that nozzle transverse speed is most significant for this analysis. Figure 5 shows that the nozzle transverses speed play a major role on the top kerf width. The top kerf width is minimum i.e 0.7700 mm when nozzle transverse is at highest level i.e. 100 mm/min (level 3) and 0.7878 mm when water pressure having its maximum value i.e. 340 MPa (level 3). Pooled response table (Table 6) marked as a rank 1st to the nozzle transverse speed followed by water pressure. Abrasive flow rate is pooled out. Thus, the optimal settings of process parameters for minimum top kerf width are water pressure and nozzle transfer speed at highest levels of 340 M Pa and 100 mm/min respectively.

Table 5: Pooled analysis of variance of means for top kerf width

Source	DF	Seq SS	Adj MS	F	P	% Contribution
Water pressure	2	0.000751	0.000375	21.47	0.022	13.619
Nozzle transverse speed	2	0.004632	0.002316	70.79	0.001	84.004
Residual error	4	0.000131	0.000033			2.375
Total	8	0.005514				

DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error. Tabulated F- ratio is 19.37

Table 6: Pooled Response Table for top kerf width

Level	Water pressure	Nozzle transverse speed
1	0.7967	0.8256
2	0.8100	0.7989
3	0.7878	0.7700
Delta	0.0222	0.0556
Rank	2	1

5.1.2 Effect of Process Parameter on the Kerf Taper Angle

Figure 5 gives the residual plots for means of kerf taper angle. This normal probability plot shows the normal distribution of residuals i.e. the residual are falling on a straight line. Versus fits shows the residuals that the residuals are randomly distributed and do not follow a pattern. Hence, data is well fitted to the observations and adequately represents the process.

The effect of process parameters on kerf taper angle is shown in Figure 6. It shows the influence of water pressure on the kerf taper angle. It is found that from the Figure that the kerf taper angle slightly increased with increased the water pressure from level 1 to level 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 (1999). It can be seen from Figure 6 that, the taper angle is found to increase with increasing traverse speed from level 1 to level 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. Although a decrease in traverse speed will practically increase the production time, lower speed is always favorable in achieving small kerf angles. This figure also reveals that the kerf taper angle exhibits a slight increase with the abrasive flow rate from level 1 to level 2 and then decreases from level 2 to level 3, although the influence is not as significant as that of other process parameters.

ANOVA is carried out to analyze the effect of process parameters on the kerf taper angle and to distinguish the most significant parameters in the generation of kerf taper angle. The output of the ANOVA for means of observation data of kerf taper angle is presented in Table 7 and Table 8 indicates the pooled response data. Table 7 shows that nozzle traverse speed is the primary variable that has 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 and in the table 7 shows that F ratio of water pressure is 1.83 and for nozzle transverse speed is 47.41. Thus, nozzle transverse speed is the most significant factor with a maximum contribution of 92.505% followed by water pressure with 3.584% contribution. Figure 7 shows that the nozzle transverses speed play a major role on the kerf taper angle. The kerf taper angle is minimum (0.3256°) when the nozzle transverse speed having its minimum value i.e. 50 mm/min (level 1) and 0.3437° when the water pressure have the minimum value 200 MPa (level 1). Table 8 marked rank first to the nozzle transverse speed followed by water pressure and abrasive flow rate is pooled out. Thus, optimal settings of process parameters for minimum kerf taper angle are at lowest levels of water pressure and nozzle transfer speed at 200 M Pa and 50 mm/min respectively.

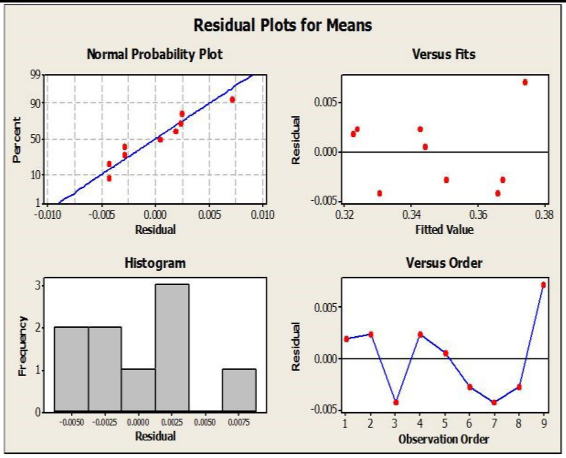

Fig. 5. Residuals plot analysis kerf taper angle

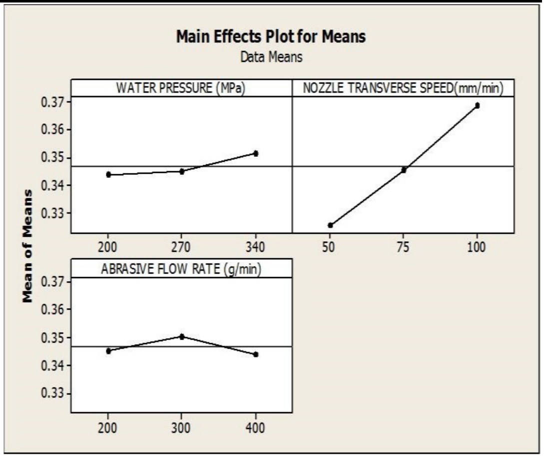

Fig. 6. Effect of process parameters on Kerf taper angle

Table 7: Pooled analysis of variance of means for kerf taper angle (degree)

Source	**DF**	**Seq SS**	**Adj MS**	**F**	**P**	**% Contribution**
Water pressure	2	0.000110	0.000055	1.83	0.273	3.584
Nozzle Transverse Speed	2	0.002839	0.001420	47.41	0.002	92.505
Residual Error	4	0.000120	0.000030			3.910
Total	8	0.003069				

DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error. Tabulated F- ratio is 19.37

Table 8: Pooled Response table for kerf taper angle (degree)

Level	Water pressure	Nozzle transverse speed
1	0.3437	0.3256
2	0.3450	0.3457
3	0.3516	0.3690
Delta	0.0080	0.0435
Rank	2	1

6. Confirmation tests

Data about the confirmatory experiments performed at the optimum settings of process parameters are is presented in table 9. It is important to mention that predicted mean values as shown in table 9 are calculated using MINITAB 16. It shows that error between the predicted and actual values is less than 5%. Hence, confirmatory experiments confirm the reproducibility of results.

7. Conclusions

Present work explored the abrasive water jet machining of marble using Taguchi's design of experiments and subsequent analysis. From the work, following inferences can be drawn:

- Preliminary study bracketed the range of selected process parameters taking into consideration the minimum values of water pressure and abrasive flow rate as well as maximum value of nozzle traverse speed at which through cutting of marble can take place. These come out to be 200 MPa for water pressure, 200 g/min for abrasive flow rate and 100 m/min for nozzle traverse speed.
- For top kerf width, nozzle transverse speed has emerged as most significant parameter with a percent contribution of 84.004% followed by water pressure (13.619%). It was found that abrasive flow rate failed the test of significant at 95% confidence level therefore it was pooled out.
- Optimal settings of process parameters for minimum top kerf width are water pressure and nozzle transfer speed at highest levels of 340 M Pa and 100 mm/min respectively.
- 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 termed as less significant for kerf taper angle with a percent contribution of 3.584 %.
- For minimum kerf taper angle lowest levels of water pressure and nozzle transfer speed at 200 M Pa and 50 mm/min emerged as optimal settings.

Table 9: Confirmation experiments at optimum settings

S. No.	Response	Optimum Setting	Predicted Mean	Actual Value	% Error
1.	Top Kerf Width	A_3B_3	0.759 mm	0.792mm	4.16 %.
2.	Kerf Taper Angle	$A_1 B_1$	0.322°	0.334°	3.59 %

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