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Research Paper

Machining of Makrana White Marble Surfaces by Abrasive Water Jet Machining

Vishal Gupta[1*], M.P. Garg[2], N.K.Batra[2], Arjun S. Wadwa[3]
[1]Indian Institute of Technology Delhi, Delhi, India
[2]Mechanical Engineering Department, M. M. University, Mullana, India
[3]École de Technologie Supérieure, Montreal, Canada
[*]Email of the Corresponding Author: vishaltayal86@gmail.com
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Abstract
In the present study, experimental investigations were conducted to find out the effect of abrasive water jet machining (AWJM) process parameters on the surface roughness (Ra) of white Makrana Marble. The approach was based on Taguchi's method and analysis of variance (ANOVA) to optimize the AWJM process parameters for effective machining. Nozzle transverse speed, water pressure, and stand of distance were selected as the input parameters while the other was kept constant. It was found that the water pressure and nozzle transverse speed were significant control factors and the stand of distance was the insignificant control factor in controlling the surface roughness (Ra).

Keywords
Surface Roughness, AWJM, Taguchi Method, White Marble

1. Introduction

Abrasive waterjet (AWJ) 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 utilizing erosion. This technology is less sensitive to material properties as it does not cause chatter, has no thermal effects, imposes minimal stresses on the workpiece, and has high machining versatility and flexibility [1, 2]. However, many aspects of this technology require it to be fully understood to increase its cutting capacity and optimize the cutting process. Because of these capabilities, it makes an important contribution to machining materials with higher performance and is more cost effective than traditional and some non-traditional machining processes.

AWJ is widely used in the machining of materials such as titanium, steel, brass, aluminum, stone, Inconel, and any kind of glass and composites [3]. The intensity and the efficiency of the machining process depend on several AWJ process parameters [4, 5]. They are classified as hydraulic, abrasive, work material, and cutting parameters. Surface roughness, which is used to determine and evaluate the quality of a product, is one of the major quality attributes of an AWJ machining product. The present work is focused on optimizing the process parameter of abrasive water jet cutting of marble to analyze the surface roughness. Nowadays, marble is widely used for commercial and industrial purposes.

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 the traditional cutting of marble various problems were observed like a time-consuming process, dust and noise nuisance, material wasted while cutting slots, not suitable in loose and crack strata, and jamming of hammer and bit.

Because of the present problems encountered in the conventional cutting of marble, attempts can be made for cutting marble using nontraditional machine processes such as EDM, WEDM, ultrasonic, Water jet, Abrasive Water Jet, laser beam machining, etc. The problem with EDM, WEDM, is that the workpiece needs 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, an attempt can be made to find out the machining characteristic of marble using abrasive water jet machining.

2. Surface roughness

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 [6].

There are several ways to describe surface roughness, such as roughness average (Ra), root-mean-square (RMS) roughness (Rq) and maximum peak-to-valley roughness (Ry or Rmax), etc.

- Statistical descriptors that give average behavior of the surface height. For example, average roughness
- Ra; the root means square roughness Rq; the skewnessSk and the kurtosis K.
- Extreme value descriptors that depend on isolated events. Examples are the maximum peak height Rp, the maximum valley height Rv, and the maximum peak to valley height Rmax.
- Texture descriptors that describe variations of the surface based on multiple events. An example of this descriptor is the correlation length.

Among these descriptors, the Ra measure is one of the most effective surface roughness measures commonly adopted in general engineering practice. It gives a good general description of the height variations on the surface.

3. Experimental work

3.1 Material and dimensions

The material used for the present study is Makrana white Marble. Marble is a brittle material and has various applications as a building/construction material. The dimensions of these Makrana white marble were 80 mm × 80 mm × 15 mm. The Chemical composition and physical properties of Makrana white Marble are shown in Table 1.

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

3.2 Equipment

The equipment used for machining the samples was OMAX 80160 jet machining center as shown in Fig. 1. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve, and a workpiece table with a dimension of 6170 mm x 3405 mm. The 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.

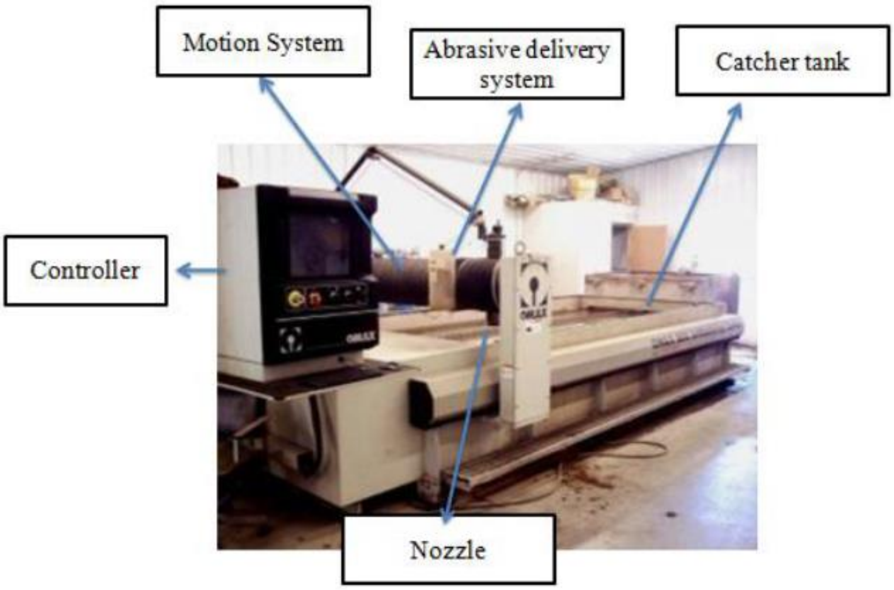

Figure 1: Pictorial view of OMAX 80160 jet machining center

3.3 Design of experiments

The various process variables are there, which are affecting the cutting performance of abrasive water jet machining as discussed in the introduction section. Out of them, only three parameters are selected as a controlling factor in the present study as shown in Table 2. The parameters and their levels are selected based on the pilot study and the literature review. The rest of the parameters are kept constant which are shown in Table 3.

Table 2. 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 3. 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

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, Kevlar composite [7], ceramic materials [8], structural metal alloys [9], metallic coated sheet steels [10], fiber-reinforced plastics [11], and Cast iron [12]. The preliminary experiments were carried out to find out the minimum value of water pressure as well as the 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 the maximum value of velocity for the through cut. It comes out to be 100mm/min at threshold levels of the other two input variables for through cutting. Since there are three process parameters each with three levels in this cutting of marble experiment. Various strategies ensure an appropriate choice of runs. One of the strategies is 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 L9 orthogonal was selected for the experimentation. The standard L_9 orthogonal array (OA) has been shown in Table 4.

Table 4. L_9 Orthogonal arrays for the experimental design and data summary Surface roughness Ra

Experiment No	Parameters			Surface roughness Ra (µm)		
	Water pressure (MPa)	Nozzle transverse speed (mm/min)	Abrasive flow rate (g/min)	Trial 1	Trial 2	Trial 3
1	200	50	200	3.61	3.67	3.6
2	200	75	300	4.07	4.09	4.08
3	200	100	400	4.5	4.6	4.55
4	270	50	300	2.94	2.95	2.96
5	270	75	400	3.66	3.68	3.68
6	270	100	200	3.8	3.85	3.8
7	340	50	400	3.37	3.34	3.4
8	340	75	200	4.19	4.25	4.23
9	340	100	300	4.37	4.34	4.39

3.4 Experimentation

Based on the process factors and their levels, a standard OA of L9 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 in the same setting to get the appropriate S/N ratio. All the specimens were cut out with full penetration over a length of 40 mm. The study has been made for optimizing the process parameter cutting of marble including the output response parameter i.e. surface roughness.

3.5 Data Acquisition

In the present study surface roughness is measured by the Mitutoyo SJ-301 roughness tester having a least count of 0.01 µm is used. Table 4 shows the data summary of surface roughness for an experiment against the input parameter setting for the L_9 orthogonal array.

4. Results and discussion

4.1 Statistical analysis of the significance of process parameters

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. To identify the process parameters that are significant in affecting the kerf taper angle, an ANOVA (analysis of variance) has been carried out. ANOVA is a computational technique that helps to estimate the relative contributions of each control factor and is found to be a very helpful DOE tool. ANOVA has been carried out to analyze the effect of process parameters on surface roughness. The effect of process parameters on surface roughness is shown in Figure 2. For a good analysis, three tests must be verified i.e. normally distributed plot, residual versus fits, and constant variance test. Figure 3 gives the residual plots for the 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 indicates that the reliability of the observations is up to the mark and obeys a 95 % confidence interval.

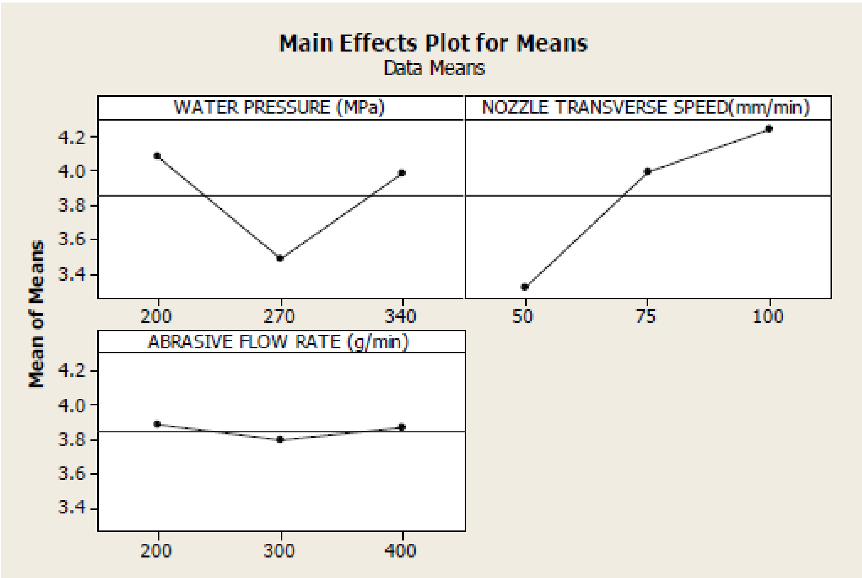

Figure 2. Effect of Process Parameters on surface roughness

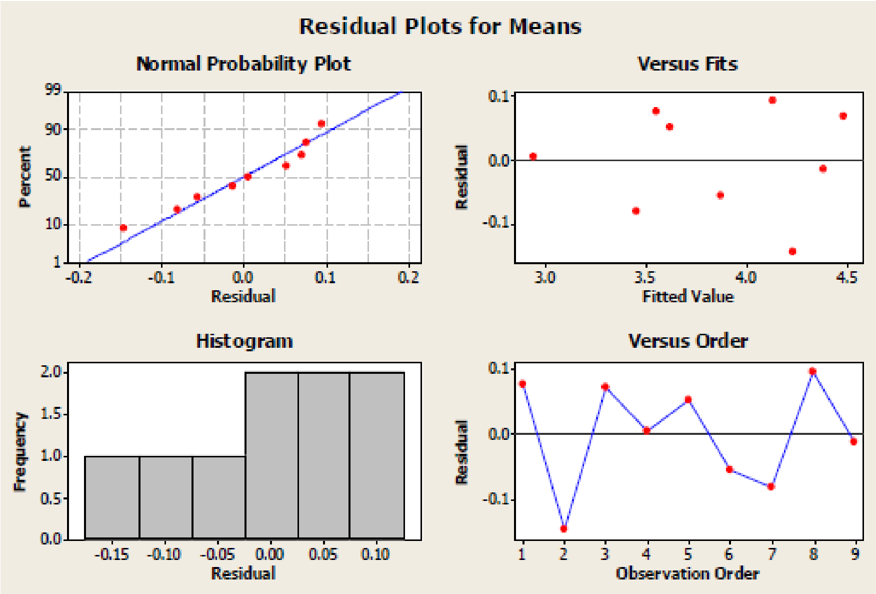

Figure 3. Residuals Plot Analysis for surface roughness

4.2 Effect of process parameters on surface Roughness

- Effect of water pressure on surface roughness

From figure 2 it is observed that surface roughness decreases initially with an increase in water pressure from level 1 to level 2. With a further increase in water pressure from level 2 to level 3, surface roughness dramatically increases. There are two reasons for this manner: Firstly a further increase in water pressure the energy at the outer rim tends to increase the irregularity and surface roughness because of the uneven energy distribution of the jet region; secondly, high water pressure causes the particles to be fragmented which in turn results in the abrasive losing their cutting ability.

- Effect of nozzle transverse speed on surface roughness

It is clear from figure 2 that surface roughness increased with the increase of the nozzle transverse speed from level 1 to level 3. The result follows the same trend as given by [13, 14]. This is because of as increasing the traverse rate allows less overlap machining action and fewer abrasive particles to impinge the surface, increasing the roughness of the surface. It was found that the roughness of the cut profiles changes with traverse rate and it is more obvious at the highest traverse rate. In this case, a lower traverse rate is desirable to produce a better surface finish as shown in Figure 2.

- Effect of abrasive flow rate on surface roughness

The effect of abrasive flow rate on the top kerf width as shown in figure 4.5, exhibits that an increase in abrasive flow rate from level 1 to level 3 results in non-significant surface roughness.

- Statistical analysis for surface roughness

The study to identify the primary process parameters for the surface roughness is carried out by statistical analysis using the Minitab - 16 software. The output is given in Tables 5 and 6. It is found that nozzle transverse speed is the primary variable followed by the water pressure on the surface roughness and the abrasive flow rate has been pooled. The tabulated Fratio values for this are 19.37

and Table 5 shows that the F ratio of water pressure is 23.32 and for nozzle transverse speed is 50.99. Factor nozzle transverse speed has 66.801 % contribution for the variation in top kerf width while water pressure has 30.562 % contribution. So it is observed for factor nozzle transverse speed is most significant for this analysis.

Table 5. A pooled analysis of variance for surface roughness (µm)

Source	DF	Seq SS	Adj MS	F	P	Contribution (%)
Water pressure	2	0.63319	0.31659	23.32	0.006	30.562
Nozzle transverse speed	2	1.38433	0.69216	50.99	0.001	66.801
Residual error	4	0.05430	0.01358			2.620
Total	8	2.07182				

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

Table 6. Pooled response table for surface roughness (µm)

Level	Water pressure	Nozzle transverse speed
1	4.086	3.316
2	3.480	3.992
3	3.987	4.244
Delta	0.606	0.929
Rank	2	1

Figure 2 shows that the nozzle transverses speed plays a major role in the surface roughness. Surface roughness has the minimum value of 3.316 µm when nozzle transverse speed has its minimum value i.e. 50 mm/min (level 1) and 3.480µm when water pressure has its value i.e 270 MPa (level 2). Table 6 marked a rank 1st to the nozzle transverse speed followed by water pressure and abrasive flow rate is pooled out.

5. Confirmation tests

Data about the confirmatory experiments performed at the optimum settings of process parameters are presented in Table 7. It is important to mention that predicted mean values as shown in Table 7 are calculated using MINITAB 16. It shows that the error between the predicted and actual values is less than -2.17%. Hence, confirmatory experiments confirm the reproducibility of results.

Table 7. Confirmation Experiments at Optimum Settings

Sr. No.	Response	Optimum Setting	Predicted Mean	Actual Value	Error (%)
1	Surface Roughness	$A_2B_1C_2$	2.944 µm	2.864 µm	-2.17 %

6. Conclusion

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

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 the maximum value of nozzle traverse speed at which through the 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.
Out of all the selected parameters, only water pressure and nozzle transverse speed were significantly affecting the surface roughness in AWJ machining of Makrana white marble. About the average response, nozzle transverse speed has emerged as the most significant with a percent contribution of 66.801% followed by water pressure (30.562%). It was found that the abrasive flow rate failed the test of significance at a 95% confidence level therefore it was pooled out. It has been concluded from the results that input parameter settings of nozzle transverse speed at 50 mm/min (level 1), water pressure at 270 MPa (level 2), and abrasive flow rate at 300 g/min (level 2) has given the optimum results for surface roughness; when Makrana white marble was machined with AWJM.

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