An Experimental Investigation of Abrasive Water Jet Machining on Granite

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Abstract

Abrasive water jet machining, one of the non-traditional processes for machining and cutting uses the abrasive particles mixed with the water jet and is impinged onto the workpiece for manufacturing processes. In this study focus is on the investigation of experimental work based on Taguchi method for machining of granite material with abrasive water jet machine. Three control factors were selected - Traverse speed (mm/min), Water pressure (MPa) and Stand-off distance (mm) with two response parameters – Material removal rate (gm/min) and Surface roughness (μm). With the help of ANOVA (Analysis of variance), it was observed that traverse speed was the most significant parameter affecting Material removal rate (MRR), while Stand-off distance (SOD) was found to be the most significantly affecting factor for the surface roughness parameter. It was also observed that with increase in traverse speed, MRR and surface increases. A multiple linear regression model was also developed for prediction of results.

Keywords: MRR, Surface Roughness, Stand-off Distance, Traverse Speed, Granite

I. INTRODUCTION

Granite, a composite of several minerals, is becoming a prime choice as a building material worldwide. Owing to its aesthetic properties and toughness, its demand in the interior design is increasing. There has been continuous research going on the machining of granite and similar materials using abrasive water jet machining technique which is an emerging technology for all the engineering materials.

Kerf characteristics in abrasive water jet machining were experimentally investigated with the process parameters like water pressure, nozzle traverse speed and abrasive water flow rate. It was observed that only the nozzle traverse speed was significantly affecting the kerf taper angle [1]. Experimental studies for granite indicated that the depth of cuts decreased with an increase in the traverse speed and decrease in the abrasive size. On the other hand, increase in the abrasive mass flow rate and water pressure led to an increase in the cut depths. Also it was observed that the stand-off distance had no discernible effect on the cut depths while stand-off distance and the traverse speed has more significant effects on the kerf widths. Statistically, it was found that the water pressure and the abrasive flow rate were most significant factors influencing the surface roughness of granites [2], [3], [4], [5].

Gokhan et al. [6] have analyzed the rock cutting performance of abrasive water jet using artificial neural network (ANN) considering the kerf angle (KA) as a performance criteria and operating variables like traverse speed, Stand-off Distance, and abrasive mass flow rate. They performed regression analysis done of granitic rock as a sample material. They found that both ANN and regression models can give adequate prediction for the KA with an acceptable accuracy level, with ANN model having more reliability. The Stand-off Distance and traverse speed were statistically determined as dominant operating variables on the KA, respectively.

Wei Zhao et al. [7] carried out research on the surface topography and microstructure of the cutting surfaces machined by AWJ on Four different kinds of ductile metallic materials 6061 Aluminum alloy, 304 Stainless steel, Q345, High-strength low alloy structural steel, CrWMn, Cold work mold steel. With the AWJ processing technique, smooth surfaces were easily obtained with a lower surface roughness about 2 to 3 μm. The results show that a smooth cutting surface is more easily obtained on hard materials, while erosions on soft material surfaces are more serious.

Experimental results for aluminum showed that water pressure was the most influencing factor for the surface roughness of granitic material. With an increase in water pressure, a decrease in surface roughness was noticed. Surface roughness constantly decreased as the mass flow rate was allowed to increase. As nozzle traverse speed increases, surface roughness increases.

Surface smoothness increase as Stand-off Distance decreases. When the effect of three different single mesh size abrasives were investigated, it was observed that the multi mesh size abrasives yielded higher single surface roughness than the single mesh size abrasives. Study of 6063-T6 aluminium alloy suggests that by maintaining the orifice size and focusing the nozzle size within certain limits, less taper on kerf can be achieved [8], [9], [10].

For glass/epoxy composites, hydraulic pressure is the most significant factor that influences surface roughness. For all the types of abrasives used, taper of cut decreased with an increase in the jet pressure [11], [12].

II. EXPERIMENTAL STUDY

A. *Materials and Method*

The experimental work was conducted on an abrasive water jet machine, model no. DWJ1525-FA at Yogesh Industries, Ahmedabad. Garnet 80 mesh (0.180 mm) was used as abrasive. Pre-sized granite sample having dimensions 300×300×14 mm was cut by the selected machine, considering its applications in architectural and artistic applications. Pictorial view of used machine is shown in Fig. 1. Material is tested before used for experiments in material testing laboratory at Modi Laboratory, Ahmedabad. Chemical composition obtained is as per Table 1. Machine specification is shown in Table 2.

Table – 1
Material Specification of Granite

Sr. No.	*Parameter*	*Result*
1	*Silicon Dioxide as SiO_2*	*72.33 %*
2	*Aluminium Oxide as Al_2O_3*	*12.25 %*
3	*Potassium Oxide as K_2O*	*4.02 %*
4	*Soda as Na_2O*	*4.02 %*
5	*Calcium Oxide as CaO*	*1.82 %*
6	*Iron as Fe_2O_3*	*1.22 %*
7	*Magnesia as MgO*	*0.71 %*
8	*Titanium Dioxide as TiO_2*	*0.33 %*
9	*Magnesium Oxide as MnO*	*2.77 %*
10	*Water Content*	*0.40 %*

Fig. 1: Setup of abrasive water jet machine

Table – 2
Machine Specification

Voltage	*415 V*
Frequency	*50 Hz*
Phases	*3*
Power	*3kW*
Current	*5.8A*
Table Size	*1600 x 2600 mm*

B. *Design of Experiments (DOE)*

DOE is a systematic technique for defining the relationship between the factors and the output parameters for any system or process. It also helps in finding out all the possible combinations of multiple factors in an experiment and to identify their best combination. Experiments were designed by one of the most popular method, Taguchi method, which involved an orthogonal array to organize the parameters affecting the process and the levels at which they should be varied. For this particular study, three control factors Traverse Speed (mm/min.), Water Pressure (MPa) and Stand-off Distance (mm) and their levels were considered, which are shown in Table 3.

Table – 3
Process parameters and their levels considered for the experimentation

Symbols	Control Factors	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
A	Traverse Speed	mm/min.	50	55	60	65	70
B	Stand-off Distance	mm	1	2	3	4	5
C	Water Pressure	MPa	200	210	220	230	240

From Taguchi's method DOE with three factors, a L25 orthogonal array table with 25 rows was selected.

III. Results and Discussion

A. *Results of Experiments*

Results for experiments are shown in Table 4.

Table – 4
Result table

Exp. No.	A	B	C	MRR (gm./min)	Surface Roughness (μm)
1	50	200	1	34.22	4.778
2	50	210	2	35.30	4.984
3	50	220	3	36.60	5.261
4	50	230	4	37.23	5.442
5	50	240	5	36.88	5.763
6	55	200	2	36.20	4.979
7	55	210	3	37.89	5.424
8	55	220	4	37.20	5.615
9	55	230	5	36.80	5.649
10	55	240	1	37.50	4.941
11	60	200	3	40.24	5.275
12	60	210	4	40.50	5.668
13	60	220	5	39.60	5.752
14	60	230	1	40.45	4.963
15	60	240	2	41.33	5.132
16	65	200	4	41.80	5.664
17	65	210	5	39.70	5.861
18	65	220	1	41.03	4.982
19	65	230	2	42.40	5.263
20	65	240	3	43.88	5.547
21	70	200	5	41.70	5.862
22	70	210	1	41.10	5.149
23	70	220	2	42.55	5.234
24	70	230	3	42.88	5.559
25	70	240	4	42.64	5.765

B. *Analysis of Variance (ANOVA)*

In the ANOVA, F_{ratio} determines that which the significant process parameters are. F_{ratio} is a tool, which checks significance of process factor on the response parameters of the specimens. Calculation of experimental results gives the F_{ratio} and then it is compared with the critical value. In case where F_{ratio} is larger than the $F_{critical}$ value, it is a clear indication that the statistical test is significant at the selected confidence level. If not, it indicates that the statistical test is not significant at the confidence level. In addition, larger F_{ratio} indicates that due to the variation of the process parameters, there is a considerable change on the performance characteristics [6]. At 95% of confidence level this analysis was carried out. Table 5 & 6 show the results of ANOVA for the selected Response parameters for the machined samples, respectively.

Table – 5
ANOVA table for MRR

	Source	DF	Sum of Squares	Mean Squares	F	% Contribution
MRR (gm/min)	A	4	153.623	38.406	106.8	87.75
	B	4	9.593	2.398	6.67	5.47
	C	4	7.537	1.884	5.24	4.30
	Error	12	4.315	0.36	-	1.27
	Total	24	175.068	-	-	100

Table – 6
ANOVA table for surface roughness

	Source	DF	Sum of Squares	Mean Squares	F	% Contribution
Surface Roughness (μm)	*A*	*4*	*0.23407*	*0.05852*	*20.89*	*8.88*
	B	*4*	*0.04335*	*0.01084*	*3.87*	*1.64*
	C	*4*	*2.32293*	*0.58073*	*207.36*	*88.19*
	Error	*12*	*0.03361*	*0.00280*	*-*	*1.27*
	Total	*24*	*2.63396*	*-*	*-*	*100*

Percentage of each factor contributing (P) to the total variation can be seen in Table 5 & 6, thus portraying the degree of influence on the final result and conclusions. P-values in the table are the most important observations.

From Table 5 & 6, it can be observed that the factor A (87.75%) showed a higher significant effect, followed by the factor B (5.47%) and the factor C (4.30%) for the MRR, whereas for the Surface Roughness, the factor C (88.19%) showed the highest significant effect, followed by A (8.88%) and B (1.64%).

C. *Effect of the Process Parameters on the MRR and Surface Roughness*

Main effect plot for MRR and Surface Roughness is shown in Fig. 2 & Fig. 3 respectively.

As the water jet passes at higher speed, less number of particles will be available which pass through a unit area. Thus, in unit area there will be lesser impacts and cutting edges available which will result in rougher surfaces. Consequently, the higher the traverse speed the higher the surface roughness for abrasive water jet machining. At higher traverse speed higher surface roughness is obtained while MRR is increased, but at the cost of higher surface roughness. It can be observed that at higher MRR there is higher Surface Roughness on the cut samples, which is not desirable.

At Higher water pressure there is increase in the kinetic energy of the individual particles inside the jet and it enhances their capability for the material removal. However, higher water pressure may also result in random particle collisions due to higher acceleration and also due to more energy disbursement from the abrasives to the area bombarded by the water jet, so rougher cut surfaces are obtained.

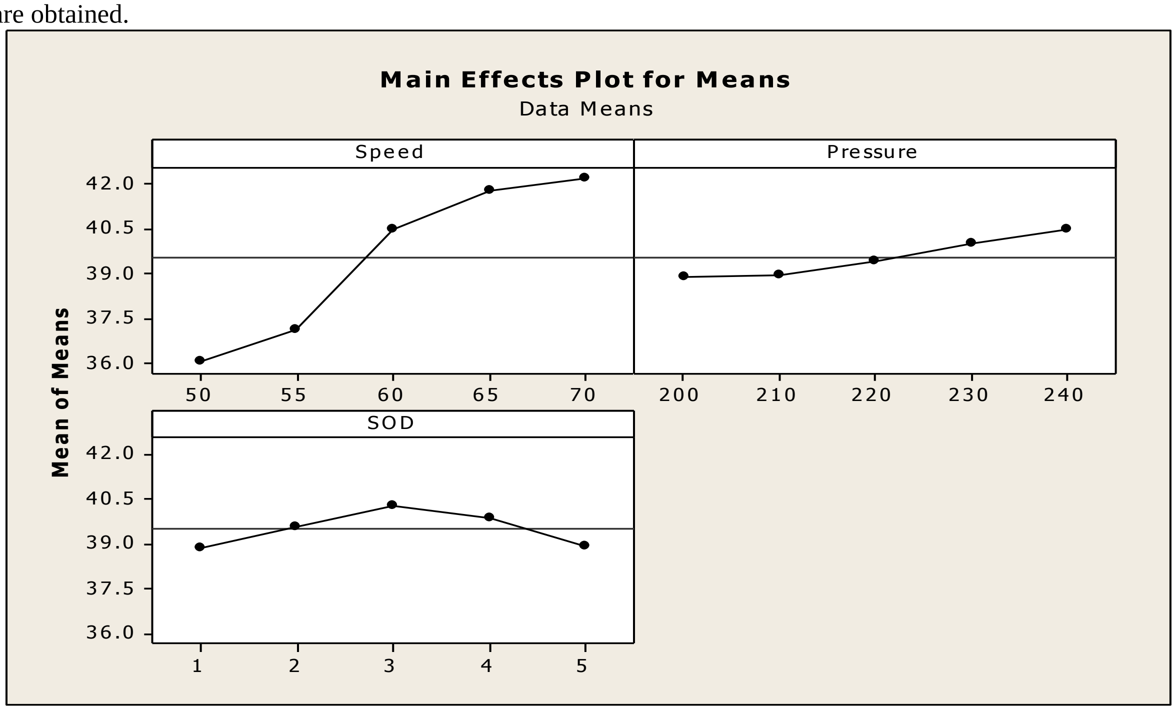

Fig. 2: Main effects plot for MRR

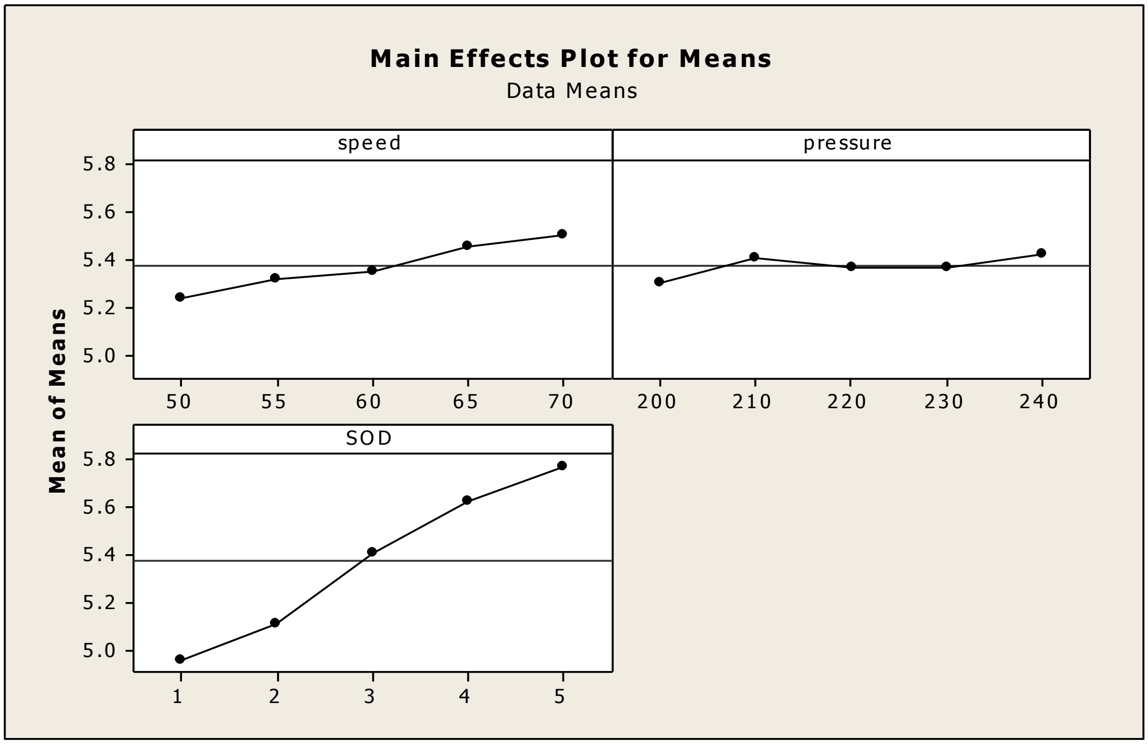

Fig. 3: Main effects plot for surface roughness

Basically, effective jet diameter is related to higher stand-off distances. That is, when the jet spreads out of the nozzle, it diverges and the effective jet diameter is reduced. Vulnerability to the external drag from the surrounding environment may also be increased. Consequently, increment in jet diameter or divergence in jet can easily lose its kinetic energy and may produce rougher surfaces as in our case 3, 4, 5 mm stand-off distance results in higher surface roughness while 1 and 2 mm stand-off distance results in lower surface roughness.

D. Multiple Linear Regression Models

The multiple regression analysis expresses a linear relationship between a response variable and two or more independent or predictor variables.

A multiple linear regression models were developed in order to predict the values of Material Removal Rate and Surface roughness of Granite work piece. The regression Model for the MRR and Surface roughness was generated with the help of MINITAB 16.

Regression model for MRR (gm/min):

$$\text{MRR (gm. /min.)} = 9.66 + 0.3380\,A + 0.0428\,B + 0.047\,C \quad (1)$$

Regression model for surface roughness (µm):

$$\text{Surface Roughness } (\mu m) = 3.49724 + 0.013564\,A + 0.00194\,B + 0.2142\,C \quad (2)$$

E. Comparison of Regression Model with Experimental Results

Table 7 shows that the error computed is very less so it can be deduced that the prepared Multiple Linear Regression Model is suitable for estimating MRR and Surface Roughness values.

Table – 7
Comparison of regression model with experimental results

Exp. No.	MRR (gm./min)			Surface Roughness (µm)		
	Experimental value	Regression model	Error	Experimental value	Regression model	Error
1	34.22	35.167	-0.947	4.778	4.75132	0.02668
2	35.30	35.642	-0.342	4.984	5.00768	-0.0237
3	36.60	36.117	0.483	5.349	5.26404	0.08496
4	37.23	36.592	0.638	5.442	5.52040	-0.0784
5	36.88	37.067	-0.187	5.763	5.77676	-0.0138
6	36.20	36.904	-0.704	4.979	5.06292	-0.0839
7	37.89	37.379	0.511	5.424	5.31928	0.10472
8	37.20	37.854	-0.654	5.615	5.57564	0.03936
9	36.80	38.329	-1.529	5.876	5.83200	0.044
10	37.50	38.569	-1.069	4.941	4.94416	-0.0032

11	40.24	38.641	1.599	5.275	5.37452	-0.0995
12	40.50	39.116	1.384	5.784	5.63088	0.15312
13	39.60	39.591	0.009	5.973	5.88724	0.08576
14	40.45	39.831	0.619	4.963	4.99940	-0.0364
15	41.33	40.306	1.024	5.132	5.25576	-0.1238
16	41.80	40.378	1.422	5.664	5.68612	-0.0221
17	39.70	40.853	-1.153	5.861	5.94248	-0.0815
18	41.03	41.093	-0.063	4.982	5.05464	-0.0726
19	42.40	41.568	0.832	5.263	5.31100	-0.0480
20	43.88	42.043	1.837	5.547	5.56736	-0.0204
21	41.70	42.115	-0.415	5.862	5.99772	-0.1357
22	41.10	42.355	-1.255	5.289	5.10988	0.17912
23	42.55	42.83	-0.280	5.234	5.36624	-0.1322
24	42.88	43.305	-0.425	5.994	5.62260	0.3714
25	42.64	43.78	-1.1400	5.765	5.87896	-0.1140

IV. CONCLUSION

Following points are inferred after the analysis of obtained experimental results:

- Traverse speed is the most affecting factor for MRR, followed by water pressure and stand-off distance.
- With increase in the traverse speed and water pressure, MRR increases significantly.
- MRR increases with the increase in SOD up to a certain extent and after that it starts decreasing which indicates towards an optimal SOD for this particular process and material.
- Stand-off distance is the most significantly affecting factor for Surface Roughness, followed by Traverse speed and Water Pressure.
- Higher level of all above process parameters results in higher Surface Roughness which is not desirable, from application point of view.
- The developed Multiple Linear Regression Model is found very adequate for all the responses because the error is found in an acceptable range on comparison with the experimental values.

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