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Parametric investigation on abrasive waterjet machining of alumina ceramic using response surface methodology

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Abstract. This research paper consists of machining of alumina ceramic done by abrasive waterjet technology. Ceramic is brittle in nature and has some distinctive properties such as heat resistant, high corrosion resistant and no thermal distortion but machining of these by other methods leads to complexity such as dimensional inaccuracy and tendency of brittle fracture. Abrasive waterjet can be used for machining of these materials due to no thermal distortion and lesser stress induction on work piece material. In this study response surface methodology involving box-Behnken design was applied to analyse the effects of process parameters like abrasive mass flow rate, water pressure and traverse speed over the output responses namely material removal rate, surface roughness and taper angle. ANOVA analysis was conducted to determine the significance of the model and regression equations were developed from the same. Multi objective optimisation of responses was done using desirability approach which gave optimal values of material removal rate as 53.051 mm3/min, surface roughness as 8.125 µm and 0.09134 of taper angle with input parameter level set at 38MPa of water pressure, 290 gm/min of abrasive flow rate and 210 mm/min of traverse speed simultaneously.

1. Introduction

Abrasive water jet machining got its roots into the world of advanced cutting technology during the early 1980s. It made its significance amongst the other cutting technology by its significant features of being independent of any electrical or thermal conductivity of the materials that lead to the machining of the materials which are not thermally or electrically conductive like ceramics, glass, etc. with precision. In Abrasive water jet machining, material removal is done by the action of high-velocity water and abrasive mixture jet that act upon the work piece using the principle of erosion and removal. In AWJM water is used which is pressurized up to 2800 bar. This pressurized water then enters at the top of the cutting nozzle and is forced through an orifice assembly. Pressured water is then accelerated to a high-speed jet with more than 600 m/min. This fast moving stream of water creates a suction that draws in the abrasives which are stored in the hopper installed on the moving head. Water along with abrasives enters into the mixing tube, abrasive bounce away due to the effect of buoyancy and drag force. They interact with the jet and the inner walls of the mixing tube until they are accelerated using the momentum of the water jet hence nozzles are made resistant to abrasion to avoid harm to the nozzle. The material used for nozzle is sapphire or tungsten carbide, sapphire has a longer working life than tungsten carbide. It is the mixing tube where they get mixed and forms an abrasive jet which is high-speed slurry at the bottom of the tube that is acted upon the material to be machined.

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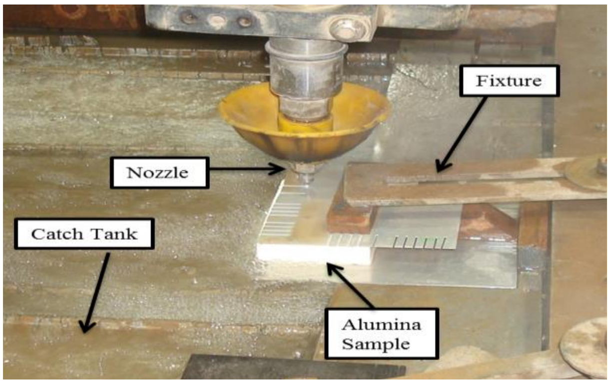

Figure 1. Abrasive waterjet machining at Al_2O_3 sample.

Alumina ceramics comes under the category of hard to machine materials. It has high corrosion resistance, resistance to oxidation. It remains stable at even high temperatures also and can retain its hardness at high temperatures. Alumina ceramics have wide area of applications as it's used in valves, ballistic armors, cutting tools, ceramic composite brakes and seals. They are also being used in biomedical field in form of artificial bones, joints and teeth.

While machining with conventional methods, large machining forces are induced in the material due to tool work piece contact. These forces lead to vibration and chattering of the work piece. Also, due to highly brittle nature of alumina ceramic, it exhibits a tendency of fracture that leads to material damage and may also give a poor surface quality. Its non- electrical conductivity and chemically inertness make it more difficult to machine with any other non- conventional processes. Abrasive water jet machining can be employed for machining of alumina ceramic as no direct contact of tool and work piece is present lead to lesser machining forces and negligible stresses induced. Further, due to cold cutting process, no thermal distortion occurs during machining. Further, due to flexibility of the process, it also cut any shape contours which are a difficult task with conventional machining.

Some of the works reported earlier in this field are discussed here. Wang J and Wong W C K [1] have carried experiments on metallic coated sheet steels using AWJM process to analyse the effect on kerf width. Hashish M [2] conducted experiments to study the effect of pressure on the power requirement. It was found that for same power consumption, high pressure is more efficient. Jegaraj J J R and Babu N R [3] studied the effect of various parameters on the machining responses. They concluded that kerf width, depth of cut and MRR could be optimized by varying input parameters whereas surface quality does not change significantly. Ma C and Deam R T [4] analysed the kerf geometry with the help of an optical microscope. It was observed that as the speed increased, kerf width decreased and kerf width increased at low cutting speeds. Khan A A and Haque M M [5] analysed AWJM of glass by using different abrasive particles. The results obtained showed that taper of cut increased with standoff distance due to water jet widening and it decreased with increase in pressure. Hascalik A, Çaydaş U and Gürün H [6] conducted experiments on titanium alloys to analyze the effect of traverse speed by AWJM process. Experiments concluded that traverse speed has an effect on the width of cut, and also SR along with kerf taper ratio increased with increased speed. Azmir M A and Ahsan A K [7] investigated abrasive water jet machining on glass/epoxy composite laminate. Influence of input parameters on SR and kerf width ratio was analysed. Taguchi method and ANOVA was used for optimization of the process. Aich U, Banerjee S, Bandyopadhyay A and Das P K [8] investigated the depth of cut by cutting borosilicate glass by AWJM. Results were analyzed using scanning electron microscopy (SEM). Shanmughasundaram P [9] conducted experiments to study SR of Al-graphite composites. Observations concluded that traverse speed and standoff distance is less significant parameters than water pressure. Ramprasad U G and Kamal H [10] conducted experiments over stainless steel 403. Taguchi and ANOVA method was used to analyse the results. Water pressure was found to be the most significant factor then standoff distance and AFR in descending order. By the literature studied, it was found that less amount of work has been reported on machining of ceramic material using AWJM. AWJM are also been used in machining of composite [11, 12], turning operation [13, 14], for surface treatment [15, 16] and for disintegration of rocks [17, 18]. In this research paper influence of water pressure, AFR and traverse speed are observed over the output responses such as MRR, taper angle and SR while machining alumina ceramic work material.

2. Materials and method

In this research paper, Alumina ceramic (Al_2O_3) of 18mm thickness and of 96mm in length and 55mm in width is selected for the experiments to be done using Abrasive water jet machining.

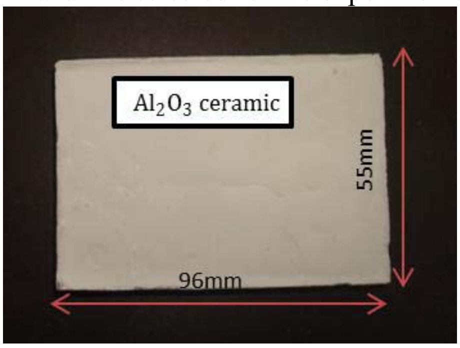

Figure 2. Al_2O_3 sample

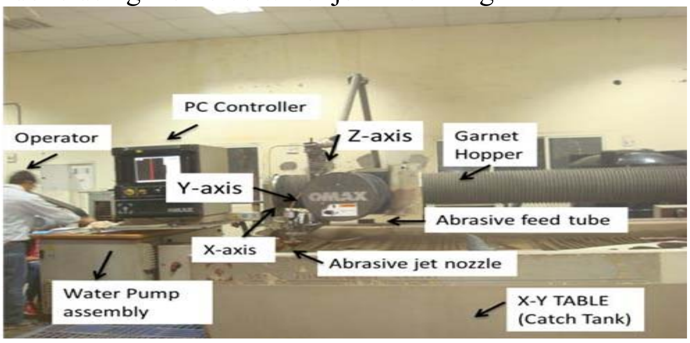

Figure 3. OMAX 55100 jet machining Centre

Experiments were performed on OMAX 55100 jet machining Centre. Abrasive particles garnet of 80 mesh size is used. Process parameters varied are water pressure, AFR and traverse speed of nozzle to see their effects on SR, taper angle and MRR. The levels of each parameter are taken after conducting pilot experiments over whole range of values available. Improper cut at different levels led to rejection of that level and levels with distinct and proper cut are used for final experiments.

Table 1. Parameters and levels taken for the experiment.

Parameter	Levels		
Water Pressure(MPa)	36	39	42
AFR(gm/min)	60	190	320
Traverse speed(mm/min)	210	255	300

Experimental runs are designed using RSM technique. The SR of each sample is measured using Surfcom-1900SD profilometer and taper angle of the cut was calculated using equation 1. Machining time for each experiment is noted down to calculate the MRR of each experimental run. ANOVA analysis is carried out on the obtained results to determine the factors influencing significantly on the output responses. Regression equations were modelled using the results obtained by the ANOVA analysis. Optimisation and confirmatory tests were carried out using desirability approach, and error between the predicted and actual values was reported.

$$Taper\ Angle = \tan^{-1}\frac{top\ kerf\ width - bottom\ kerf\ width}{2 \times sample\ thickness} \quad (1)$$

3. Results and discussion

All 15 experiments were conducted according to the design table given by RSM technique as listed in table 1. Results of Analysis of the output responses are shown in Table 2.

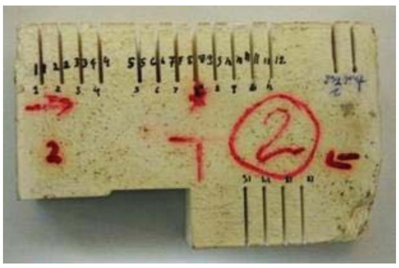

Figure 4. Sample after experiment

Table 2. ANOVA analysis of output responses.

(a)Surface roughness					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	8.40495	1.20071	90.01	0.000
Linear	3	6.90835	2.30278	172.63	0.000
Square	2	1.27943	0.63972	47.96	0.000
2-Way Interaction	2	0.21716	0.10858	8.14	0.015
Error	7	0.09338	0.01334		
Lack-of-Fit	5	0.04213	0.00843	0.33	0.863
Pure Error	2	0.05125	0.02562		
Total	14	8.49832			
S=0.115497, $\mathbf{R^2}$=98.90%, $\mathbf{R^2}$(adj) =97.80%, $\mathbf{R^2}$ (pred) =95.54%					

(b)Taper angle					
Model	6	0.045643	0.007607	96.08	0.000
Linear	3	0.043570	0.014523	183.43	0.000
Square	2	0.001816	0.000908	11.47	0.004
2-Way Interaction	1	0.000256	0.000256	3.23	0.110
Error	8	0.000633	0.000079		
Lack-of-Fit	6	0.000576	0.000096	3.38	0.246
Pure Error	2	0.000057	0.000028		
Total	14	0.046276			
S=0.0088982, $\mathbf{R^2}$=98.90%, $\mathbf{R^2}$(adj) =97.60%, $\mathbf{R^2}$(pred) =92.99%					

(c)Material Removal Rate (MRR)					
Model	6	372.931	62.155	171.01	0.000
Linear	3	259.085	86.362	237.61	0.000
Square	2	110.071	55.035	151.42	0.000
2-Way Interaction	1	3.775	3.775	10.39	0.012
Error	8	2.908	0.363		
Lack-of-Fit	6	2.573	0.429	2.57	0.307
Pure Error	2	0.334	0.167		
Total	14	375.839			
S=0.602877, $\mathbf{R^2}$ =99.23%, $\mathbf{R^2}$(adj) =98.65%, $\mathbf{R^2}$(pred) =96.44%					

Regression Equation for the Surface roughness:

$$SR = 7.11 + 0.3092 \times pressure + 0.00993 \times AFR - 0.0933 \times traverse\ speed + 0.000026 \times AFR \times AFR + 0.000211 \times traverse\ speed \times traverse\ speed - 0.000405 \times pressure \times AFR - 0.000029 \times AFR \times traverse\ speed \quad (2)$$

Regression Equation for the Taper Angle:

$$TA = 2.380 - 0.1244 \times pressure - 0.000505 \times AFR + 0.00279 \times traverse\ speed + 0.001326 pressure \times pressure - 0.000009 \times traverse\ speed \times traverse\ speed + 0.000059 \times pressure \times traverse\ speed \quad (3)$$

Regression Equation for the MRR:

$$MRR = 50.6 + 2.533 \times pressure + 0.12928 \times AFR - 0.544 \times traverse\ speed - 0.000256 \times AFR \times AFR + 0.001474 \times traverse\ speed \times traverse\ speed - 0.00720 \times pressure \times traverse\ speed \quad (4)$$

The output responses were plotted with respect to the input parameters to observe their effect on the output responses.

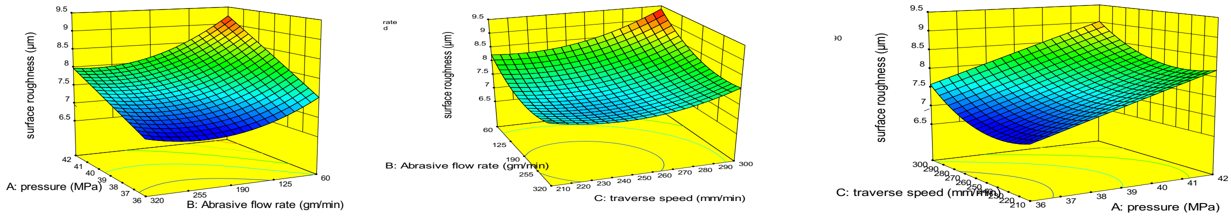

Figure 5. Surface Roughness plot with pressure, traverse speed and abrasive flow rate.

Figure 5 shows that highest SR value of 9.326µm was obtained at 42MPa pressure, 255mm/min traverse speed and 60gm/min AFR and lowest value of SR 6.82µm obtained at 36MPa pressure, 255mm/min traverse speed and 320 gm/min AFR. It was observed that on increasing pressure, SR increases as the kinetic energy of the particles gets increased that result in the increased random motion of the individual abrasive particles which further leads to the increase in SR. Increasing the traverse speed, SR showed an increment in value, due to increased nozzle speed which causes less interaction between the jet and the work piece surface and effective erosion does not occur resulting in a rougher surface. However, on increasing AFR, SR decreases as more number of impacts by abrasive particle on the work piece surface increases.

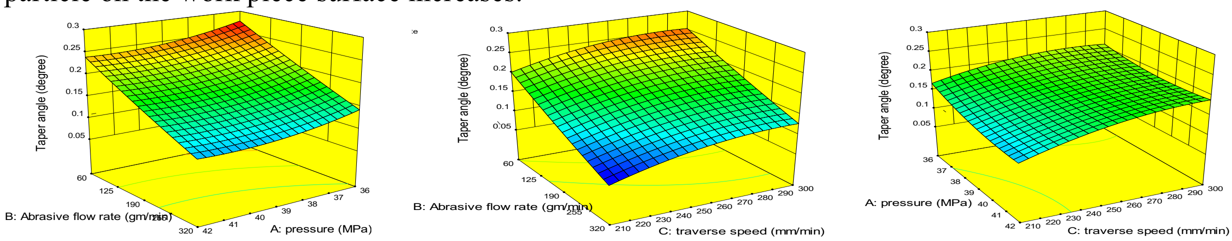

Figure 6. Taper angle plot with pressure, traverse speed and abrasive flow rate.

Figure 6 depicts that the largest taper angle was found to be 0.2789^0 at 36MPa pressure, 60gm/min and 255mm/min traverse speed and lowest value of taper angle equals to 0.076^0 at 39MPa, 320gm/min, 210mm/min. Analysis showed that increasing pressure, taper angle increases as above stated that at high water pressure, the kinetic energy of abrasive particles increases which easily overcomes the penetration resistance offered by the thickness of the material. On increasing traverse speed, taper angle increases because of less interaction time with material. It also leads to poor dimensional accuracy on increasing the traverse speed. Effect of increasing AFR resulted in a decrease of taper angle because a large number of abrasive particles interact with the material. The loss in energy rate of the particles is less in high AFR in comparison with less AFR hence resulting in approximately uniform cross-section.

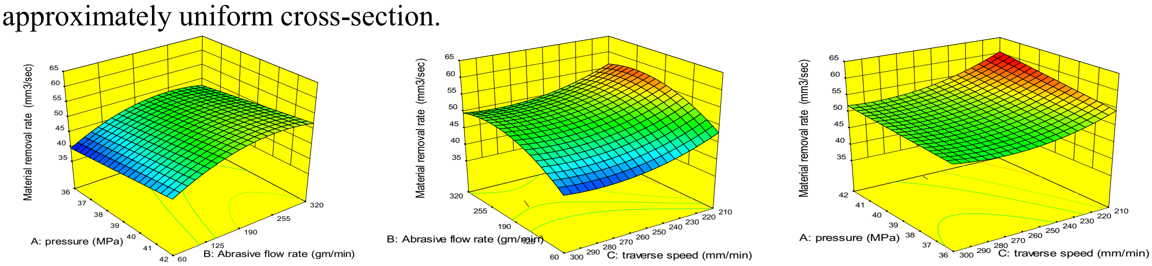

Figure 7. Material removal rate plot with pressure, traverse speed and abrasive flow rate.

Figure 7 depicts that the highest MRR value achieved is $59.567mm^3/sec$ corresponding to 42MPa pressure, 210mm/min traverse speed and 190 gm/min AFR whereas the lowest value of MRR obtained is $39.117mm^3/sec$ associated with 36MPa pressure, 255mm/min traverse speed and 60gm/min. MRR in AWJM is associated with removal of material with slurry, when abrasive mixed with, water causes shearing along with associated trowelling action of abrasive particles. Hence if abrasive particles get more time for reciprocal action with the material it gives high MRR, therefore with low traverse speed

MRR increases. On increasing AFR, MRR increases due to more interacting abrasive particles at a time. It was also observed that on increasing pressure, MRR increases as above stated the fact that random motion increases of the abrasive particles hence they are in more reciprocal action with the material resulting in increased MRR.

Optimization of the output responses are carried out using desirability approach. The Table 3 shows the optimal level of the machining parameters and optimal values obtained after confirmatory test of the output responses obtained by desirability approach. The minimal error value calculated showed the difference in the values of the predicted and actual values obtained by the experiments. The results concluded that the regression equations formulated holds a good relation with the actual values within the selected parametric domain.

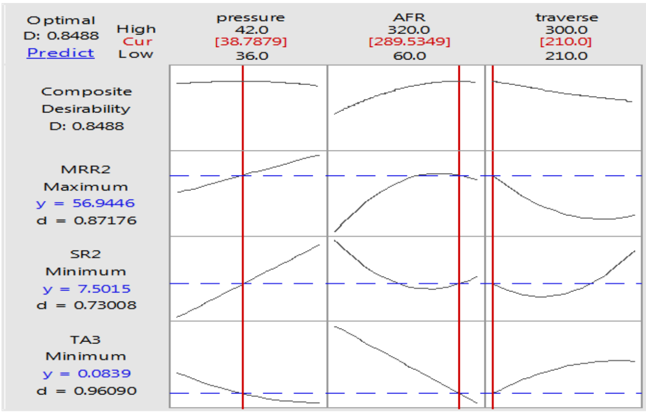

Figure 8. Multi objective optimization plot

Table 3. Optimal values of parameter and their responses.

Output response	Pressure	AFR	Traverse speed	Predicted values	Actual values	% error
MRR	42	251	210	60.570 mm^3/sec	56.250 mm^3/sec	7.132
SR	36	228	237	6.665μm	7.202 μm	8.059
Taper angle	42	320	210	0.0529^0	0.0577^0	9.240
MRR, SR, taper angle	38	289	210	56.944 mm^3/sec,7.501 μm, 0.0839^0	53.051 mm^3/sec,8.125 μm, 0.09134^0	6.836, 8.324, 8.867

4. Conclusion

1. Present study showed that machining alumina ceramic with AWJM can be done without any significant brittle fracture and also with better dimensional accuracy.
2. ANOVA analysis of the output responses were performed which showed that all the input parameters selected such as pressure, traverse speed AFR significantly affected the output responses.
3. An increase in MRR was obtained with increase in pressure and AFR along with decrease in traverse speed. SR increased with increase in pressure and decrease in AFR and traverse speed. Taper angle increased with decrease in pressure and AFR along with increase in traverse speed.
4. Optimal value of MRR, SR and TA obtained after multi objective optimization of responses at optimal level of parameters suggested by desirability approach were 53.051mm^3/sec, 8.125μm and 0.09134^0.

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