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

Tanmay Tiwari¹, Saket Sourabh¹, Akash Nag¹, Amit Rai Dixit¹, Amitava Mandal¹, Alok Kumar Das¹, Niladri Mandal², Ashish Kumar Srivastava¹

¹Department of Mechanical Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, India
²Defence Research and Development Laboratory, Kanchanbagh, Hyderabad 500058, Telangana, India
³Department of Mechanical Engineering, Noida Institute of Engineering & Technology, G.B Nagar, 201301, India

tnmymac@gmail.com

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.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
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). Shanmugasundaram 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.

**Figure 1.** Abrasive waterjet machining at Al₂O₃ sample.
2. Materials and method

In this research paper, Alumina ceramic (Al₂O₃) 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.

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.

| 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.

\[
Taper\ Angle = \tan^{-1}\left(\frac{\text{top kerf width} - \text{bottom kerf width}}{2 \times \text{sample thickness}}\right)
\]

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.
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, $R^2=98.90\%$, $R^2$ (adj) =97.80%, $R^2$ (pred) =95.54%

(b)Taper angle

| Source                | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|-----------------------|----|----------|----------|---------|---------|
| 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, $R^2=98.90\%$, $R^2$ (adj) =97.60%, $R^2$ (pred) =92.99%

(c)Material Removal Rate (MRR)

| Source                | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|-----------------------|----|----------|----------|---------|---------|
| 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, $R^2=99.23\%$, $R^2$ (adj) =98.65%, $R^2$ (pred) =96.44%

Regression Equation for the Surface roughness:

\[ SR = 7.11 + 0.3092 \times pressure + 0.00993 \times AFR - 0.0933 \times traverse speed + 0.000026 \times AFR \times AFR + 0.000211 \times \text{traverse speed} \times \text{traverse speed} - 0.000405 \times \text{pressure} \times \text{AFR} - 0.000029 \times AFR \times \text{traverse speed} \]

(2)

Regression Equation for the Taper Angle:

\[ TA = 2.380 - 0.1244 \times \text{pressure} - 0.000505 \times \text{AFR} + 0.00279 \times \text{traverse speed} + 0.001326 \times \text{pressure} \times \text{pressure} - 0.000009 \times \text{traverse speed} \times \text{traverse speed} + 0.000059 \times \text{pressure} \times \text{traverse speed} \]

(3)

Regression Equation for the MRR:

\[ MRR = 50.6 + 2.533 \times \text{pressure} + 0.12928 \times \text{AFR} - 0.544 \times \text{traverse speed} - 0.000256 \times AFR \times AFR + 0.001474 \times \text{traverse speed} \times \text{traverse speed} - 0.00720 \times \text{pressure} \times \text{traverse speed} \]

(4)

The output responses were plotted with respect to the input parameters to observe their effect on the output responses.
IOP Conf. Series: Materials Science and Engineering 377 (2018) 012005 doi:10.1088/1757-899X/377/1/012005

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 0.27890 at 36MPa pressure, 60gm/min and 255mm/min traverse speed and lowest value of taper angle equals to 0.0760 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 59.567mm³/sec corresponding to 42MPa pressure, 210mm/min traverse speed and 190 gm/min AFR whereas the lowest value of MRR obtained is 39.117mm³/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 mm³/sec   | 56.250 mm³/sec| 7.132   |
| SR              | 36       | 228 | 237            | 6.665µm          | 7.202 µm      | 8.059   |
| Taper angle     | 42       | 320 | 210            | 0.0529⁰          | 0.0577⁰       | 9.240   |
| MRR, SR, taper angle | 38   | 289 | 210            | 56.944 mm³/sec, 7.501 µm, 0.0839⁰ | 53.051 mm³/sec, 8.125 µm, 0.09134⁰ | 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 53.051 mm³/sec, 8.125 µm and 0.09134⁰.
References

[1] Wang J and Wong W C K 1999 A study of abrasive waterjet cutting of metallic coated sheet steels Int. J. Mach. Tools Manuf. 39 855–70

[2] Hashish M 2002 Observations on cutting with 600-MPa waterjets Trans. Soc. Mech. Eng. J. Press. Vessel Technol. 124 229–33

[3] Jegaraj J J R and Babu N R 2005 A strategy for efficient and quality cutting of materials with abrasive waterjets considering the variation in orifice and focusing nozzle diameter Int. J. Mach. Tools Manuf. 45 1443–50

[4] Ma C and Deam R T 2006 A correlation for predicting the kerf profile from abrasive water jet cutting Exp. Therm. Fluid Sci. 30 337–43

[5] Khan A A and Haque M M 2007 Performance of different abrasive materials during abrasive water jet machining of glass J. Mater. Process. Technol. 191 404–7

[6] Hasçalık A, Çaydaş U and Gürün H 2007 Effect of traverse speed on abrasive waterjet machining of Ti-6Al-4V alloy Mater. Des. 28 1953–7

[7] Azmir M A and Ahsan A K 2009 A study of abrasive water jet machining process on glass/epoxy composite laminate J. Mater. Process. Technol. 209 6168–73

[8] Aich U, Banerjee S, Bandyopadhyay A and Das P K 2014 Abrasive water jet cutting of borosilicate glass Procedia Mater. Sci. 6 775–85

[9] Shanmughasundaram P 2014 Influence of abrasive water jet machining parameters on the surface roughness of eutectic al-si alloy–graphite composites Mater. Phys. Mech. 19 1–8

[10] Ramprasad U G and Kamal H 2015 Optimization MRR of Stainless steel 403 in abrasive water jet machining using ANOVA and Taguchi method Int. J. Eng. Res. Appl. 5 86–91

[11] Srivastava A K, Nag A, Dixit A R, Tiwari S, Scucka J, Zelenak M, Hloch S and Hlavacek P 2017 Surface integrity in tangential turning of hybrid MMC A359/B 4 C/Al 2 O 3 by abrasive waterjet J. Manuf. Process. 28 11–20

[12] Mardi K B, Dixit A R, Mallick A, Pramanik A, Balloko B, Hvizdos P, Foldyna J, Scucka J, Hlavacek P and Zelenak M 2017 Surface integrity of Mg-based nanocomposite produced by Abrasive Water Jet Machining (AWJM) Mater. Manuf. Process. 1–8

[13] Nag A, Srivastava A K, Dixit A R, Chattopadhyaya S, Mandal A, Klichová D, Hlaváček P, Zelenák M and Hloch S 2018 Influence of Abrasive Water Jet Turning Parameters on Variation of Diameter of Hybrid Metal Matrix Composite Applications of Fluid Dynamics (Springer) pp 495–504

[14] Nag A, Ščučka J, Hlavacek P, Klichová D, Srivastava A K, Hloch S, Dixit A R, Foldyna J and Zelenak M 2017 Hybrid aluminium matrix composite AWJ turning using olivine and Barton garnet Int. J. Adv. Manuf. Technol. 1–8. doi: https://doi.org/10.1007/s00170-017-1036-0

[15] Srivastava M, Tripathi R, Hloch S, Rajput A, Khublani D, Chattopadhyaya S, Dixit A R, Foldyna J, Adamčík P and Klich J 2018 Surface Treatment of AISI 304 Using Pulsating Water Jet Peening Applications of Fluid Dynamics (Springer) pp 535–48

[16] Srivastava M, Tripathi R, Hloch S, Chattopadhyaya S and Dixit A R 2016 Potential of using water jet peening as a surface treatment process for welded joints Procedia Engineering vol 149

[17] Tripathi R, Srivastava M, Hloch S, Adamčík P, Chattopadhyaya S and Das A K 2016 Monitoring of acoustic emission during the disintegration of rock Procedia Engineering vol 149

[18] Tripathi R, Srivastava M, Hloch S, Chattopadhyaya S, Das A K, Pramanik A, Klichová D and Adamcik P 2018 Performance Analysis of Pulsating Water Jet Machining During Disintegration of Rocks by Means of Acoustic Emission Applications of Fluid Dynamics (Springer) pp 515–24