Machining alumina plates using abrasive jet of silicon carbide

D K Adak¹, P Dutta², S Das³ and B Haldar⁴

¹ Department of Mechanical Engineering, College of Engineering and Management, Kolaghat, Purba Medinipur –700106, West Bengal, India.
² &³ Department of Mechanical Engineering, Kalyani Govt. Engineering College, Kalyani, Nadia-741235, West Bengal, India.
⁴ Mechanical Engineering Department, College of Engineering, Al Imam Mohammad Ibn Saud Islamic University, PO Box: 5701, Riyadh- 11432, Kingdom of Saudi Arabia.
E-mail: sdas.me@gmail.com

Abstract. The abrasive jet machining (AJM) is used in many engineering applications including brittle material machining and finishing, surface preparation of the metal for welding and thermal spray coatings, etc. In this process, fine grain abrasive particles are given high speed through carrier gas which is directed to impinge on a target surface to be machined. The high kinetic energy of the abrasive particles is responsible to erode materials from the surface. In this work, three input cutting parameters such as abrasive flow rate, abrasive grain size, and stand-off distance (SOD) are chosen to experiment on 99.7% pure alumina plate of 4 mm thickness, using silicon carbide (SiC) abrasive. Material removal rate (MRR) and nozzle wear rate are the output responses that are to be investigated using response surface methodology, keeping working pressure constant at 6 kgf/cm² throughout.

Keywords: Abrasive Jet Machining, Material removal rate, Abrasive grain size, Abrasive flow rate, Stand-off distance, Response surface methodology.

1. Introduction
Superior quality sintered ceramic materials are now in use for various industrial applications. Uses of alumina (Al₂O₃) parts are in biomedical implants (hip and knee joints), ballistic protection components, ceramic seals, corrosion and wear protection linings, etc. [1]. Material removal in a brittle material was proposed [2] to be due to solid particle impact. Fracture toughness and hardness of workpiece was found to be critical parameters affecting MRR in Abrasive Jet Machining (AJM).

AJM process is capable of providing higher tolerance and greater surface finish [4]. It was invented a few decades ago, but still, several research works are being continued [5] towards its advancement. Wakuda et al. [6] examined the response of using different abrasive particles like aluminum oxide, silicon carbide (of moderate hardness), and Synthetic Diamond (SD) on alumina ceramic material, whereas Xu et al. [7] investigated the Abrasive Water Jet (AWJ) cutting of alumina ceramics with controlled nozzle oscillation. They found cutting at small nozzle oscillation angles could increase the depth of cut by as much as 82%. A statistical model was developed [8] for prediction and process optimization of micro-abrasive intermittent jet machining. Similar work was also done [9] to increase the efficiency of a jet in micro-grooving process. Hot air AJM was also carried out [10] to enhance MRR. The air temperature was found responsible for higher MRR and roughening of the machined surface due to plastic deformation accompanied by brittle fracture. Srikanth et al. [11] investigated the MRR and kerf characteristics by the AJM process using tungsten carbide nozzle by varying process parameters on glass, granite, and ceramic sheets. Results obtained by Taguchi were nearly close to that of ANOVA. Wear resistance for AJM and WAJM nozzles could be increased [12] by using porous cylindrical nozzle inserts, while some others investigated [13] on AJM of alumina using a fluidized bed, SiC abrasive and response surface methodology (RSM) to perform the experiment. AJM.
performance on porcelain tiles, soda-lime glass and soda-lime laminated glass [14, 15] was explored on an indigenously made system using SiC and common silica sand.

AJM has its inherent advantages, but still has many challenges to overcome, such as pollution issues, homogeneous mixing of air and abrasive, maintaining a set exit flow rate of abrasive, etc. In this investigation, an indigenously made AJM setup is used to optimize MRR and nozzle wear by setting suitable mass flow rate, abrasive grain size and SOD using SiC while machining alumina plate.

2. Experimental Investigation
The experiment is carried out on 99.7 % pure alumina plate. As per the RSM matrix, experiments are carried out with three levels of three parameters i.e. stand-off distance, mass flow rate, grain size as shown in Table 1. The pressure is kept constant at 6 kgf/cm² during all experiments. The nozzle is made from stainless steel with 10 mm inlet diameter, 2 mm outlet diameter and 20 mm in length.

![Figure 1 Close view of nozzle and alumina plate](image1)

![Figure 2 Flow rate calibration graph of silica sand at 6 kgf/cm²](image2)

| Table 1 Process parameter used in experiments at 6 kgf/cm² pressure |
|---------------------------------------------------------------|
| Parameters (Coded value) | Level 1 (-1) | Level 2 (0) | Level 3 (1) |
| Stand off distance (mm) | 2          | 3          | 4          |
| Grain size (µm)        | 100        | 150        | 200        |
| Flow rate(gm/min)      | 120        | 130        | 140        |

2.1 Flow Rate calibration of Silicon Carbide
To calculate the abrasive flow rate, a constant mass of 50 gm SiC passed through an abrasive flow controller. Required abrasive flow rate obtained by controlling rotational RPM of the flow controller. The graph of the abrasive flow rate with the variation of rotor RPM of the flow controller is presented in Figure 2. The flow rate is directly proportional to the rotor RPM of the flow controller that is expected as per the design of the abrasive flow controller. It is observed that flow characteristic lines of 150 µm and 200 µm abrasive sizes are closer than 100 µm size of abrasive. This may be due to higher adhesive force between smaller grain sizes of abrasive grains and the flow passage wall. This plot of flow characteristic line guides to opt for any intermediate abrasive flow rate.

2.2 Procedure for Experiments
Experiments are conducted as per the design matrix as obtained from RSM and the Box-Behnken Design matrix. In these experiments, silicon carbide (SiC) with three different grain sizes are used as abrasive particles. With 20 sec of machining time, blind cavities are formed in the workpieces for calculating MRR and nozzle wear rate. Changes in nozzle diameter are measured by digital Vernier calipers. Nozzle wear is measured by taking the weight of the nozzle after each experiment.

3. Results and Discussions
3.1 Results and Discussion for MRR
Regression analysis has been done on MRR results obtained in the experiments conducted at 6 kgf/cm² pressure. The regression equation of MRR corresponds to linear and quadratic input parameter interaction is evaluated and shown in equation (1).
MRR = -5.12 + 0.00458 \times D + 0.323 \delta + 0.0689 \dot{m} - 0.000015 \ D^2 - 0.01405 \delta^2 - 0.000250 \dot{m}^2 - 0.000072 \ D \times \delta + 0.000001 \ D \times \dot{m} - 0.001713 \delta \times \dot{m} \tag{1}

where, \( D \) = grain size, \( \dot{m} \) = mass flow rate, \( \delta \) = SOD

### Table 2 Analysis of Variance for MRR

| Source                | DF | Adj SS    | Adj MS    | F-Value | P-Value |
|-----------------------|----|-----------|-----------|---------|---------|
| Model                 | 9  | 0.009645  | 0.001072  | 5.19    | 0.042   |
| Linear                | 3  | 0.001268  | 0.000423  | 2.05    | 0.226   |
| \( D \)               | 1  | 0.000368  | 0.000368  | 1.78    | 0.239   |
| \( \delta \)          | 1  | 0.000191  | 0.000191  | 0.92    | 0.380   |
| \( \dot{m} \)         | 1  | 0.000709  | 0.000709  | 3.44    | 0.123   |
| Square                | 3  | 0.007150  | 0.002383  | 11.55   | 0.011   |
| \( D \times D \)      | 1  | 0.004982  | 0.004982  | 24.14   | 0.004   |
| \( \delta \times \delta \) | 1 | 0.000729  | 0.000729  | 3.53    | 0.119   |
| \( \dot{m} \times \dot{m} \) | 1 | 0.002301  | 0.002301  | 11.15   | 0.021   |
| 2-Way Interaction     | 3  | 0.001227  | 0.000409  | 1.98    | 0.235   |
| \( D \times \delta \) | 1  | 0.000051  | 0.000051  | 0.25    | 0.639   |
| \( D \times \dot{m} \) | 1  | 0.000002  | 0.000002  | 0.01    | 0.929   |
| \( \delta \times \dot{m} \) | 1 | 0.001174  | 0.001174  | 5.69    | 0.063   |
| Error                 | 5  | 0.001032  | 0.000206  |         |         |
| Lack-of-Fit           | 3  | 0.001032  | 0.000344  | 3684.45 | 0.000   |
| Pure Error            | 2  | 0.000000  | 0.000000  |         |         |
| Total                 | 14 | 0.010677  |           |         |         |

The analysis of variance (ANOVA) shown in Table 2, is used to analyze the effect of individual and interactive parameters on MRR. Statistical analysis software, Minitab 17 is utilized to tabulate experimental results at a 95% confidence level. Small values of \( p \) for interactions of SOD and mass flow rate (\( p = 0.063 \)) and the squared terms of grain size (\( p = 0.004 \)) and mass flow rate (\( p = 0.021 \)) correspond to a good correlation with the response. The correlation coefficient, \( R^2 \) of the regression model for MRR has a value of 90.34% which is greater than 90%, and so, the model is valid and parameters are significant. This is also supported by the small \( p \)-value of 0.042 of the model. Observed contour and surface plots of MRR with respect to interactive input parameters at 6 kgf/cm\(^2\) pressure are shown Figure 3 and Figure 4.

![Figure 3 Contour plot of MRR with variation in grain size and SOD](image1)

![Figure 4 Surface plot of MRR with variation in grain size and SOD](image2)

![Figure 5 Contour plot of MRR with variation in grain size and flow rate](image3)
In Figure 3 and Figure 4, MRR varies with SOD and grain size keeping flow rate constant at 130 gm/min. It is observed that MRR gradually increases with the use of bigger grain size and attains maximum MRR when grain sizes are within 145-165µm. The MRR then decreases with further large size particles. It may be because larger grain sizes transfer more impact energy up to a certain level at the constant air pressure, and cause more minute brittle fractures of work material thereby removing more materials from the work surface. Further increase in grain size may likely cause fewer impacts of the particles on the unit work surface area and higher intra-grain impacts thereby losing energy of impact on to the work surface within a certain time resulting in decreasing MRR. MRR gradually increases with the increment of SOD and attains a maximum value near 3mm then MRR decreases with a further increase in SOD. Initially, with the increase of SOD, abrasive particles get sufficient displacement to be accelerated before striking the work surface, but after passing a certain SOD, velocity is reduced due to normal air resistance and flow becomes divergent. Because of these, high SOD beyond a value causes less impact on the work surface, decreasing MRR.

Surface and contour plots of MRR with the variation of flow rate and grain size at a constant SOD of 3 mm are depicted in Figure 5 and Figure 6 respectively. It is observed that MRR is maximum within 145-165µm grain sizes and decreases when it goes further left or right like before. At the flow rate of between 125 gm/min and 130 gm/min above 160µm grain sizes, it gives maximum MRR, and it gradually decreases if the flow rate increases further. For smaller grain-size particles, MRR decreases with increasing flow rate because when flow rate increases, more particles are likely to collide with each other and may lose their energy.

In Figure 7 and Figure 8, variation of MRR is shown concerning flow rate and SOD by contour and surface plots respectively keeping grain size constant at 150 µm. These figures show that MRR is maximum with a SOD in between 2.75-4 mm and a flow rate within 122-132 gm/min. It can be said that within a higher range of SOD, abrasive particles get sufficient length to accelerate to increase the kinetic energy of the particles with increasing SOD thereby increasing MRR. The above observations also show that change in MRR is more rapid towards lower abrasive flow rate and higher SOD.

3.2 Results and Discussion for Nozzle Wear

In some experiments with the same input parameters, stainless steel nozzles wears are calculated and a regression model is developed for nozzle wear.

| Source     | DF | Adj SS      | Adj MS      | F-Value | P- Value |
|------------|----|-------------|-------------|---------|----------|
| Model      | 9  | 0.000056    | 0.000006    | 7.48    | 0.019    |
| Linear     | 3  | 0.000012    | 0.000004    | 4.81    | 0.062    |
| D          | 1  | 0.000004    | 0.000000    | 4.47    | 0.088    |
| δ          | 1  | 0.000000    | 0.000008    | 0.08    | 0.788    |
| m          | 1  | 0.000008    | 0.000009    | 9.89    | 0.026    |
| Square     | 3  | 0.000026    | 0.000026    | 10.60   | 0.013    |

Table 3 Analysis of Variance for Nozzle Wear
Analysis of variance (ANOVA) shown in Table 3, is also done at a confidence level of 95%. Small p values of mass flow rate (p = 0.026), the squared terms of grain size (p = 0.002), and interactions of grain size and SOD (p = 0.007) show that there is a curvature in the response surface. The correlation coefficient R-sq for nozzle wear has a value of 93.17% which reveals that the modeled equation is significant; this is also validated by the small model p-value of 0.019. The regression equation for nozzle wear rate (WR) is given in Equation (2).

\[
WR = -0.0941 + 0.000543D - 0.00213\delta + 0.00105\dot{m} - 0.000001D^2 - 0.000197\delta^2 - 0.000005\dot{m}^2 - 0.000039D\times\delta - 0.000001D\times\dot{m} + 0.000072\delta\times\dot{m}
\]

where, WR = nozzle wear rate, D = grain size, \(\dot{m}\) = mass flow rate, \(\delta\) = SOD

In Figure 9 (contour plot) and Figure 10 (surface plot), variation of nozzle wear rate concerning grain size and SOD is shown, keeping flow rate constant at 130 gm/min. From the above graphical representation, it is observed that nozzle wear increases with increasing grain sizes and attains the maximum value between 152µm-195µm grain sizes with 2 mm SOD. With the increase of SOD, nozzle wear rate increases more rapidly with the same grain sizes and attains a maximum with 127µm-
152µm grain size and at 4 mm SOD; after that nozzle wear rate decreases. Increase of SOD increases abrasive velocity up to an extent, thus increasing nozzle wear rate even with small grain sizes.

Variation of nozzle wear concerning grain size is more significant at higher SOD. With lower grain size, nozzle wear rate increases with SOD. But with higher grain size, nozzle wear rate decreases as SOD increases. Due to less dragging effect with smaller grain size, nozzle wear rate increases with SOD may be because of velocity enhancement. Similarly, more dragging effect may have reduced the velocity of higher grain size particles, thus reducing nozzle wear rate.

In the contour and surface plots (Figure 11 and Figure 12), variation of nozzle wear rate with mass flow rate and SOD are shown when grain size of 150µm is constant. It is observed that nozzle wear rate decreases rapidly with increasing mass flow rate at lower SOD. At higher SOD, the rate of wear decreases slowly with mass flow rate. At a lower mass flow rate, nozzle wear rate decreases slowly as SOD increases. At the higher mass flow rate, nozzle wear rate increases as SOD increases. Nozzle wear rate becomes maximum when both mass flow rate and SOD are minimum (120-121 gm/min and 2-2.2 mm respectively). High mass flow rate reduces abrasive velocity and nozzle wear at low SOD.

In Figure 13 and Figure 14, contour and surface plots of nozzle wear rate with varying grain size and mass flow rate are shown keeping SOD constant at 3mm. Nozzle wear rate initially increases with increasing grain size and after a certain limit, it decreases with increasing grain size. With the same grain size, nozzle wear rate decreases as the mass flow rate increases. At a higher mass flow rate, nozzle wear rate shows a reducing trend with grain size increment. Initially nozzle wear rate increases as grain size increases due to higher plowing, but as grain size increases, may be due to dragging effect, wear rate reduces. Similarly when mass flow rate increases, nozzle wear rate also decreases.

4 Conclusions

- With increasing grain size at the constant mass flow rate, MRR and nozzle wear both are initially increased and then decreased. With increasing mass flow rate, initially, MRR increases but then decreases, but the nozzle wear rate decreases. The primary reason for nozzle wear is plowing and striking with the rebounding particle, rather than friction with nozzle surface.
- The flow becomes divergent with increasing SOD as a result the rebounding of the abrasive particle is decreased with increasing SOD. The abrasive grain size and mass flow rate are having significant effects on the nozzle wear rate as compared to SOD.

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