Material removal rate in AJM of zirconia ceramic using silicon carbide abrasive: Investigation, modelling, and optimization

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Abstract. This research focuses on material removal rate in abrasive jet machining (AJM) of zirconia ceramic under varying process conditions (grain size of silicon carbide abrasive, air pressure, stand-off-distance). Combined approach of orthogonal array, and response surface methodology are respectively, applied for assessment, predictive modelling as well as response optimization. The influence of air pressure emerged as the most critical factor in enhancing MRR during AJM of zirconia ceramic. At elevated pressures, the surface morphology exhibits characteristic deep chipping and larger crater marks. The proposed predictive model for MRR utilizing the regression method proves effective, demonstrating adequacy, statistical significance, and probabilistic validation, indicated by its high R^2-value (0.995), P-value below 0.05 (0.016), and substantial AD-test P-value (0.327). By employing DFA to solve the response optimization problem, optimal MRR (0.0000619 gm/min) for AJM of zirconia ceramic is achieved at abrasive grain size of 750 µm, air pressure of 7 kgf/cm^2, and stand-off distance of 2 mm.

1 Introduction

Science and technology continuously evolve to discover advanced materials and alloys characterized by high hardness, strength, and lightweight properties. Conventional machining processes struggle to handle these materials, requiring advanced manufacturing methods for precision and accuracy. Zirconia ceramic products with intricate designs are in high demand, achievable only through advanced manufacturing. Among over twenty non-traditional manufacturing processes developed over the past six decades, abrasive jet machining stands out as an effective approach for machining brittle materials like ceramics, glass, and composite [1]. Despite existing studies [2-6], further research is needed to optimize abrasive jet machining parameters for enhanced material effectiveness. This research focuses on analysis, modelling and optimization of material removal rate in AJM of zirconia ceramic using statistical approach namely response surface methodology.

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2 Experimental details

For the machining process, a square-shaped workpiece made of zirconia (ZrO_2) ceramic measuring 20 mm × 20 mm × 4 mm was utilized. Abrasive materials consisting of silicon carbide (SiC) powder with varying grain sizes were chosen for the operation. In this research, the machining experiments were conducted using an internally designed, developed, and indigenously patented fluidized bed-AJM setup housed within the NTM laboratory of VSSUT-Burla [7], as presented in Figure 1. The process factors have a significant influence on machining performances. This study uses stand-off-distance (*SOD*), grain size of abrasive (GS) and air pressure (*P)* three of the most important variables, as input variables. The three levels of process parameter adjustment were P (3, 5, 7 kgf/cm²), SOD (2, 4, 6 mm) and GS (250, 500, 750 µm). The operational duration was maintained at 1 minutes across all trials of the experiment. According to L9 OA design of experiments, a total of nine trial runs were performed, each factor with a factor level of three. The capabilities of the AJM machine tool system determine the range of input parameters. To find the process parameter operating range, we combed through the relevant literature extensively. Table 1 displays the experimental plan arrangement in addition to the findings of the different coating criteria. This study examines material removal rate (*MRR*) as it pertains to AJM. For evaluation of MRR, a digital weighing device (VWR; LA124) was utilized to measure the variation in weights of workpiece before and after coating.

Table 1. Experimental design layout with results

Run	**P_{air} (kgf/cm^2)**	**SOD (mm)**	**GS_{abr} (µm)**	**MRR (gm./min)**
	P	SOD	GS	MRR
1	3	2	250	0.0000203
2	3	4	500	0.0000352
3	3	6	750	0.0000368
4	5	2	500	0.0000484
5	5	4	750	0.0000493
6	5	6	250	0.0000514
7	7	2	750	0.0000616
8	7	4	250	0.0000595
9	7	6	500	0.0000505

Fig. 1. Experimental setup for AJM

2.1 Development of predictive model

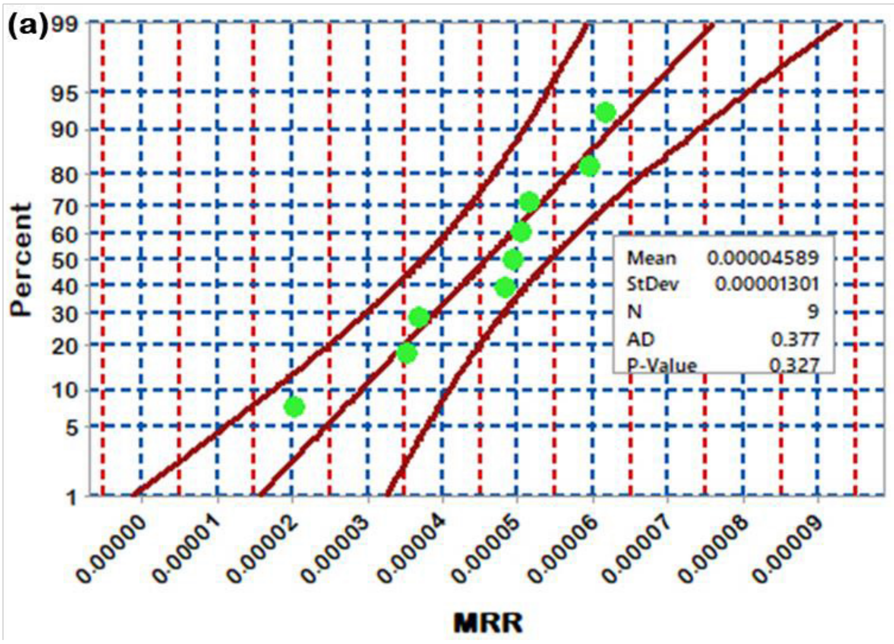
The outcomes derived from numerous machining experiments based on the L_9 OA design of experiment are examined using RSM to ascertain a relationship between the process parameters (P, SOD, GS) and the performance characteristic (here, MRR) of AJM. The regression model formulated as a result is showcased by,

$$\begin{aligned} MRR= & -0.000053 + 0.000013P + 0.000009SOD + 0.000000GS - 0.000000P*SOD \\ & - 0.000000P*GS - 0.000000SOD*GS \end{aligned}$$

Table 2. ANOVA results for MRR model

F	P	R^2	R^2 (adj)
62.70	0.016	99.47%	97.88%

The reliability of the developed regression models is confirmed through various diagnostic examinations. With a P-value less than 0.05 and an R^2 value of 0.995 at a 95% confidence level, the predictive response model clearly plays a substantial role, according to the statistical ANOVA analysis (see Table 2). The suggested models also have good predictive ability, since the experimental and predicted values for the response, MRR are highly congruent (Figure 2a). The normal probability plot (Figure 2b) shows the results of the Anderson-Darling test, which, with a P-value of 0.327, is exceeding 0.05, imply that the null hypothesis cannot be rejected. Additionally, the data seems to be well-fit by the model, since the residual distribution is normal (i.e., it lies close to the standard line).



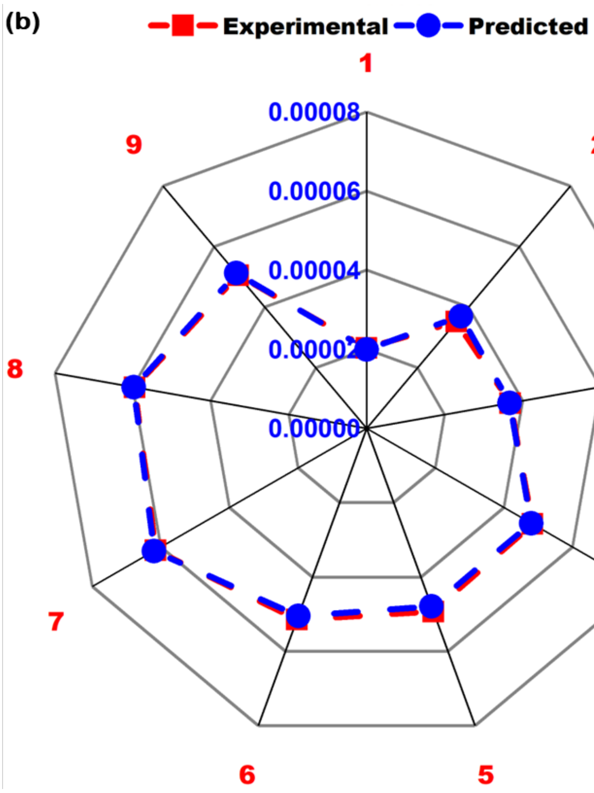
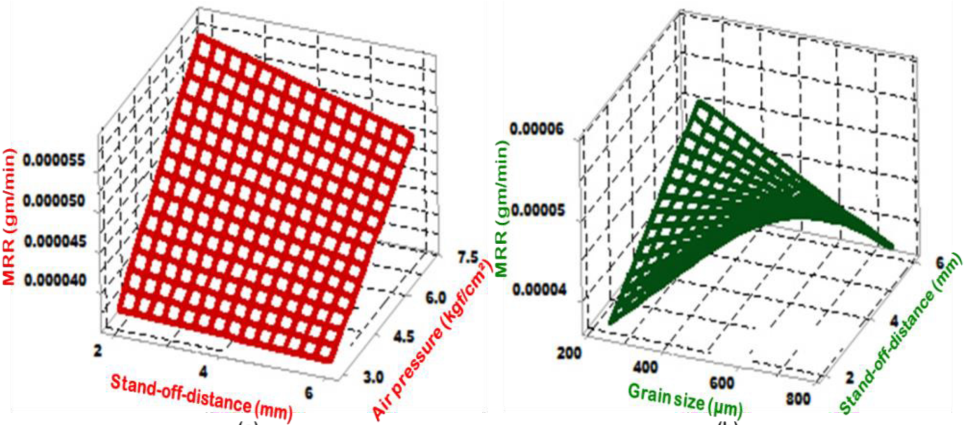


Fig. 2. (a) Predictive ability, and (b) Normal probability plots for MRR

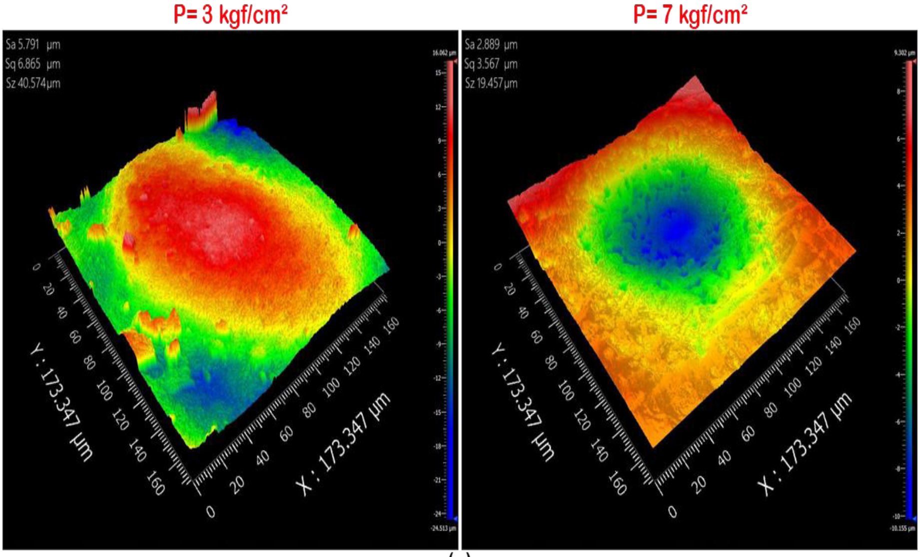
2.2 Analysis on material removal rate

The results of statistical study show that MRR is considerably affected by the variables P and SOD*GS, as detected by ANOVA. The F-value surpasses the critical value (4.27) from Fisher's standard distribution table with a 95% confidence level, and it's P-value is under 0.05. Among all the cutting variables, pressure stands out with the highest influence on MRR, contributing 77.44%. Figure 3 shows the surface plot that explains the influence various of process factors on material removal rate (MRR) during AJM. Clearly, it is shown that the MRR in AJM improves with pressure primarily due to the heightened kinetic energy imparted to the abrasive particles. As pressure rises, the velocity of the abrasive particles also increases, leading to more forceful impacts on the workpiece surface. This enhanced kinetic energy results in greater material removal efficiency as the abrasive particles effectively dislodge and erode the target material [8,9]. Additionally, higher pressure promotes deeper penetration of abrasive stream into the work surface (refer, Figure 4a), allowing for more extensive material removal within a given timeframe. One potential rationale suggests that with the ongoing stroking of abrasive particles on the target, there is a consequent rise in temperature within the target area, as confirmed by the thermal imaging camera (refer to Figure 4b). Consequently, this leads to the formation of deeper and larger scoops, as evidenced by the substantial material erosion attributed to the incidence of deep chipping on the work surface during AJM [10]. MRR typically improves with the increase of abrasive grain size, as shown in Figure 3b. Larger abrasive grains possess greater mass and kinetic energy, resulting in more substantial impacts upon collision with the workpiece surface. This enhanced impact energy facilitates more efficient material removal, as larger grains can dislodge and erode the target material more effectively [11]. Additionally, larger abrasive grains often exhibit sharper edges and greater cutting ability, further augmenting their material removal capabilities. However, there's a delicate balance to consider, as excessively pressure and large abrasive grains can lead to increased nozzle wear, surface roughness and compromised dimensional accuracy. The standoff distance, referring to the distance between nozzle and workpiece surface in AJM, significantly influences the MRR, as shown in Figure 3c. As the stand-off-distance decreases, the abrasive particles have less time to disperse and lose momentum before reaching the workpiece surface. Consequently, this results in more concentrated and forceful impacts, leading to a higher MRR due to increased abrasive energy transfer to the material [12]. However, as the standoff distance decreases beyond an optimal point, the abrasive particles may cluster together, reducing the efficiency of material removal and potentially causing surface irregularities. Conversely, increasing the standoff distance can lead to a reduction in MRR as the abrasive particles disperse and lose energy before reaching the workpiece surface [13].



(a) (b)

Fig. 3. Effect of process parameters (SOD, GS, and P) on MRR



(a)

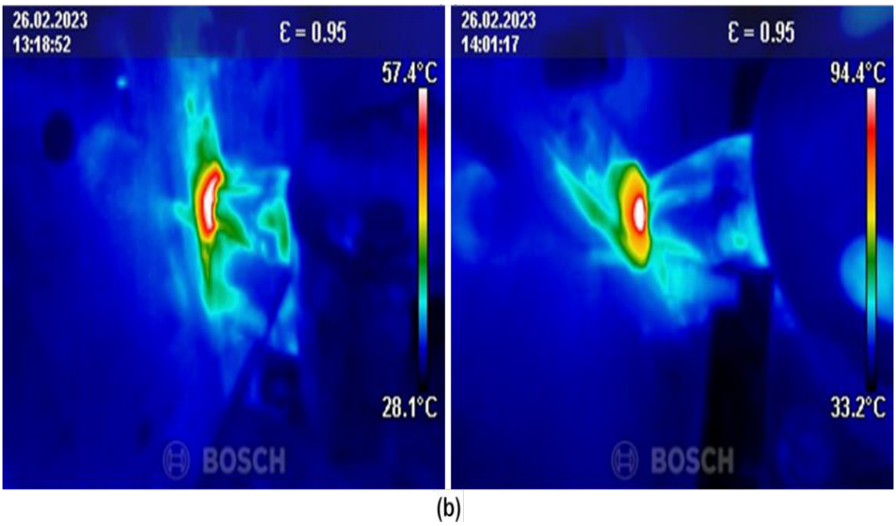


Fig. 4. (a) Machined surface topography images illustrating crater mark, and (b) Thermographic images at cutting zone under varying air pressure

2.3 Response optimization

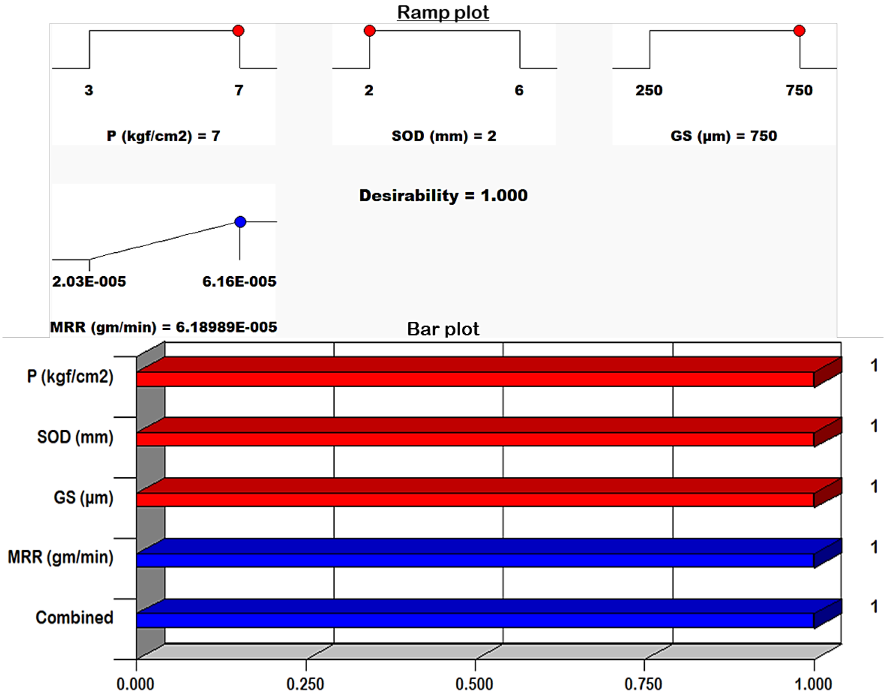


Fig. 5. Response optimization results using DFA

In this study, the desirability function analysis (DFA) is served as the optimization technique aimed at maximizing the performance characteristic, specifically the material removal rate. The optimization results were determined using a scale-free range of 0 to 1, which is known as the desirability value. According to previous research [14,15], an optimization problem is considered unfavorable when the desirability score is 0, and ideal or desired when the score is 1. For the AJM process to be useful in industry, it is necessary to optimize responses using DFA. This allowed us to produce a set of parameters that would improve accuracy and productivity. Figure 5 shows the optimization plot with the result with the most desirability value (closest to 1) displayed out of 23 possible options. The curve also displays the attractiveness of MRR. The optimal operating conditions for AJM of zirconia ceramic are depicted in the optimization plot using DFA, with process conditions at air pressure of 7 kgf/cm^2, grain size of 750 µm, and a SOD of 2 mm. The value of 0.0000619 gm/min, MRR is at its optimal.

3 Conclusion

The influence of air pressure emerged as the most critical factor in enhancing MRR during AJM of zirconia ceramic. At elevated pressures, the surface morphology exhibits characteristic deep chipping and larger crater marks. The proposed predictive model for MRR utilizing the regression method proves effective, demonstrating adequacy, statistical significance, and probabilistic validation, indicated by its high R^2-value (0.995), P-value below 0.05 (i.e. 0.016), and substantial AD-P-test value (0.327). By employing DFA to solve the response optimization problem, optimal MRR (0.0000619 gm/min) for AJM of zirconia ceramic is achieved at abrasive grain size of 750 µm, air pressure of 7 kgf/cm^2, and SOD of 2 mm.

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