Experimental investigation of Marble powder mixed micro-electric discharge machining

Rupali Baghel
Department of Mechanical Engineering, Vivekananda Global University, Jaipur
rupali.baghel@vgu.ac.in

Abstract. Micro-electrical discharge machining (EDM) is among the most important machining techniques for creating micro features, notably for cutting challenging materials such as superalloys, ceramics, and composite materials. To improve machining performance characteristics, micro-EDM technology was integrated with the mixing of marble powder in the dielectric fluid in this research. This work investigates the potential of marble powder mixed micro-EDM (PM-EDM) to manufacture high aspect ratio micro holes in a newly designed ceramic, TiN-Al2O3. SEM photos of the action of marble powder on the machined surface are also examined, with thermal cracking (Spalling) and melting being the most prominent mechanisms of material removal.

Keywords: EDM, marble powder, Ceramics, MRR, EWR.

1. Introduction
Advanced manufacturing technologies are mostly utilized to create miniaturized goods with dimensions ranging from 1 to 999 micrometers. Sensors, turbine blades, a printed circuit board, injection nozzles, and other miniature goods have a wide range of applications in the automobile, aircraft, optical, and biomedical industries [1]. To resist wear and promote heat transmission, microdevices such as micro heat exchangers and microreactors with micro features such as micro holes, micro-channels, and fins are required [2]. Miniaturized advanced ceramics goods have low weight and great mechanical strength, which are required for certain applications in the current environment.

Ceramic matrix composites (CMCs) are appropriate for modern material requirements. CMCs have physiological qualities that are superior to metals, particularly high toughness, hot hardness, low density to weight ratio, and high stiffness [3]. In MMcs and CMCs, Micro-electro-discharge machining (-EDM) offers the distinct benefit of cutting complicated micro-features [4]. Although -EDM has drawbacks such as high energy consumption, low material removal rate (MRR), and high tool wear when cutting micro-features with high aspect ratios, there is always the issue of debris flushing [5]. By hybridizing the machining process, the limitations of innovative machining operations could be addressed. In a hybrid-EDM, two or more processes work together to achieve improved response parameters. [6] [7]. Baghel et al. [8] used vibration-aided -EDM to drill a 200 m
diameter micro hole in Titanium Nitride Aluminium Oxide and found that MRR was enhanced by 1.98 times under the effect of low-frequency vibration. They also used diamond grinding aided EDM to machine Titanium Nitride Aluminium Oxide and could see a considerable increase in MRR [9]. Powder mixed EDM is a technique proposed by several researchers. By adding impurities into the dielectric fluid, the properties of the dielectric fluid are modified. Fig. 1 is showing the process in three stages, as machinability in EDM is highly dependent on dielectric properties [10]. When a potential difference is applied to the electrodes in powder mixed EDM, the particles polarise and align themselves as a bridge across the electrodes in the first stage, resulting in effortless dielectric fluid breakdown and persistent sparking. The frequency of discharge is increased by the presence of microparticles. Researchers incorporate a range of powders to improve EDM performance, including aluminum, chromium, copper, and others. The proposed paper is based on marble powder mixed electro-discharge machining of Titanium Nitride-Aluminium Oxide (TiN-Al₂O₃), an advanced ceramic-matrix composite. The foreign particle reduces the dielectric strength of the fluid, resulting in a persistent spark.

2. Experimentations
Titanium Nitride-Aluminium Oxide (TiN-Al₂O₃) is a newly discovered CMC with better mechanical qualities to metal, especially high toughness and chemical and mechanical wear resistance. High-temperature reaction sintering has been used to make this CMC. Traditional machining techniques have had trouble fabricating micro-features on these ceramics because they are exceptionally brittle and have a high hardness. In this study, an attempt is made to use PM-EDM to create micro-holes with a high aspect ratio, i.e. 12. All tests were conducted out using a Hybrid-EDM (DT-110i) machine. These experiments are designed using a Taguchi L16 orthogonal array. The parameters are determined by a review of the literature and the machine's capabilities. Table 1 shows the range of process parameters used in the trials. The response parameters are materials removal rate (MRR in mm³/min) and electrode wear rate (EWR in mm³/min). The MRR and EWR are calculated by dividing the volume loss by the machining time.

Table 1 Input parameters for PM-µEDM

| Sn | Input parameter | Level of input parameters |
|----|----------------|--------------------------|
| 1  | Speed (rpm)    | 1000 1200 1400 1600     |
| 2  | Voltage (Volt) | 85 100 115 130          |
| 3  | Marble-Powder Concentration (g/l) | 0 2 4 6 |

3. Results and Discussion
The Taguchi L16 orthogonal array design has been used in all of the experiments, with three control factors at four levels and two response parameters. For each response parameter in Table 2, the signal to noise (S/N) ratio is obtained. If the output parameter has to be maximized, the (S/N) ratio can be calculated by equation 1. For MRR (S/N) ratio follow the “Larger the Better” model.

\[
\frac{S}{N} \text{ ratio} = \log_{10} \frac{\sum_{i=1}^{n} y_i^2}{n} \quad \text{.................. (1)}
\]

“Electrode wear” is the terminology for this type of damage. The change in the volume of the electrode in each machine time is used to determine the electrode wear rate (EWR). The value of electrode wear should be as low as possible, and if the value of the response parameter must be lowered, the signal-to-noise ratio can be determined using equation 2 and the principle “smaller is better.”

\[
\frac{S}{N} \text{ ratio} = \log_{10} \frac{\sum_{i=1}^{n} y_i^2}{n} \quad \text{.................. (2)}
\]

Each response parameter is tested to an analysis of variance (ANOVA) test. Table 2 provides the experimental observations. Figure 2 depicts the main effect curves for MRR and EWR. In Fig. 2(a), the MRR plot shows a high concentration of marble powder, with MRR being the largest. The high particle concentration represents a low discharge gap and high conductivity, resulting in a steady spark with a high MRR. EWR, on the other hand, is largest at high marble powder proportions, as illustrated in Fig. 2 (b). As
mentioned earlier, a high concentration of marble powder causes persistent sparking, which causes the temperature of the tool-tip to rise. The high temperature of the tool-tip accelerates tool degradation, resulting in a larger EWR. It also shows that speed is the most major determinant, followed by voltage and focus. Consistent sparking affects the geometry and size of the electrode, resulting in increased EWR. Table 3 shows the ranking of several factors.

Table 2 Experimental design matrix with a set of process parameters and corresponding response parameters

| speed | voltage | Conc. | MRR  | EWR  | S/N Ratio (MRR) | S/N Ratio (EWR) |
|-------|---------|-------|------|------|-----------------|-----------------|
| RPM   | Volt    | g/l   | mm³/min | mm³/min |                 |                 |
| 1000  | 85      | 0     | 0.022847 | 0.028730 | -32.8234        | 32.5149         |
| 1000  | 100     | 2     | 0.024870 | 0.027540 | -32.0865        | 30.8333         |
| 1000  | 115     | 4     | 0.026730 | 0.028750 | -31.4600        | 31.2007         |
| 1000  | 130     | 6     | 0.034870 | 0.026780 | -29.1510        | 30.8272         |
| 1200  | 85      | 2     | 0.027467 | 0.024856 | -31.2238        | 31.4438         |
| 1200  | 100     | 0     | 0.030128 | 0.022145 | -30.4206        | 32.0914         |
| 1200  | 115     | 6     | 0.036740 | 0.025735 | -28.6972        | 33.0945         |
| 1200  | 130     | 4     | 0.027462 | 0.023780 | -31.2254        | 31.7895         |
| 1400  | 85      | 4     | 0.026439 | 0.025483 | -31.5551        | 32.4758         |
| 1400  | 100     | 6     | 0.033749 | 0.035820 | -29.4348        | 31.8750         |
| 1400  | 115     | 0     | 0.025387 | 0.035629 | -31.9078        | 28.9175         |
| 1400  | 130     | 2     | 0.028946 | 0.025473 | -30.7682        | 28.9639         |
| 1600  | 85      | 6     | 0.034779 | 0.024582 | -29.1737        | 31.8784         |
| 1600  | 100     | 4     | 0.027888 | 0.039760 | -31.0917        | 32.1877         |
| 1600  | 115     | 2     | 0.028638 | 0.034500 | -30.8611        | 28.0111         |
| 1600  | 130     | 0     | 0.027894 | 0.028730 | -31.0898        | 29.2436         |

Table 3 Response table for the signal to noise ratios

| Level | speed | voltage | Conc. | EWR  | S/N Ratio |
|-------|-------|---------|-------|------|-----------|
| 1     | -31.38 | -31.19 | -31.56 |      |           |
| 2     | -30.39 | -30.76 | -31.23 |      |           |
| 3     | -30.92 | -30.73 | -31.33 |      |           |
| 4     | -30.55 | -30.56 | -29.11 |      |           |
| Delta | 0.99   | 0.64   | 2.45   |     |           |
| Rank  | 2      | 3       | 1      |     |           |

(a) For MRR (b) For EWR

Fig. 2 Main effects plot SN ratio
Table 4 ANOVA table for Material removal rate

| Source  | DOF | Seq SS    | Adj SS   | Adj MS    | F       | P      |
|---------|-----|-----------|----------|-----------|---------|--------|
| Speed   | 3   | 0.0000226 | 0.0000226| 0.0000075 | 2.98    | 0.118  |
| Voltage | 3   | 0.0000081 | 0.0000081| 0.0000027 | 1.07    | 0.430  |
| Conc.   | 3   | 0.0001926 | 0.0001926| 0.0000642 | 25.34   | 0.001  |
| Error   | 6   | 0.0000152 | 0.0000152| 0.0000025 |         |        |
| Total   | 15  | 0.0002385 |          |           |         |        |

S = 0.00159163  R-Sq = 93.63%  R-Sq(adj) = 84.07%

Table 5 ANOVA table for Electrode wear rate

| Source  | DOF | Seq SS    | Adj SS   | Adj MS    | F       | P      |
|---------|-----|-----------|----------|-----------|---------|--------|
| Speed   | 3   | 0.0000969 | 0.0000969| 0.0000323 | 7.70    | 0.018  |
| Voltage | 3   | 0.0001373 | 0.0001373| 0.0000458 | 10.91   | 0.008  |
| Conc.   | 3   | 0.0001519 | 0.0001519| 0.0000506 | 12.07   | 0.006  |
| Error   | 6   | 0.0000252 | 0.0000252| 0.0000042 |         |        |
| Total   | 15  | 0.0004112 |          |           |         |        |

S = 0.00204816  R-Sq = 93.88%  R-Sq(adj) = 84.70%

Fig. 3 SEM images of the machined surface by PM-µEDM

Tables 4 and 5 show the findings of the ANOVA. According to the ANOVA results, marble powder concentration has a significant effect on MRR, and all three parameters have a major effect on EWR. The model's goodness of fit is shown by the determination coefficient (R2). MRR has a determination coefficient of 0.9363 and EWR has a determination coefficient of 0.9386, indicating that the model only explains around 7% of total variance for both MRR and EWR.

The adjusted determination coefficient (adjusted R2=0.8407 for MRR, adjusted R2=0.8470) is also high and close to the determination coefficient, suggesting that these models are highly significant. Scanned electrode microscopy (SEM) can be used to analyze the interior surface of micro-holes, as shown in Fig. 3. On the machined surface, there are pools (with debris) of melting metals. As the melted metal in it shrunk, micro-cracks appeared.

It has cracks and debris, indicating that it is melting and vaporizing in a machined zone. Thermal cracking and flakes removal, sometimes known as thermal spalling, are used to remove materials. The mechanisms by which materials are removed are melting, vaporization, and thermal shock failure, i.e. significant internal stresses induced by a fast temperature gradient causing the material to flake and shatter in advanced ceramics like TiN-Al2O3.
4. Conclusions

On a TiN-Al₂O₃ ceramic-composite workpiece, a powder mixed micro-electro-discharge machining method is applied to produce micro-holes. The following conclusions have been drawn from the analysis of the data:

1. The percentage of marble particles is the most affecting parameter for MRR during PM-EDM machining of TiN-Al₂O₃, followed by the applied voltage and electrode rotation speed.
2. The electrode wear rate has mostly been influenced by the powder percentage and the rotation speed of the electrode.
3. PMEDM has now been confirmed to be the recommended way for machining TiN-Al₂O₃ ceramic-composite because the material removal rate is much higher than EDM since the presence of micro powder increases the frequency of discharge, resulting in continuous sparking.
4. Melting for metals, such as TiN, and thermal spalling for ceramics, such as Al₂O₃, are the mechanisms for material removal in composites.
5. PM-EDM is an effective process for machining difficult-to-cut materials such as TiN-Al₂O₃ ceramic-composite, based on the above-mentioned research observations.

REFERENCES

1. M. Hourmand, A. A. D. Sarhan, and N. Mohd Yusof, "Development of new fabrication and measurement techniques of micro-electrodes with high aspect ratio for micro EDM using typical EDM machine," Measurement, vol. 97, pp. 64-78, 2017.
2. S. Ravisubramanian and M. S. Shumugam, "Investigations into peck drilling process for large aspect ratio micro-holes in aluminum 6061-T6," Materials and Manufacturing Processes, vol. 33(9), pp. 935-942, 2018.
3. R. Baghel, H. S. Mali and S. K. Biswas, "Parametric optimization and surface analysis of diamond grinding-assisted EDM of TiN-Al₂O₃ ceramic composite," The International Journal of Advanced Manufacturing Technology, vol. 1, pp. 1-10, 2018.
4. R. Kumar, A. Singh, and I. Singh, "Electric discharge hole grinding in hybrid metal matrix composite," Materials and Manufacturing Processes, vol. 32(7), pp. 127-134, 2017.
5. M. S. Rayat, S. S. Gill, R. Singh, and L. Sharma, "Fabrication and machining of ceramic composites-A review on the current scenario," Materials and manufacturing process, vol. 1, pp. 1-24, 2017.
6. R. Baghel and H. S. Mali, "A study on effects of discharge energy on geometric characteristics of high aspect ratio micro-holes on TiN-Al₂O₃ ceramics," in 8th International Conference on Materials Processing and Characterization (ICMPC), India, 2018.
7. R. Baghel and H. S. Mali, "An Experimental Study on Fabrication of Micro Channels in Titanium Nitride Alumina Composite Using Electro-discharge Milling," International Journal of Modern Manufacturing Technologies, vol. 10(2), pp. 24-29, 2018.
8. R. Baghel, H.S. Mali, & S.K. Biswas, "Micro hole fabrication in TiN-Al₂O₃ ceramic composite by SiC powder assisted micro-EDM," Engineering Research Express 2 (2020), 015028, https://doi.org/10.1088/2631-8695/ab6ce
9. R. Baghel, H. S. Mali and S. K. Biswas, "Parameter Optimization of Diamond Grinding Assisted EDM of TiN-Al₂O₃ Ceramics using Taguchi Method," in 6th International & 27th All India Manufacturing Technology, Design, and Research Conference, Coep, Pune, 2016.
10. G. S. Prihandana, M. Mahardika, M. Hamdi, Y. S. Wong and K. Mitsui, "Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes-Taguchi approach," International Journal of Machine Tools and Manufacture, vol. 49(12-13), pp. 1035-1041, 2009.