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# Modeling the Effects of Electrical and Non-Electrical Parameters on the Material Removal and Surface Integrity in Case of $\mu$ EDM of a Non-Conductive Ceramic Material using a Combined Fuzzy-AOM Approach

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## Abstract

*Micro-EDM is a non-contact process based on the thermoelectric energy between a tool electrode and a workpiece. In  $\mu$ EDM process, the mechanism of material removal is melting and evaporation. The thermal energy in the discharge plasma helps remove material from the workpiece, at the same time deteriorates the quality and integrity of the workpiece surface. The material removal phenomenon in  $\mu$ EDM of partially conductive and non-conductive materials is very complex. This paper presents a novel approach to model the effects of electrical and non-electrical parameters on the material removal phenomenon and surface integrity for a non-conductive ceramic material. The fuzzy logic modeling system is employed for predicting the  $\mu$ EDM process responses. The trends in the material removal rate and hardness values with the chosen electrical and non-electrical parameter for the model and obtained using AOM approach are compared. The average deviation between the model predictions and the results obtained using AOM plots is less than 10%. The material removal rate (MRR) decreases linearly with voltage, indicating a difference in material removal mechanism in the  $\mu$ EDM of non-conductive materials.*

**Keywords:** *Machining,  $\mu$ EDM, Material removal, Surface integrity, Process parameter, Analysis of means*

## 1. Introduction

Micromachining is a basis technology used to fabricate miniaturized components such as microneedles, micro pins, micro punches, micro dies, *etc.*, that are in high demand for different industries [1]. Among the micromachining processes, micro-EDM is widely used for manufacturing of variety of micro components with complex features [2]. The array of research works conducted on micro-EDM internationally have shown that the process models for electrical discharge machining are not applicable to micro-EDM process [3]. The processing conditions and the governing factors controlling the processes change significantly at the micro-scale in the micro-EDM. As a result, a successful scientific characterization of the micro-EDM process and development of process models at the micro-scale becomes highly challenging. A few researchers have attempted to characterize micro-EDM process. The influence of tool electrode as well as workpiece properties and characteristics on the performance of the micro-EDM was studied in Ref. [4]. The mechanism of material removal including melting and evaporation of the workpiece was analyzed using single discharge investigation [5]. The variations in the discharge energy was studied considering a heat transfer model. Recently, a response surface methodology was used to develop relationships between process inputs and outputs during machining of Ti-6Al-4V superalloy [6]. CCD have been used for performing the experiments. The spark erosion-based processes including micro-EDM are

machining techniques mostly used for conductive workpiece materials. A few researchers have attempted to machine non-conductive materials using electrical discharge machining [20-22]. But, the sparking phenomenon is found to be different because the process is modified with an assisting electrode. In another recent investigation, an attempt has been done to use  $\mu$ EDM for machining of non-conductive zirconia ceramic [7]. The material for micro-EDM is non-conductive, therefore, it is envisaged that non-electrical parameters have more importance in the material removal mechanism. However, it is important that the influence of electrical as well as non-electrical parameters on the characteristics of a  $\mu$ EDM process be investigated. Therefore, in this paper, effect of the chosen electrical and non-electrical parameter on material removal and integrity characteristics of  $\mu$ EDM process is presented, and Ref. [7] is referred for experimental data. The material removal rate (MRR) and the hardness of the recast layer were selected process outputs for the analysis. The  $\mu$ EDM processing conditions are modeled using fuzzy logic approach and the process responses are predicted. The analysis of means technique is used for analysis, and the model results and the results obtained after analysis of experimental data of micro-EDM are compared and studied.

## 2. Electrical and Non-Electrical Parameters in $\mu$ EDM

Several investigations have been conducted earlier on study of electrical and non-electrical parameters in the micro-EDM process. A parametric study of the  $\mu$ EDM of an aluminium alloy have been conducted in terms of material removal rate and surface roughness [8]. The parameters studied in the investigation were voltage, resistance, capacitance, gap feed rate, gap control factor and gap threshold voltage. The capacitance and voltage directly influence the discharge energy. The power density is an important factor to be taken into account to characterize and analyze machining conditions in a micro-EDM process [9]. In this approach, energy used for discharge breakdown and the energy distributed to the workpiece determines the efficiency of the process. The energy of the plasma is mainly the kinetic energy of the electrons, which depends on the density [10], and velocity of the electrons. The electron density ( $n_e$ ) is given by,

$$n_e = k \frac{d_{plasma}}{A_{plasma}} \frac{m_e v_c}{e^2} \frac{I_d}{V_d} \quad (1)$$

where,  $e$  is the electron charge,  $m_e$  is the electron mass,  $k$  is a constant,  $v_c$  is the electron collision frequency,  $I_d$  is the discharge current,  $V_d$  is the discharge voltage,  $A_{plasma}$  is the area of the plasma and  $d_{plasma}$  is the diameter of the plasma. The controllable variables directly influencing the electron density are  $I_d$  and  $V_d$ . The discharge voltage  $V_d$  [11] at the onset of breakdown is:

$$V_b = \alpha S A^{-n} dt^{-1/3} \quad (2)$$

where,  $\alpha$  is a correction factor associated with dielectric strength,  $S$  is a constant based on electric field,  $n$  is a constant depending on the polarity,  $d$  is the inter-electrode gap length,  $A$  is the area of the tool electrode exposed to electric field and  $t$  is the time of breakdown. Furthermore, because of movement of electrons, the kinetic energy is converted into heat energy developed at the anode surface [12]. The heat flux  $q(r)$  at a radial coordinate  $r$  is given by:

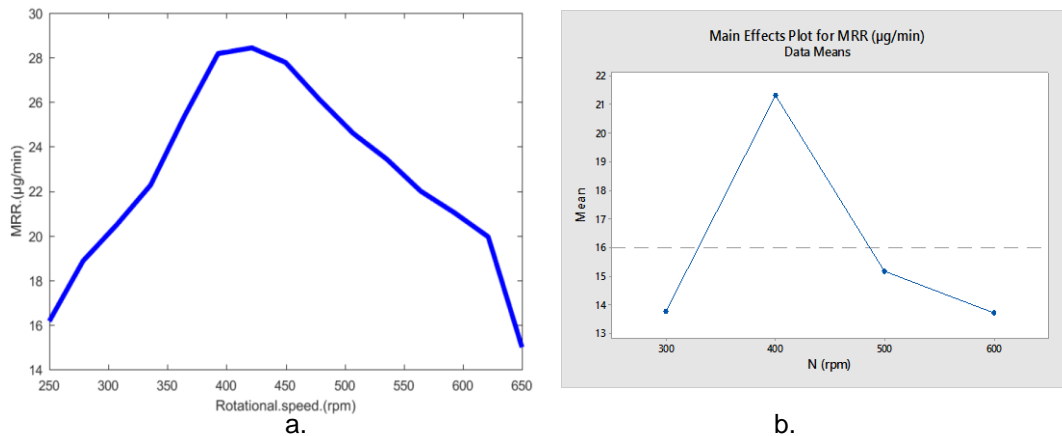
$$q(r) = \frac{BF I_{av} V_{av}}{\pi R^2} \exp\left[-C \frac{r^2}{R^2}\right] \quad (3)$$

where,  $R$  is the radius of the heat source,  $F$  is the fraction of heat source distributed to the workpiece,  $I_{av}$  is the average current over the entire pulse duration,  $V_{av}$  is the average voltage over the entire pulse duration and  $B$  and  $C$  are constants. The other governing parameters for micro-EDM include pulse duration and duty cycle [13]. Non-electrical

parameters chosen in the earlier electrical discharge machining investigations include pressure, spindle speed and amplitude or frequency of ultrasonic vibrations [14-15].

### 3. Analysis of Material Removal Rate (MRR)

In micro-EDM, the material removal rate is defined as the amount of material that is removed from the workpiece in unit time [16]. Because of the small inter-electrode gap and short pulse ‘on-time’ in micro-EDM, the phenomenon of material removal is not completely understood yet. However, there have been few investigations on analysis of the removal mechanisms in the micro-EDM. A molecular dynamic simulation has been developed by Yang *et. al.* [17] to study the melting, evaporation and crater formation in micro-EDM. The fuzzy logic modeling has been an important technique for prediction of performance outputs in different machining processes. Fuzzy logic model was developed for dry end milling experiments in Ref. [18]. Recently, the same research group has applied neuro-fuzzy modeling approaches for machining of GFRP composites [19]. Thus, considering the importance of modeling techniques in predicting the performance characteristics of  $\mu$ EDM, a model is developed to correlate the processing conditions with the MRR as well as the hardness of the recast layer. The effects of rotational speed ( $N$ ) and the voltage ( $V$ ) on MRR are investigated.



**Figure 1. a-b Effect of Rotational Speed on the Material Removal Rate, a. Model Prediction and b. AOM Results**

The effect of rotational speed on the MRR is presented in Figure 1 *a-b*. Statistical analysis of data reveal that rotational speed is the main parameter controlling the MRR. In  $\mu$ EDM process, an increase in MRR with speed is expected. An improvement in MRR by 49% is reported in electrical discharge machining studies [23].

It is evident from Figure 1 *a-b* that the trends in the variation of MRR are similar for fuzzy and AOM approaches. As the spindle speed increases from 300 to 400 rpm, an increase in the MRR is observed. This could be because of the effect of centrifugal force that helps flush out the debris out of the discharge gap [24]. However, with an increase in spindle speed after 400 rpm, the MRR decreases drastically. This could be because of the difficulty in machining with assisted electrodes, as it causes poor stability. Five key points on the plots are chosen for this comparative study. A comparative analysis of the model and AOM results are presented in Table 1. Based on the variations in the slopes in the plot in various parts, the percentage variations in MRR are determined with reference to the previous key point. The maximum variation observed for the model is 16.2% whereas that for AOM approach is 28.6%.

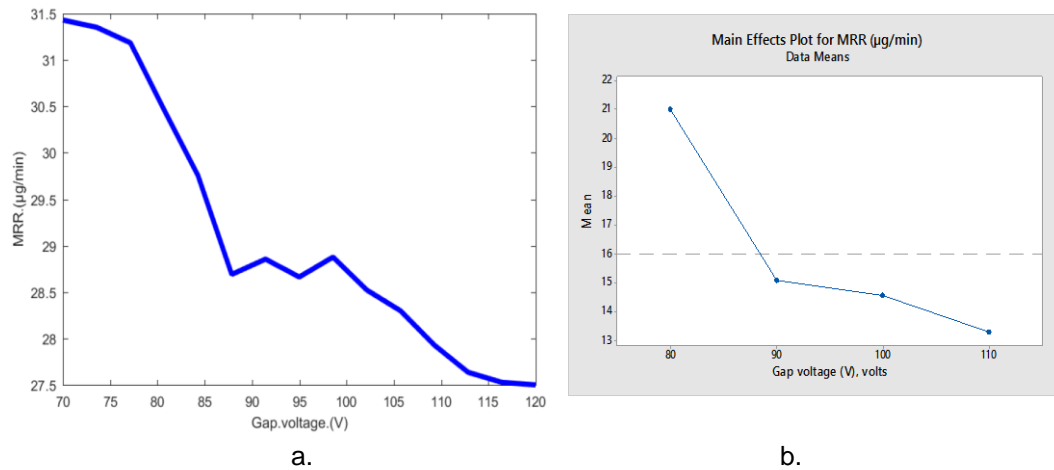
**Table 1. A Comparative Analysis of Fuzzy Model and AOM Results for Variation in MRR with Rotational Speed**

Points for comparative analysis	N (rpm)	Variation in MRR - model	Increase or decrease	Variation in MRR - AOM	Increase or decrease	Remarks
Key point 1	350	16.2%	increase	28.6%	increase	The average variation between model and AOM is less than 10%
Key point 2	400	14.3%	increase	16.6%	increase	
Key point 3	450	1.0%	increase	13.9%	decrease	
Key point 4	500	10.7%	decrease	16.6%	decrease	
Key point 5	550	8.0%	decrease	20.0%	decrease	

The electrical parameters have equal importance as non-electrical parameters in influencing MRR in  $\mu$ EDM process. The gap voltage is expected to cause an increase in the MRR. The energy of a single discharge in micro-EDM is given by,

$$E = \frac{1}{2} (C_n + C_d) V^2 \quad (4)$$

where,  $E$  is the energy of a single discharge in J,  $C_n$  is the nominal capacitance in F,  $C_d$  is the discrete capacitance in F, and  $V$  is the gap voltage in V.



**Figure 2. a-b Effect of Gap Voltage on the Material Removal Rate, a. Model Prediction and b. AOM Results**

The plots of MRR with gap voltage obtained using model and using AOM approach are shown in Figure 2 *a* and *b* respectively. An overall decrease in MRR is observed with an increase in voltage, which is in contrary to the result expected. It is mentioned in Ref. [7] that the process was highly unstable due to longer machining time and arcing at higher voltages. A decrease in MRR with an increase in gap voltage could also be attributed to an increase in gap distance at higher voltages. A comparative analysis of fuzzy model and AOM is presented in Table 2.

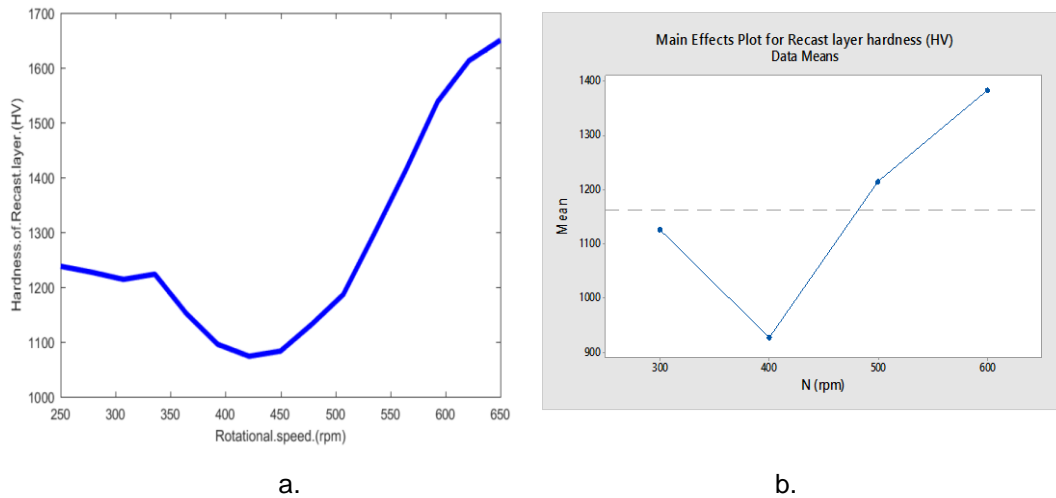
**Table 2. A Comparative Analysis of Fuzzy Model and AOM Results for Variation in MRR with Gap Voltage**

Points for comparative analysis	V (V)	Variation in MRR - model	Increase or decrease	Variation in MRR - AOM	Increase or decrease	Remarks
Key point 1	85	3.3%	decrease	14.0%	decrease	The average variation between model and AOM is less than 10%
Key point 2	90	3.4%	decrease	16.6%	decrease	
Key point 3	95	0.5%	decrease	3.3%	decrease	
Key point 4	100	0.5%	decrease	1.3%	decrease	
Key point 5	105	2.0%	decrease	1.0%	decrease	

The maximum variation observed from the model plot is 3.4%, but, the variation in MRR with voltage is very high. This could be attributed to unstable discharge plasma, which occurs during practical machining.

#### 4. Analysis of Surface Integrity

The surface integrity in  $\mu$ EDM process is analyzed using variations in hardness of the recast layer and, the variations in the hardness values with the chosen non-electrical parameter  $N$  and the electrical parameter  $V$  are studied.



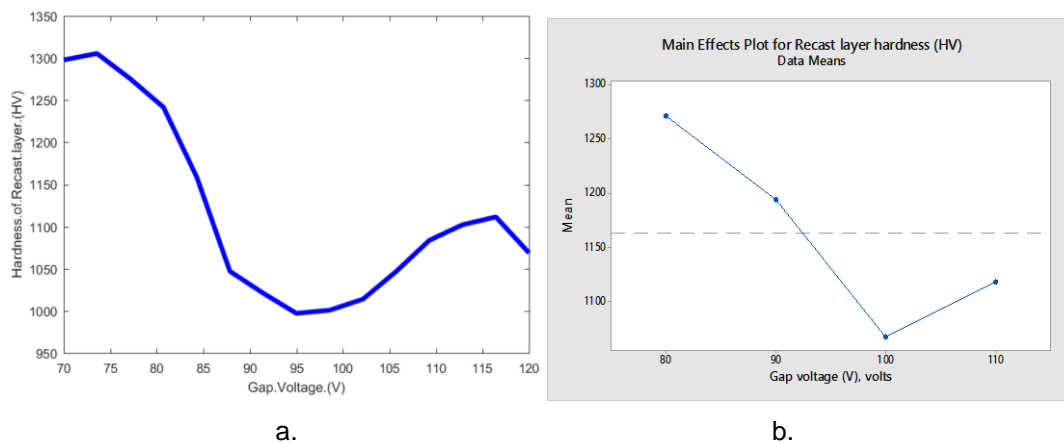
**Figure 3. a-b Effect of Rotational Speed on the Hardness, a. Model Prediction and b. AOM Results**

The effect of rotational speed on the material removal rate is presented in Figure 3 *a-b*. In both model (Figure 3-*a*) and the AOM plot (Figure 3-*b*), there is a slight decrease in hardness at low rotational speeds. The rate of this decrease is low in model, whereas in the actual experiments, this decrease is sudden. However, with a further increase in speed, the hardness of the recast layer increases. A comparative analysis of fuzzy model and AOM results is presented in Table 3.

**Table 3. A Comparative Analysis of Fuzzy Model and AOM Results for Variation in Hardness with Rotational Speed**

Points for comparative analysis	N (rpm)	Variation in Hardness - model	Increase or decrease	Variation in Hardness - AOM	Increase or decrease	Remarks
Key point 1	350	8.75%	decrease	3.57%	decrease	The average variation between model and AOM is less than 5%
Key point 2	400	8.33%	decrease	8.82%	decrease	
Key point 3	450	0.8%	decrease	18.05%	Increase	
Key point 4	500	7.27%	Increase	8.92%	Increase	
Key point 5	550	12.5%	Increase	6.55%	Increase	

The maximum variation in the hardness as observed from the plot is 12.5% for the model and 18.05% for the AOM. The relationship between hardness and gap voltage is considered, and Figure 4 *a-b* shows the variation in the hardness with the gap voltage. The hardness decreases with an increase in voltage. This could be because of a decrease in discharge energy observed with an increase in voltage in  $\mu$ EDM. This effect is reflected on MRR with a linear decrease with voltage, as discussed earlier in Section 4. A higher transfer of thermal energy to the workpiece causes an increase in thickness of the recast layer as well as the hardness [24]. The rate of decrease or increase in hardness is higher in the actual results using AOM than that predicted using fuzzy model.



**Figure 4. a-b Effect of Gap Voltage on the Hardness, a. Model Prediction and b. AOM Results**

A comparative analysis of fuzzy model with AOM is presented in Table 4. The average variation between the prediction using the model and the AOM results is less than 5%. The maximum variation in the hardness values predicted using the model is 10.52%, whereas that with AOM is 5.83%.

**Table 4. A Comparative Analysis of Fuzzy Model and AOM Results for Variation in Hardness with Gap Voltage**

Points for comparative analysis	V (V)	Variation in MRR - model	Increase or decrease	Variation in MRR - AOM	Increase or decrease	Remarks
Key point 1	85	10.52%	decrease	2.35%	decrease	The average variation between model and AOM is less than 5%
Key point 2	90	8.62%	decrease	3.67%	decrease	
Key point 3	95	2.88%	decrease	5.83%	decrease	
Key point 4	100	0.5%	Increase	5.31%	decrease	
Key point 5	105	1.9%	Increase	2.72%	Increase	

## 5. Conclusions

In  $\mu$ EDM process, the governing factors are broadly classified into electrical and non-electrical. This paper has investigated the influence of two factors: voltage (electrical) and rotational speed (non-electrical) on  $\mu$ EDM of a non-conductive ceramic material using fuzzy logic modeling and prediction method. Through extensive comparative studies on material removal rate (MRR) and recast layer hardness, the model data is validated using analysis of means method. Based on this work, the following conclusions can be drawn:

- The study has shown that the material removal rate (MRR) as well as the recast layer hardness are prominently controlled by rotational speed ( $N$ ), a non-electrical factor, as compared to the gap voltage ( $V$ ), an electrical factor, contrary to the expectations. In  $\mu$ EDM process, electrical factors directly control the spark energy, and therefore, a higher significance is expected. This could be because of a change in the machining characteristics and instability during  $\mu$ EDM of non-conductive ceramics.
- A fuzzy logic-based model have been developed for the prediction of material removal rate and hardness in  $\mu$ EDM process. The trends in the variation of MRR and hardness are similar for the model and AOM results.
- Key points were selected on the model plots as well as AOM plots to closely evaluate and to determine the MRR and hardness values. As the spindle speed increases from 300 to 400 rpm, an increase in MRR is observed. However, after a spindle speed of 400 rpm, the MRR decreases drastically. This could be because of the unstable machining conditions in  $\mu$ EDM process of the non-conductive ceramic.
- The average deviation between the model predictions and the results obtained using AOM plots is less than 10%. The largest deviation has been observed in the case of modeling of MRR with rotational speed; deviation for the model is 16.2% whereas that for AOM approach is 28.6%.
- The MRR as well as hardness decrease linearly with the voltage. It was expected that an increase in the voltage would cause an increase in the discharge energy, thereby causing an increase in MRR as well as hardness. This could be due to a difference in material removal mechanism in  $\mu$ EDM of non-conductive materials, which necessitates further elaborated investigations.

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