Micro-electro discharge machining (Micro-EDM) models for conductive and nonconductive materials: A review

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Abstract. Models are useful in controlling the process effectively and efficiently in micro electro discharge machining (Micro-EDM). There are two types of models which are empirical models and theoretical models. Most of the models are basically formulated for conductive work materials. However, nowadays there is a trend to cut nonconductive materials using micro-EDM where the models developed for conductive materials are not applicable. There are only few models that are developed to cut nonconductive materials with micro EDM but these models have limitations. In this article, models for cutting conductive materials and nonconductive materials using micro EDM are compared in view of their applications.

Keywords: Micro EDM, Modelling, nonconductive materials, ceramics, aluminium oxide

1. Introduction

Micro-electro discharge machining (Micro-EDM) is a special application of electro discharge machining to produce micro sized products with metallic materials. The material removal process in micro-EDM is similar with general EDM process which is based on a series of electrical sparks between the electrode and workpiece [1]. Any materials to be cut using micro-EDM must have electrical conductivity more than 0.1 S cm⁻¹. The material hardness and brittleness do not affect the cutting process [2-3]. In micro-EDM, thermal energy evolved from the electrical sparks flows into the electrode, workpiece and dielectric fluid. A fraction of spark energy or heat conducted into a highly localized area on workpiece causes temperature rise, melting and vaporization which eventually creates a micro crater [4]. As such most of the theoretical models were developed based on single spark only although that is not the real case in practice where millions of sparks were used to create desired shape [5-6]. In addition, the process becomes more complicated when applied for cutting nonconductive materials (electrical conductivity less than 0.1 S cm⁻¹) as it involves assisted electrode to create initial spark between real electrode and workpiece. In addition to melting and vaporization, there exist a complex and uncountable phenomena call “spalling” in material removal process [7].

Models are useful in controlling the process effectively and efficiently. Two approaches are widely used for modelling in micro-EDM. The first one is empirical models that are developed on the basis of experimental investigations. The second one is theoretical models that are developed using the
fundamentals of the electrical circuit, theories of thermodynamics and heat transfer. In theoretical modelling, it is presumed that the electrical energy is converted to thermal energy and causes the material removal of the workpiece. Theoretical models can be categorized based upon the assumption of heat flux whether it is uniform (disc), point heat source, or cylindrical plasma [8]. The models can be further divided into three categories: anode erosion, cathode erosion and plasma channel modelling. Each of the models has its own characteristics according to the variation of hypothesis and development process. Although there are mathematical models for to estimate micro EDM characteristics for conductive materials are of plenty, there are scarcity of models for nonconductive materials. In this article a comparison of EDM models for conductive and nonconductive materials are compared.

2. Micro-EDM Models for Conductive Materials

2.1 Dibitonto’s model

Functional relationship between the input parameters and crater radius in EDM has been assuming that the plasma radius at the cathode is smaller than the anode [9]. A schematic diagram of an EDM crater as assumed in this model is shown in Figure 1. Point heat source was approximated with spherical symmetry of melt front. As a result, the crater profile was assumed hemispherical. The cathode was assumed to consume 18% of the total energy. In this modelling, the crater radius was expressed as the function of heat energy. The temperature distribution during EDM is expressed by:

\[ T_m = T_0 + \frac{q r}{K_i} \text{erfc} \left( \frac{r}{2\sqrt{at}} \right) \]

where \( T_m \) = melting temperature of the material, \( r \) = crater radius, \( q \) = power, \( t \) = discharge duration, \( T_0 \) = room temperature, \( K_i \) = workpiece heat conductivity, \( \alpha \) = workpiece heat diffusivity \((K_i/\rho C_p)\), \( \rho \) = workpiece density, and \( C_p \) = workpiece specific heat.

![Figure 1. Schematic diagram of an EDM crater](image1)

2.2 Salonitis’ Model

MRR and \( R_a \) models have been developed in EDM using three dimensional heat conduction equation. In the modelling, uniform heat source and craters of circular paraboloid geometry with no recast layer were assumed. It was also postulated that the idling time is insignificant compared with the discharge duration. The crater geometries are as shown in Figure 2. The crater diameter on the surface has been determined from empirical relations. The developed models in terms of the MRR and \( R_a \) are expressed by:

\[ MRR = \frac{\pi s r_c^2 \times N_s}{2 \times t} \]

\[ R_a = \frac{1}{4} \left( \frac{r_c + r_s}{r_s} \right)^2 s \]

where \( s \) = crater depth, \( r_c \) = crater radius, \( r_s \) = heat input radius (μm), \( N_s \) = number of sparks in unit time, and \( t \) = time. However, \( s \) and \( r_c \) can be presented as,
\[ s = \frac{q_w I}{\rho [L_v + c_p (T_s - T_0)]} \]  

where \( q_w \) = heat source intensity distribution, \( \rho \) = density, \( L_v \) = latent heat of vaporization, \( c_p \) = specific heat, \( T_s \) = erosion front temperature, and \( T_0 \) = ambient temperature. Similarly, \( r_c \) can be presented as,

\[ r_c = \frac{d}{2} = M \times (I \times t)^W \]  

In Equation (5), M and N are material dependent properties which are determined from experimental investigations.

3. Micro-EDM Models for Nonconductive Ceramics

Theoretical models which could be applied in micro-EDM of nonconductive ceramics are not available in the literature. Therefore, some models developed based on experimental investigations have been reviewed in this section. The effect of tool polarity, voltage, feed rate and rotational speed of electrode on MRR and surface roughness in ED milling of insulating Al\(_2\)O\(_3\) has been investigated with a very thin copper sheet AE, steel wheel tool electrode and water based emulsion dielectric. AE was fed continuously in the machining zone which was fed back immediately after the spark occurrence [10]. Therefore, heat was absorbed by Al\(_2\)O\(_3\) workpiece instead of AE [11]. The overall findings of the investigation on the machining characteristics in ED milling of Al\(_2\)O\(_3\) are summarized in Table 1.

The effects of emulsion concentration, NaNO\(_3\) concentration, polyvinyl alcohol concentration and flow velocity of the machining fluid on the characteristics in ED milling of alumina has been investigated using water-based emulsion dielectric fluid [10]. Other models of EDM with powder addition in dielectric fluid [12] are considered out of the scope of this paper. The study showed that a higher MRR and good surface quality can be obtained using suitable emulsion concentration. It was also observed that the MRR increases with higher flow velocity of fluid, with negligible change in surface roughness.

Empirical models of the MRR and surface roughness in EDM of nonconductive ZrO\(_2\) have been developed by the Taguchi method [13]. Table 2 shows the optimal combination of the machining parameters for MRR and surface roughness. It was observed in the investigation that the main parameters of material removal in EDM of ZrO\(_2\) are peak current (I\(_p\)) and pulse-on time (t\(_p\)). Higher I\(_p\) and t\(_p\) increase MRR due to enlarged energy in a single pulse. The machined surface becomes coarser at higher I\(_p\) and t\(_p\), i.e. surface roughness is increased. Effect of tool materials on output characteristics MRR and surface roughness has been investigated in EDM of Al\(_2\)O\(_3\) ceramic material using colloidal graphite solution AE and electrodes of Cu, graphite (Poco EDM-3) and Cu-infiltrated-graphite (PocoEDM-C3) [14]. This research identified the effect of electrode material and polarities on EDM characteristics viz. MRR and surface roughness.

**Table 1. Effect of parameters on characteristics in ED milling of Al\(_2\)O\(_3\) [10]**

| Parameter                          | MRR                         | Surface roughness       |
|-----------------------------------|-----------------------------|-------------------------|
| Tool polarity (TP)                | 2-4 times higher in +ve     | Higher in +ve           |
| Peak voltage (PV)                 | Rises with an increase in PV| Rises initially with the increase in PV and then decreases with the increase in PV |
| Rotational speed (RS) of the tool electrode | Initially increases faster with the increase of RS and then increases slowly with an increase in RS | Initially increases with the increase of RS and then increases slowly with an increase in RS |
| Feed speed (FS) of the workpiece  | Initially increases faster with the increase of FS and then decreases with an increase in FS | Initially decreases with an increase of FS and then increases slowly with an increase in FS |
4. Comparison of Models for Conductive and Nonconductive Materials

From the above review it can be concluded that there is some specific difference between the modelling of EDM of conductive materials and nonconductive ceramic materials. A comparison between EDM modelling for conductive and nonconductive ceramics is given in Table 4. It is observed that the models of micro-EDM for conductive materials have been developed on the basis of melting and vaporization phenomena, assuming that the energy supplied to the workpiece surface increases the temperature to the boiling point and is removed by vaporization immediately. In micro-EDM, about 90% of the molten material is removed by vaporization and the material beneath the surface gets less energy which is removed by melting [17]. Melting and vaporization are the usual mechanisms in EDM and most of the theoretical models have been developed considering fundamental heat transfer theories.

Micro-EDM shows some differences from macro-EDM with respect to the level of energy, crater diameter and power density, although the material removal mechanism is the same. Spalling is assumed negligible and insignificant in micro-EDM of conductive materials. But in micro-EDM of nonconductive ceramics, the main material removal mechanism is spalling, although melting and vaporization occur depending on the type of ceramic. A comparison between EDM modelling for conductive and nonconductive ceramics is given in Table 4.

### Table 2. Optimal combination of the machining parameters for EDM on ZrO$_2$ ceramic [13]

| Process characteristics | AE optimized process parameters | Optimized process parameters |
|-------------------------|--------------------------------|----------------------------|
| Maximum MRR (0.2869 mm$^3$/min) | Cu foil | I$_p$ (A) 4, I$_H$ (A) 0.4, t$_P$ (µs) 200, EJI (s) 4, S$_v$ (V) 55 |
| Minimum TWR (0.0026 mm$^3$/min) | Al foil | I$_p$ (A) 2, I$_H$ (A) 0.9, t$_P$ (µs) 50, EJI (s) 3, S$_v$ (V) 70 |
| Minimum surface roughness (3.37 µm) | Al foil | I$_p$ (A) 2, I$_H$ (A) 0.9, t$_P$ (µs) 50, EJI (s) 3, S$_v$ (V) 40 |

### Table 3: Surface resistivity of conductive layer generated with various electrodes [14]

| Electrode material | Electrical resistivity (Ω cm) | Electrical conductivity (S cm$^{-1}$) | Negative polarity | Positive polarity |
|--------------------|------------------------------|-------------------------------------|-------------------|------------------|
| Pure copper        | $1.018 \times 10^1$         | $9.80 \times 10^{-2}$              | $25 \text{ µm}$  | $4.071 \times 10^3$ |
| Cu-infiltrated graphite | $4.924 \times 10^0$       | $2.03 \times 10^{-1}$             | $90 \text{ µm}$  | $5.471 \times 10^2$ |
| Graphite           | $1.491 \times 10^1$         | $6.70 \times 10^{-2}$              | $30 \text{ µm}$  | $4.971 \times 10^3$ |

About 40% increase in process speed and 25% increase in bore depth were observed with electrode vibration or rotation. The characteristics of voltage and current signals in micro-EDM of ZrO$_2$ were compared with micro-EDM of steel in their investigation. The result shows that current and voltage waveforms are not influenced by the machining depth and flushing conditions in micro-EDM of steel. In nonconductive ceramics, similar discharge shapes to those in metal are observed during the machining of starting AE. But it becomes short-peak-long-hold type during the machining of nonconductive ceramics which is named ceramic discharge. Peak current is also decreased with the increase of machining depth in ceramics [16].

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| Criterion                        | Conductive material                  | Nonconductive ceramics                                      | References |
|----------------------------------|--------------------------------------|-------------------------------------------------------------|------------|
| Need of AE                       | No                                   | Yes                                                         | [2]        |
| Dielectric                       | Any type                             | Carbonic for EDM or micro-EDM                               | [10]       |
| Main material removal mechanism  | Melting and vaporization             | Spalling                                                   | [17]       |
| Crater geometry                  | Regular shape                        | No regular shape                                           | [11]       |
| Voltage and current shapes       | Follow the setup value               | Different pattern than setup value                          | [14,16]    |
| Percentage of effective discharge| Higher                               | Lower                                                      | [16]       |
| Material removal rate            | Higher                               | Lower                                                      |            |
| Surface roughness                | Lower                                | Higher                                                     |            |
| Models available                 | Both theoretical and empirical for EDM and micro-EDM | Only empirical for EDM                                      |            |

5. Summary

In this article the recent development in the field of micro-EDM for cutting nonconductive ceramic materials has been discussed. Several micromachining processes have been discussed to have an overview of micro metal cutting to justify the importance of micro-EDM process usually used for cutting conductive materials. The main focus of the article was material removal rate which eventually involves process parameters and special experimental setup. Use of assisting electrode to initiate the spark and to form pyrolytic carbon for subsequent spark are the key to cut nonconductive materials. However, accurate theoretical model for cutting conductive materials is hardly possible which is almost impossible for the case of nonconductive materials. Most of the models are of combination of theoretical and experimental in nature. Although models are not perfect, a comparison has been presented for the ease of selection for any specific purpose. This review showed that there exists a huge need to conduct research to cut nonconductive materials using micro-EDM.

References

[1] Ali M Y, Banu A, Salehan M, Adesta EYT, Hazza, M and Shaffiq M 2018 Dimensional Accuracy in Dry Micro Wire Electrical Discharge Machining J. Mech. Eng. and Sci. 12(1) 3321-3329
[2] Hösel T, Müller, C and Reinecke H 2011 Spark erosive structuring of electrically nonconductive zirconia with an assisting electrode Int. J. Prec. Eng. Manuf. 11(4) 629-632
[3] Banu A, and Ali M Y 2016 Electrical Discharge Machining (EDM): A Review. Int. J. Eng. Mater. Manuf. 1(1) 3-10. https://doi.org/10.26776/ijemm.01.01.2016.02
[4] Yoo B H, Min B-K and Lee S J 2010 Analysis of the machining characteristics of EDM as functions of the mobilities of electrons and ions Int. J. Prec. Eng. Manuf. 11(4) 629-632
[5] Dhanik S, and Joshi S S 2005 Modeling of a single resistance capacitance pulse discharge in micro-electro discharge machining J. Manuf. Sci. Eng. 127(4) 759-767
[6] Ali M Y, Sabur A, Banu A, Maleque A and Adesta, E Y T 2018 Micro Electro Discharge Machining for Nonconductive Ceramic Materials Int. J. Eng. Mater. Manuf. 3(1) 55-62 https://doi.org/10.26776/ijemm.03.01.2018.07
[7] Liu Y, Yu L, Xu Y, Ji R and Li Q 2009 Numerical simulation of single pulse discharge machining insulating Al2O3 ceramic J. Eng. Manuf. 223(1) 55-62
[8] Salonitis K, Stournaras A, Stavropoulos P and Chryssolouris G 2009 Thermal modeling of the material removal rate and surface roughness for die-sinking EDM Int. J. Adv. Manuf. Technol. 40(3-4) 316-323
[9] Dibitonto D D, Eubank P T, Patel M R and Barrufet, M A 1989 Theoretical models of the electrical discharge machining process I. A simple cathode erosion model J. Appl Phys 66(9) 4095–4103

[10] Liu Y, Li X, Ji R, Yu L, Zhang H and Li Q 2008 Effect of technological parameter on the process performance for electric discharge milling of insulating Al₂O₃ ceramic J. Mater. Process Technol. 208(1) 245-250

[11] Ji R, Liu Y, Zhang Y, Wang F, Cai B and Fu X 2012 Single discharge machining insulating Al₂O₃ ceramic with high instantaneous pulse energy in kerosene Mater Manuf Process 27(6) 676-682

[12] Jamil H, N A B, Lajis, M A B and Idris M R B 2018 Modelling and optimization of Chromium Powder Mixed EDM Parameter Effect Over the Surface Characteristics by Response Surface Methodology Approach Int. J. Eng. Mater. Manuf. 3(2) 78-86 https://doi.org/10.26776/ijemm.03.02.2018.02

[13] Chen Y F, Lin Y J, Lin Y C, Chen S L and Hsu L R 2010 Optimization of electrodischarge machining parameters on ZrO₂ ceramic using the Taguchi method J. Eng. Manuf. 224(2) 195-205

[14] Muttamara A, Fukuzawa Y, Mohri N and Tani T 2009 Effect of electrode material on electrical discharge machining of alumina. J. Mater. Process. Technol. 209(5) 2545-2552

[15] Schubert A and Zeidler H 2009 Machining of nonconductive ZrO₂ ceramics with micro-EDM. Proc. 9th Int. Conf. Europe Soc. Preci Eng & Nanotechnology, San Sebastian, Spain, 2, 6-9

[16] Schubert A, Zeidler H, Wolf N and Hackert M 2011 Micro electro discharge machining of electrically nonconductive ceramics AIP Conf. Proc. 1353 1303

[17] Zahiruddin M and Kunieda M 2012 Comparison of energy and removal efficiencies between micro and macro EDM CIRP Ann. Manuf. Technol. 61(1) 187-190