

Micro Electro Discharge Machining of Nonconductive Ceramic *

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ABSTRACT

The micro-electro discharge machining (micro-EDM) models established for single spark erosion are not applicable for nonconductive ceramics because of random spalling. Moreover, it is difficult to create single spark on a nonconductive ceramic workpiece when the spark is initiated by the assisting electrode. In this paper, process development for nonconductive zirconium oxide (ZrO_2) is discussed. It is shown that the charging and discharging duration depend on the capacitance and resistances of the circuit. The number of sparks per unit time is estimated from the single spark duration derived from heat transfer fundamentals. The model showed that both the capacitance and voltage are significant process parameters for material removal rate (MRR). However, capacitance was found to be the dominating parameter over voltage. As in case of higher capacitances, the creation of a conductive carbonic layer on the machined surface was not stable; the effective window of machining $10^1 - 10^3$ pF capacitance and 80 - 100 V gap voltage or 10 - 470 pF capacitance and 80 - 110 V gap voltage. This fact was confirmed EDX analysis where the presence of high carbon content was evident. Conversely, the spark was found to be inconsistent using parameters beyond these ranges and consequently insignificant MRR. Nevertheless, the effective numbers of sparks per second were close to the predicted numbers when machining conductive copper material. In addition, higher percentage of ineffective pulses was observed during the machining which eventually reduced the MRR. In case of validation, average deviations between the predicted and experimental values were found to be around 10%.

Keywords: Micro-EDM, Nonconductive ceramics, assisting electrode, MRR

1 INTRODUCTION

Advancement in technology has opened the windows of some special materials to meet particular requirements by means of miniaturization. Nonconductive ceramics are considered one of the most promising materials that can fulfil the demands of multifarious miniaturized applications in microfluidics, reactors, electromechanical generators and for medical purposes. However, these materials are difficult to machine by conventional machining techniques due to their high hardness and brittleness. Nonconventional machining processes are regarded as promising for the structuring or shaping of nonconductive ceramics [1]. Micro-electro discharge machining (micro-EDM) is a nonconventional, noncontact and effective process for structuring conductive, hard and brittle materials. Most of the advanced ceramics are electrically nonconductive; therefore, micro-EDM cannot be used directly. In recent years, an advanced technique has been introduced to utilize micro-EDM for nonconductive ceramics in which an electrically conductive metallic layer, referred as the 'assisting electrode' (AE) is applied on the workpiece surface. Using the AE and controlling the micro-EDM process parameters such as capacitance, voltage and polarity, nonconductive ceramics (ZrO_2 , Al_2O_3 , Si_3N_4 and SiC) have been successfully structured.

1.1 Nonconductive Ceramics

Nonconductive ceramics are also known as engineering, advanced, technical, or insulating ceramics. Their electrical conductivity is less than 0.1 Scm^{-1} [2-3]. Due to the excellent chemical and physical properties, nonconductive ceramics are now being used in fabrication of domestic, industrial and building products. Specific applications include cutting

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tools, self-lubricating bearings, turbine blades, internal combustion engines, heat exchangers, ballistic armour, ceramic composite automotive brakes, diesel particulate filters, piezo-ceramic sensors and a wide variety of prosthetic products. Currently, nonconductive ceramic materials are used in the biomedical field to fabricate femoral heads and acetabular cups for total hip replacement, dental implants and restorations, bone fillers and scaffolds for tissue engineering. Nano-structured alumina (Al_2O_3) and zirconia (ZrO_2) based ceramics and composites or non-oxide ceramics could be potential candidate material for biomedical applications in the near future [4].

1.2 Micro-electro Discharge Machining

Micro-electro discharge machining (Micro-EDM) is an electro-thermal material removal process which is used for manufacturing three-dimensional micro-components. In this machining process, a series of electrical sparks or discharges occurs rapidly in a short span of time within a constant spark gap between the tool electrode and the workpiece. It is a complex process in which thermodynamic, hydrodynamic, electromagnetic and electrodynamic processes are involved. Any material having a minimal electrical conductivity of 0.1 Scm^{-1} can be machined by micro-EDM irrespective of its hardness and brittleness [3]. In micro-EDM, thermal energy evolved from the electrical sparks flows into the electrode, workpiece and dielectric fluid. A fraction of the heat is conducted through the workpiece and an enormous temperature rise causes melting and vaporization of a small amount of material from the workpiece [5]. In this way a micro-crater is formed in every effective spark. Thus, theoretical models of material removal rate (MRR) and average surface roughness (R_a) in micro-EDM of conductive materials have been developed based on electrical circuit and heat conduction theories considering the material removal by melting and vaporization [6-8]. However, the micro-EDM process can also be used for micro-structuring of electrically nonconductive ceramics applying AE [3]. In micro-EDM of nonconductive ceramics, material is removed by melting, vaporization and spalling [9].

In micro-EDM of nonconductive ceramics, after the removal of the initially applied assisting electrode, a layer of pyrolytic carbon (PyC) would be deposited on the workpiece surface, disassociating the carbonic dielectric in the absence of oxygen at the higher temperature. The new layer would have the threshold of electrical conductivity for continuation of the machining, resulting in material removal by melting, vaporization and spalling. Since the melting, vaporization and spalling is the effect of energy and energy is the function of capacitance and voltage in a RC pulse circuit, it is postulated that MRR would have a functional relationship with capacitance and voltage. The models of micro-EDM for nonconductive ceramics can certainly contribute towards making the process user-friendly and helping machining parameters selection for desired outputs.

In micro-EDM, the discharge duration and supplied energy are much lower than EDM, with discharge duration limited to around 100 ns and the amount of supplied energy being about $10 \mu\text{J}$.

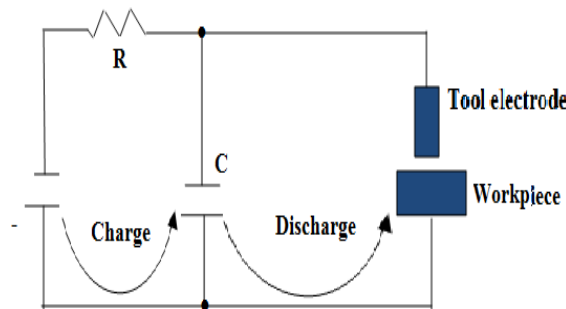


Figure 1: Schematic diagram of relaxation type pulse generator in EDM [12]

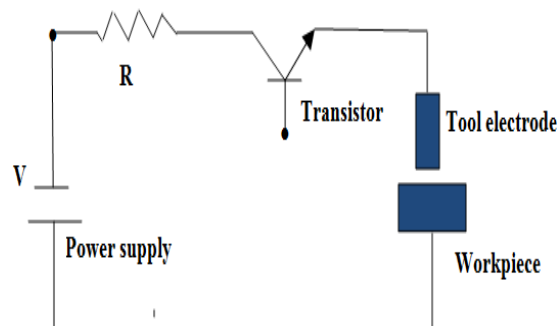


Figure 2: Schematic diagram of transistor type pulse generator in EDM [12]

However, the power density is higher in micro-EDM [10-11]. To create the pulses, relaxation or transistor type generators can be used. Schematic diagrams of relaxation and transistor type pulse generators are shown in Figure 1 and Figure 2 respectively. In a relaxation type generator, resistance and capacitance are connected to the circuit in which the capacitor charging and discharging occur alternatively. Using this circuit, discharge can be created with a high peak current for a short duration. Current and gap voltage are controlled at a predefined level throughout the pulse on-time. In a transistor type pulse generator, a series of resistance and transistors are connected in series as a switching device. This circuit can provide longer discharge duration with a larger peak current. The transistor type circuit has a longer ignition delay time.

Generator selection in micro-EDM depends on the desired machining outputs. The transistor type generator is capable of creating a higher energy with a larger peak current and longer discharge duration. On the other hand, the RC pulse generator can be controlled precisely to generate very low energy with a shorter discharge duration [12]. Therefore, the RC pulse generator is used as the pulse creator in micro-EDM to produce highly precise microstructures [13]. A multi-purpose miniature machine tool (DT-110, Mikrotools Inc., Singapore) has been manufactured for micromachining with high precision in which a RC pulse circuit is used [14-15].

As a noncontact machining process, micro-EDM is capable of machining any material which is electrically conductive, irrespective of its hardness, shape and strength [16]. Micro-EDM is useful in producing three-dimensional micro-structures with a higher *MRR*, a machining accuracy of 1-5 μm and an aspect ratio of more than 20 [17]. A minimum feature of 10 μm is possible in fabricating precise micro-hole, micro-mechanical parts, milling tools and complex micro-structures by micro-EDM [18].

1.3 Assisting Electrode

AE is an additional conductive layer on the workpiece that is applied to initiate sparks during machining or structuring of nonconductive ceramic materials [19]. There are two methods of applying AE. In the first method, AE is adhered onto the workpiece to start machining. Once the AE layer finishes, carbon molecule cracked from carbonic dielectric is deposited on the machined surface and a conductive thin layer is generated which assists in creating a further spark. The adhesive copper or aluminium foil, coated graphite, silver varnish, sputtered workpiece material with copper, silver or gold are the main materials used as AE. A schematic diagram of micro-EDM of nonconductive ceramics using fixed AE is shown in Figure 3. In the second method, conductive metallic AE foil or sheet is continuously fed into the machining zone by a servo mechanism as shown in Figure 4. Electro discharge (ED) milling of Al_2O_3 has been successfully accomplished using the continuously feeding AE method and it is considered a suitable process for large area machining [20]. In this process, a steel wheel is used as a tool electrode mounted on a rotary spindle driven by an AC motor. The tool electrode and the AE are connected to the positive and negative poles of the pulse generator respectively.

This paper presents the research development in micro-EDM of nonconductive ceramic materials. Micromachining techniques were discussed briefly to justify the selection of micro-EDM for this study. Basic principles, process parameters and characteristics of micro-EDM were highlighted. Assisting electrode techniques and material removal mechanisms in micro-EDM of nonconductive ceramic materials were discussed extensively. Special focus was given in exploring the theoretical modelling in micro-EDM of nonconductive ceramic materials. From the review, it appeared that the most of existing micro-EDM theoretical models are not applicable for nonconductive ceramic materials which results in the need to develop new models for process characteristics.

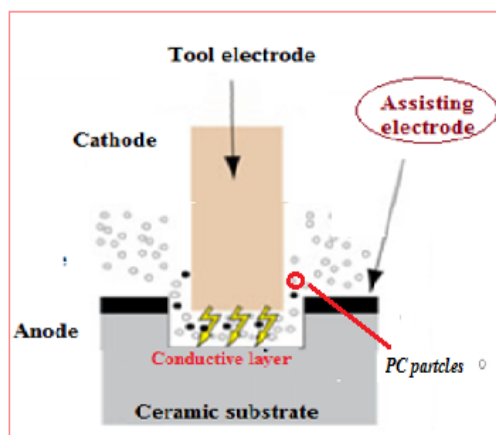


Figure 3: Schematic diagram of micro-EDM of nonconductive ceramics with fixed AE [2]

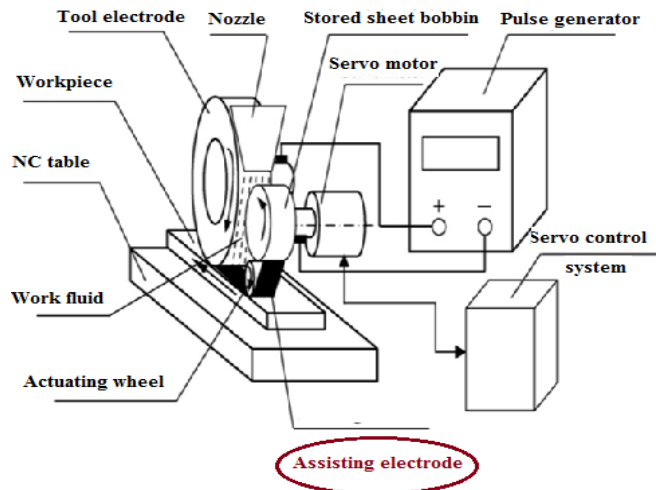


Figure 4: ED milling of nonconductive ceramics [21]

2 EFFECT OF DIFFERENT PULSES ON MRR

Pulses were recorded during micro-EDM of ZrO_2 and five categories of pulses have been identified which are as follows:

2.1 Normal (effective) Pulse:

Normal pulses are produced when the capacitor is fully charged before the spark and fully discharged during the sparks. One of the images of effective pulse is shown in Figure 5. Normal pulses are effective in material removal because of the maximum energy supply by the circuit. Normal pulses were observed during the machining of Cu AE and during the initial stage of ceramic removal. According to Figure 5, The spark had occurred after the completion of charging, without any delay. The discharge shape was almost vertical, which indicates that there was no resistance between the tool and workpiece. The calculated spark number is 909090 for $R = 10^3 \Omega$ and $C = 220 \text{ pF}$. From Figure 5, it is obvious that the effective sparks recorded by oscilloscope to be 902000 which agrees with the calculated value.

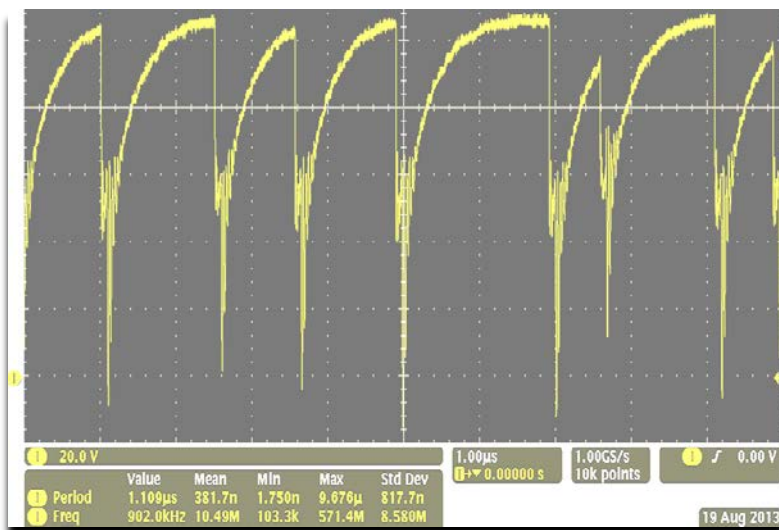


Figure 5: Normal pulse at $C = 220 \text{ pF}$ and $V = 110 \text{ V}$

2.2 Pulse During Cutting Ceramics

One of the images of ceramic pulses is shown in Figure 6. Once the copper AE was finished, sparks began to occur between PyC AE and the tool electrode, removing ceramic material. At the beginning of ceramic machining, the normal shape of voltage signal was observed in the charging stage. As the machining progressed, pulses began to

remain constant at peak for long periods which indicate that the capacitor was fully charged but was waiting to release energy. It can be assumed that the conductive PyC layer had yet to attain the sufficient thickness and conductivity for the sparks. Once the conditions were fulfilled, the sparks occurred. From Figure 6, it can be concluded that the ceramic pulses have a longer pulse-off time than normal pulses.

2.3 Effective Arc Pulse

Some pulses were observed in which the capacitor was not fully discharged and the spark had occurred at higher voltages than zero, with lower currents. These are known as effective arc pulses. One of the images of effective arcs is given in Figure 7. Effective arcs have a smaller current than normal or ceramic discharges and remove a little amount of material. Effective arcs occurred due to the presence of a small amount of debris in the gap. Fewer electrons can reach the anode because of insufficient energy [20-21]. Two types of effective arc pulses were observed. In the first type of effective arcs, pulse-off time was similar to the normal pulse. In the second category of effective arcs, pulse-off time was longer which is similar to ceramic pulse.

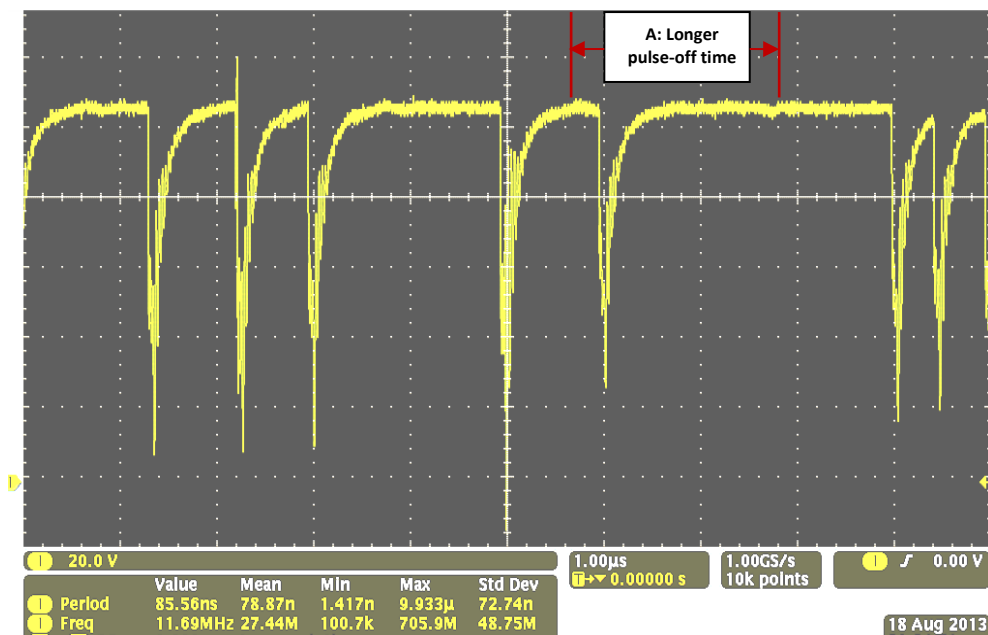


Figure 6: Pulses during cutting ceramics at $C = 100$ pF and $V = 110$ V

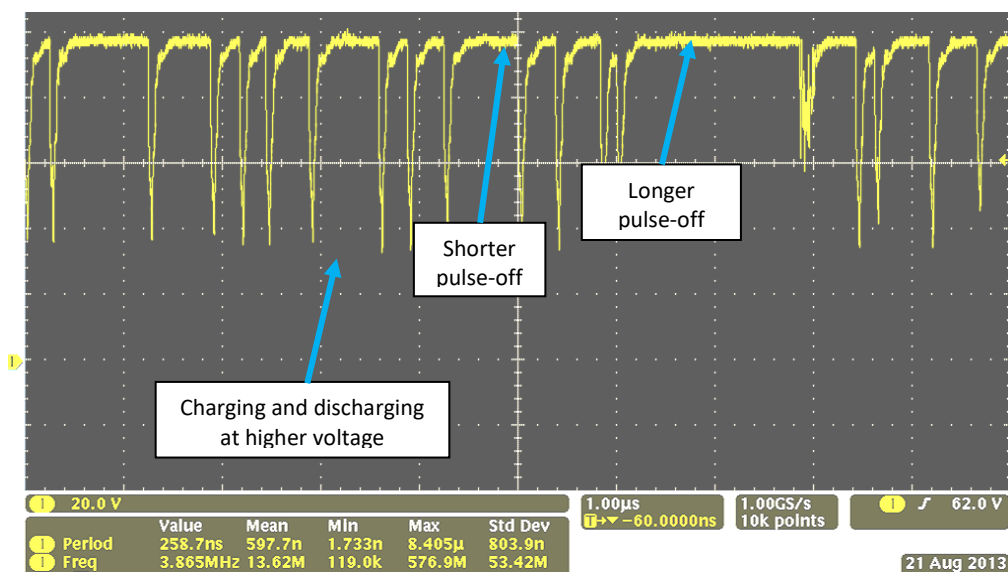


Figure 7: Effective arc discharge at $C = 100$ pF and $V = 100$ V

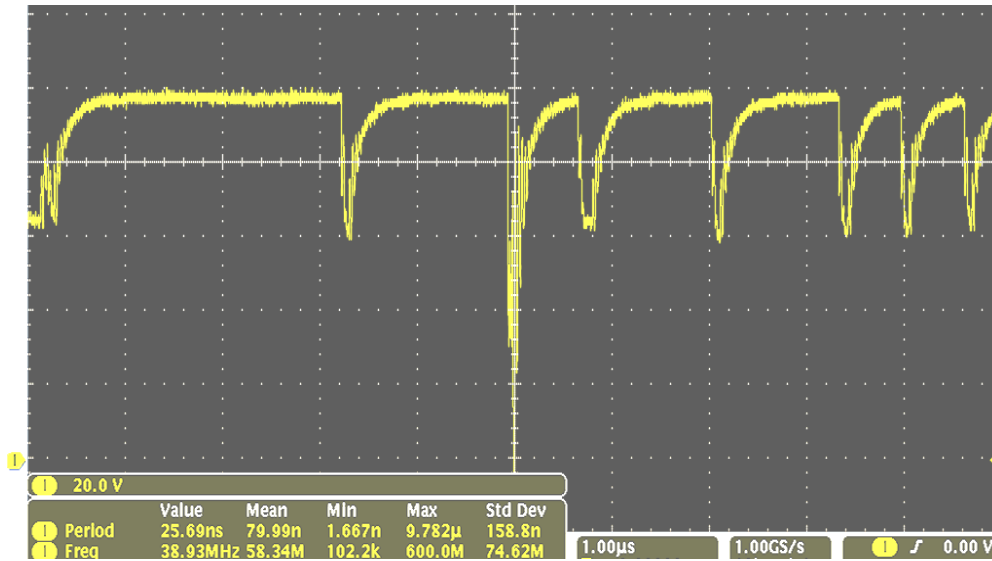


Figure Error! No text of specified style in document.8: Immature discharges at $C = 100 \text{ pF}$ and $V = 100 \text{ V}$

2.4 Immature Pulse

During the deep machining of nonconductive ceramics, several pulses were observed in which sparks occurred after the capacitor voltage had reached a peak value. But charging started at a much higher voltage. These are identified as immature pulses. Immature pulses are produced due to the presence of a huge amount of debris inside the cavity and it creates a very small amount of energy. One of the images of immature pulses is given in Figure 8. Most of the immature pulses do not follow the charging and discharging characteristics of the RC circuit. In many cases, they are mixed with normal and ceramic pulses and produce complex pulse shapes [22].

2.5 Short Circuit

The short circuit occurred frequently in micro-EDM of nonconductive ceramics mainly due to two reasons:

- i) The presence of debris which creates the channel of current flow without the sparks;
- ii) Tool movement towards the workpiece without creation of a sufficiently conductive carbonic layer.

Table Error! No text of specified style in document.1 Experimental parameters

Conditions		Values		
Workpiece		ZrO ₂		
Tool electrode		Cylindrical copper rod		
Tool electrode diameter (mm)		1		
Tool electrode polarity		-ve		
Assisting electrode		Adhesive copper foil		
Assisting electrode thickness (μm)		60		
Dielectric		Kerosene		
Pulse generator		RC		
Resistance ($\text{k}\Omega$)		1		
Variables				
Factors	Parameters	Levels		
		I	II	III
A	Capacitance, C (pF)	1000	100	10
B	Voltage, V (V)	100	90	80
C	Speed, n (rpm)	350	300	250
D	Feed rate, f ($\mu\text{m/s}$)	2	1.6	1.2

2.6 Experimental Design

The design of experiments (DOE) is the technique of defining and investigating all possible conditions in an experiment involving multiple factors. A scientific approach was used for planning and conducting the experiments and for analysing the data efficiently. The DOE was used to:

- i) Reduce the number of trials significantly.
- ii) Identify important decision variables which control and improve the characteristics of the product or the process.
- iii) Find out the optimal setting of the parameters.

In this study, the Taguchi method was used for DOE and subsequent analysis of the results. It requires a minimum of one run per condition of the experiment. But one run does not represent the range of possible variability in the results. Repetition allows determination of variance index called signal to noise ratio. The greater this value, the smaller the product variance around the target. The parameters and their levels for the *MRR* were selected based on an experimental study as presented in Table 1. In the experimental investigations for the modelling of *MRR*, it was observed that the speed and feed rate are not significant parameters in micro-EDM of ZrO₂.

To apply the models in micro-EDM of nonconductive ZrO₂ ceramic, parameters were found out by solving the developed models based on the expected *MRR_c*. Using the parameter values, micro-channels and micro cavities were machined on nonconductive ZrO₂ ceramic material. Expected *MRR_c* were compared with the experimental values.

3 CONCLUSIONS

In this research, theoretical models of the material removal rate (*MRR*) in micro-EDM of nonconductive ZrO₂ ceramic have been developed and validated. The research findings have been summarized as follows.

1. Process parameters for effective Micro-EDM of ZrO₂ have been identified by experimental study. Capacitance ranges of 1⁰¹ - 1⁰³ pF and gap voltages of 80 - 100 V or capacitance ranges of 10 - 47⁹ pF and gap voltages of 80 - 110 V have been identified as effective electrical parameters for micro-EDM of ZrO₂ with a -ve copper tool electrode and adhesive copper foil assisting electrode in kerosene dielectric fluid.
2. Models have been developed for RC pulse micro-EDM based on the single spark erosion using electro-thermal theories. Multiplying correction factor (ε) derived from experimental investigations have been introduced to adjust the *MRR* in micro-EDM of nonconductive ZrO₂. The theoretical *MRR* model has been expressed by following equation.

$$MRR_c = \frac{\varepsilon N_s k C V^2}{2\rho} \left[\frac{k_1}{H_v} + \frac{k_2}{H_m} \right]$$

$$\varepsilon = \left(-0.043 + 0.00009 \times C + 0.0022 \times V \right)^2$$

$$N_s = \frac{1}{5C(R_1 + R_2)}$$

where ε is an experimental correction factor which has been determined in terms of the process parameters of capacitance and voltage and is expressed by following equation. N_s is the number of sparks per second which is estimated from the RC pulse charging and discharging duration and is expressed by:

3. It was found that the experimental *MRR_c* is very low compared to the theoretical values due to the longer pulse-off time in micro-EDM of nonconductive ceramics and for the effect of various ineffective pulses such as delayed discharge, short circuit, arching and immature discharges. In modelling, the formation energy of PyC and the machining energy of PyC were not quantified. Therefore, in addition to spalling effect, the correction factor, ε also includes the effect of formation-dissociation of PyC and the effect of ineffective pulses.
4. From the experimental investigation, it was found that capacitance is the most significant parameter for the creation of a conductive PyC layer in micro-EDM of nonconductive ZrO₂ ceramic. However, the *MRR* is controlled by voltage as a whole.
5. The *MRR* in micro-EDM of ZrO₂ was found to be very low compared to other hard materials. Because of electrical nonconductivity, a higher number of ineffective pulses were produced, which eventually lowered the *MRR* in ZrO₂ as compared to conductive materials.
6. Experiments were conducted to validate the *MRR* in micro-EDM of conductive copper materials. The effective number of sparks were recorded by oscilloscope at the initial stage of machining about 902000,

which agrees with the calculated spark numbers of 909090 (at $R = 10^3 \Omega$ and $C = 220 \text{ pF}$). It has been also observed that the number of effective pulses decreased with the increase of depth of cut and about 50% of pulses were found to be ineffective in micro-EDM of conductive materials.

7. Micro-channels have been created on ZrO_2 with selected parameters for the expected MRR_c values as one of the applications of micro-EDM models.
8. It was shown that the MRR_c in micro-EDM of ZrO_2 were found to be in agreement with the calculated expected values by an average error of 8.86 %.

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