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MICRO-EDM FOR MICRO-CHANNEL FABRICATION ON NONCONDUCTIVE ZrO_2 CERAMIC

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ABSTRACT

In this study, microelectro-discharge (micro-ED) milling of nonconductive ZrO_2ceramicsis investigated using a Cu tool electrode in kerosene dielectric. An adhesive Cu foil is firmly attached on the workpiece to initiate the sparks. After the machining of Cu foil, an electrically conductive carbonic layer is formed on the ceramic workpiece disassociating the kerosene dielectric, which allows micro-ED milling to be continued on ZrO_2.A micro-channel of 1500 µm length, 920 µm width and 150 µm depth is created. Energy-dispersive X-ray spectroscopy showed evidence of higher C precedence on the workpiece surface, which is the main element of the carbonic layer. It is shown that material removal rate increases with the increase of capacitance and voltage initially but it decreases at higher values. *MRR* and average surface roughness of the micro-channel are found to be 1.29×10^{-5} mm^3/s and 0.25 µm, respectively, when machined with a capacitance of 0.1 nF and voltage of 80 V. This study shows that micro-ED milling is applicable for creating micro-channels on nonconductive ZrO_2 ceramic with the assisting electrode technique.

***Keywords*:** Micro-electro discharge milling; nonconductive ceramics; assisting electrode; pyrolytic carbon; surface roughness.

INTRODUCTION

In microelectromechanical systems (MEMS), silicon has been used for micro device manufacturing. Instead of exclusive dependence on silicon, the trend has shifted tothe use of glass, metals, ceramics and elastomers in recent years[1]. Micro part ceramics also have wide spread demands in biomedical fields [2]. Silicon micro fabrication techniques such as lithography, epitaxy and etching are often not suitable for the processing of ceramics[1]. Tool-based mechanical micromachining techniques are not also applicable for processing ceramics because of their high hardness and brittleness [3]. Nonconventional processes such as focused ion beam (FIB) or laser ablation are applicable for micro structuring of nonconductive ceramics. However, the very low material removal rate (*MRR*) makes these processes tedious and time-consuming [4]. Microelectro-discharge machining (micro-EDM), a noncontact machining process in which electrical energy is converted to thermal energy, is widely used for microstructuring of conductive materials. It is an effective process for producing three-dimensional microstructures with a higher *MRR*, machining accuracy of 1–5 µm and an aspect ratio of more than 20:1 [1]. A minimum feature of 10 µm is possible in fabricating precise micro-hole, micro-mechanical parts, milling tools and complex microstructures with micro-EDM [5]. It has been applied to nonconductive ceramics using the assisting electrode (AE) technique [3]. In this technique, the sparks occur between an AE and tool electrode. Energy produced due to the spark causes ceramic material removal. The AE can be applied in two ways. In one method a conductive thin metal sheet is fed to the machining zone during the pulse-on time and fed back immediately after the spark occurrence. Any dielectric fluid can be used in this process and it is suitable for large area milling [6]. Machining of cavities or particular shapes on nonconductive ceramics is difficult we a continuously AE-fed technique. In the second method the AE is firmly adhered on the workpiece and submerged in carbonic dielectric[7]. After finishing the AE, a layer of conductive material is deposited on the workpiece surface disassociating the carbonic dielectric [8]. The new conductive layer acts as the AE and machining is progressed. Materials that have good electrical conductivity, such as Cu or Al foil, graphite or Ag, can be applied as an initial AE. Using this method machining of micro holes or cavities is possible. Even a microstructure with a high aspect ratio is attainable [7]. Micro-channel fabrication using a fixed AE in microelectro-discharge (micro-ED) milling is considered prospective for nonconductive ceramics [9]. But due to the limited research on micro-ED milling, its wide application in industry is still hindered.

In general, the parameter settings of electro-discharge machining (EDM) machines are specified for common steel grades [10-20]. A change in the value of a single parameter affects the machining in a complex way [21, 22]. Machining is observed as unstable in EDM ofZrO_2 and Al_2O_3at very high or very low gap voltages and currents [23, 24]. Selection of process parameters is also thought to be very important in micro-ED milling of nonconductive ceramics. Therefore, detailed investigation in micro-ED milling of nonconductive ceramics is needed to find out the essential conditions for stable machining. This study investigates the feasibility of machining a nonconductive ZrO_2 ceramic where micro-channels are fabricated as an example.

EXPERIMENTAL DETAILS

The experiments are conducted using a multipurpose miniature machine tool (DT-110, Mikrotools Inc., Singapore).A schematic diagram of the micro-EDM set-up for the machining of $ZrO_2$is shown in Figure 1. Machining conditions are listed in Table 1. The workpiece is covered by 60 µm-thick adhesive Cu foil. A cylindrical Cu rod is used as the tool electrode. Both the workpiece and tool electrode are submerged in kerosene dielectric. To investigate the capability and identify the parametric combination for effective machining with RC-pulse micro-EDM, experiments are conducted with different conditions. Then, micro-channels are created using a capacitance (C) of 0.1 nF and voltage (V) of 80 V. The depth of cut is set to 200 µm. The spark is initiated between the Cu foil AE and tool electrode. After removal of the Cu foil, a conductive carbonic layer is deposited on the machined surface, which acts as the AE, continuing the spark generation. A carbonic layer is also deposited on the side walls of the hole. Thus, during the movement of the tool, ceramic material is removed in a longitudinal direction due to the continuation of discharge. To compare the crater geometry of ZrO_2 to conductive materials, micro-EDM of Cu is also conducted. The surface texture and average surface roughness (R_a) are measured using a scanning electron microscope (SEM) (JEOL JSM-5600, USA) and optical surface profiler (WYKO, USA), respectively. The pulse waveforms are recorded with an oscilloscope (MSO 4104, Tektronix, USA) through a voltage probe (P6139A, Tektronix, China) to investigate the effectiveness of the sparks.

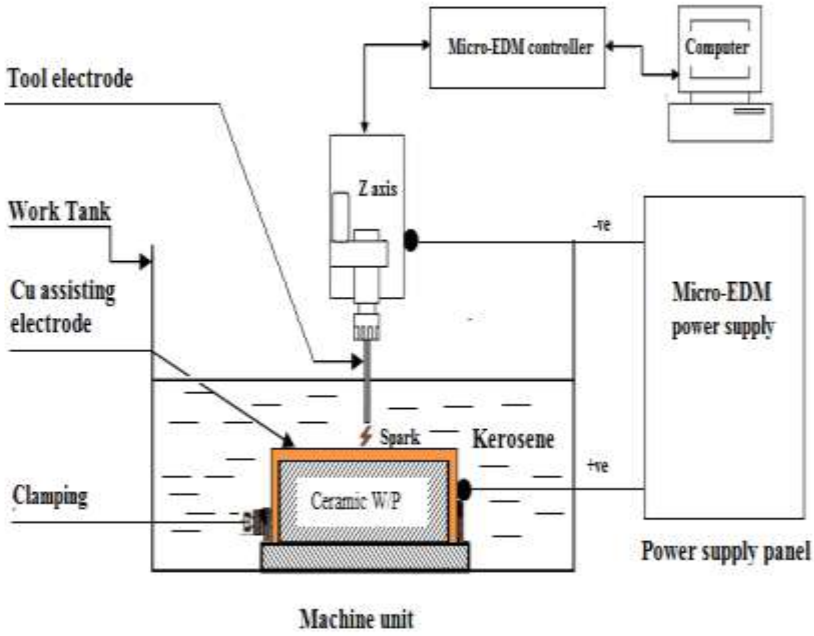

Figure 1. Schematic diagram of micro-EDM set-up for machining of nonconductive ZrO_2 with Cu foil AE.

Table 1. Conditions for Micro-EDM of ZrO_2.

Parameters [unit]	Conditions
Capacitance, *C* [nF]	0.01, 0.1, 1, 10
Voltage, *V* [V]	80, 90, 100
Rotational speed, *n* (rpm)	250
Feed rate, *f* (µm/s)	0.10
Tool electrode	Cu (ϕ 500, 900 µm)
Tool electrode polarity	–ve
Workpiece	ZrO_2 (92% purity)
Assisting electrode	Adhesive copper
Copper foil thickness (µm)	60
Dielectric	Kerosene

Identification of Parameters

As the combination of parameters is needed for the optimisation of outputs, the experiments are conducted in micro-ED milling of nonconductive ZrO_2. The results (yes/no) of experiments are listed in Table 2. Theoretically, a higher capacitance and voltage are supposed to give a higher material rate and surface roughness. However, it is observed in micro-EDM hole drilling of ZrO_2 that the higher capacitances (>1nF) are not effective and are not capable of producing a continuous conductive carbonic layer on the workpiece. Similarly, at very higher voltages(>100V) with the capacitances more than 0.1nF, a stable conductive carbonic layer does not form. It is also observed that the effective parameters for micro-EDM of ZrO_2 are capacitances of0.01–1nF and voltages of 80–100 V. Among this range, the rate of the effective pulse is observed to be higher and more consistent with the 0.1 nF capacitance and 80–90 V voltages.

Table 2. Machinability test results of preliminary experiments.

Expt. No	Capacitance, *C* (nF)	Voltage, *V* (V)	Significant machining (yes/ no)	Comments
1	100	80–100	No	
2	10	80–100	No	
3	1	80–100	Yes	
4	0.1	80–100	Yes	More stable
5	0.01	80–100	Yes	

Micro-channel Fabrication

Using the results of the preliminary experiments, micro-channels are created with a 0.1 nF capacitance and 80 V voltage. One of the SEM images of the micro-channel is shown in Figure 2. The channel edges sometimes become parabolic due to tool tip wear, which is also evident in micro-EDM of conductive materials [9]. In micro-channel machining one of the challenges is to keep the dimension within the expected range. The tool wear reduces the diameter of the tool and the width of the channel in the product. A u-shape channel was desired for the micro-EDM of ZrO_2 with a ϕ500μm tool Cu electrode. It shows that the initial width of the channel is more than the tool diameter which occurs due to tool vibration. As the machining progressed, tool diameter decreased and the channel width was reduced from the tool's initial diameter. To reduce the effect of tool wear, the tool should be dressed or new tools should be used for different axes. The micro-structure using different tools will be better than a single tool and feed.

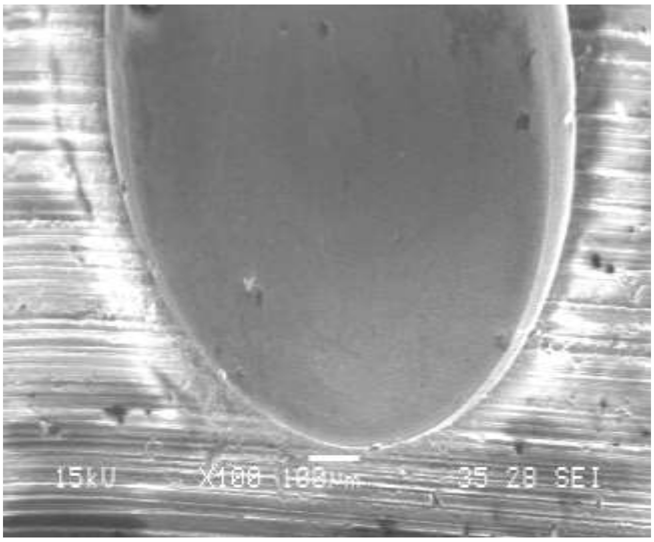

Figure 2. SEM image of micro-channel machined on nonconductive ZrO_2 by micro-EDM with Cu tool electrode and adhesive Cu foil AE in kerosene dielectric (at *C* = 0.1 nF and *V* = 80 V).

RESULTS AND DISCUSSION

Carbonic Layer Creation

The ZrO_2 workpiece was investigated with energy-dispersive X-ray spectroscopy (EDX) before and after the machining. EDX spectrograms are shown in Figure 3. It is evident that C content is not significant in the workpiece before machining (Figure 3(a)). But the machined surface contains a significant amount of C(Figure 3(b)). The presence of a higher C percentage indicates that it is utilised to create the conductive layer on the workpiece. It is thought that at high temperatures (1000–2000°C) and in the absence of O the carbonic dielectric breaks into C particles, creating a more complex pyrolytic C which is a graphite-like material with some covalent bonding between its graphene sheets crystallised in a planar order. At very high temperatures, ZrO_2 may also react with C and create conductive ZrC temporarily [9]. Due to the effective and continual creation of the conductive layer, micro-EDM of nonconductive ZrO_2becomespossible. The thickness of the layer varies during the machining according to the conditions. The spark efficiency depends on the thickness of the conductive layer, as strong discharges are assumed to occur in thicker layers which results in dissimilar energy efficiency at different locations. Thus, *MRR* and surface roughness are higher with the parameters which can create a thicker stable conductive layer.

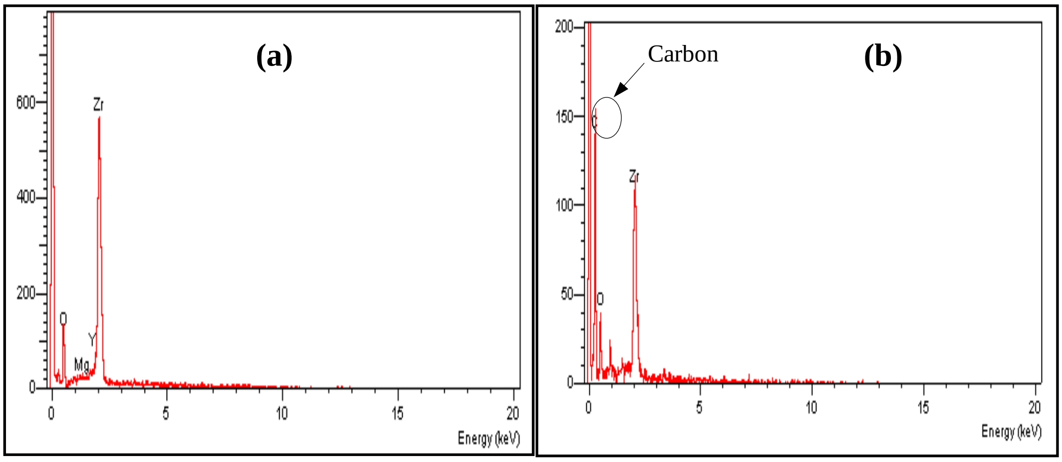

Figure 3. EDX spectrogram of ZrO_2 (a) before micro-EDM and (b) after micro-EDM, where a higher percentage of C content is observed.

Crater Geometry

To investigate crater geometry, SEM images of machined ZrO_2 and the Cu workpiece are captured. Cu micro-craters are observed to have clear and identical geometric patterns, as shown in Figure 4(a). Due to the melting and vaporisation of Cu, material is removed in a regular fashion without the creation of cracks on the machined surface. However, in the micro-EDM-ed ZrO_2 surface, no regular geometric crater shapes are identified. One of the surface textures of $ZrO_2$is shown in Figure 4(b), in which globules and broken edge are clearly observed. The irregular shape is the result of spalling which occurs because of the dominance of alternating heat stress on the ceramic workpiece.

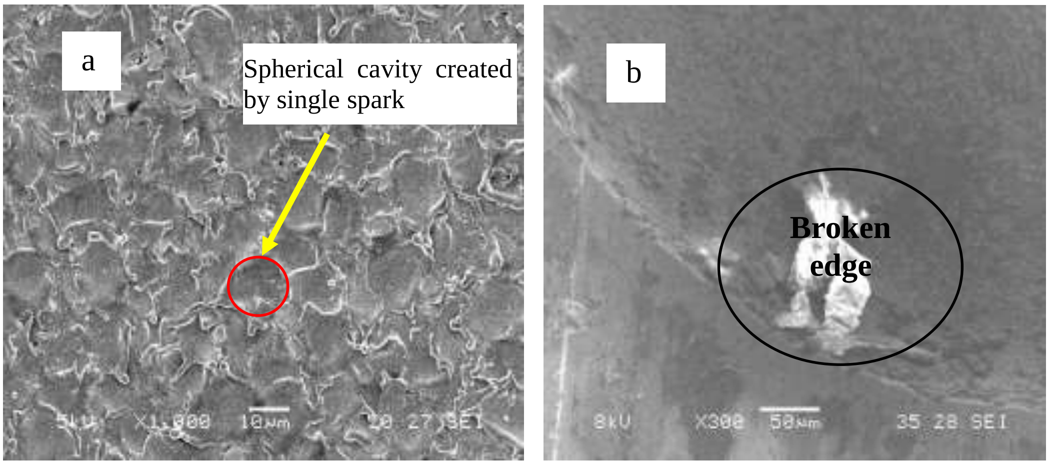

Figure 4. SEM image of surface texture in micro-EDM of (a) Cu showing a micro-crater with a regular geometric shape and (b) ZrO_2 showing a micro-crater with an irregular geometric shape.

Pulse during Micro-EDM of ZrO_2

In RC-pulse micro-EDM, pulse shapes are controlled by resistance and capacitance in the circuit. A capacitor stores the charges until it attains peak voltage. Dielectric breakdown occurs at peak voltage. Colliding electrons and ions create the spark. In ideal charging conditions, voltage signal is supposed to be the shape shown in Figure 5. During the machining of Cu foil, voltage signal in the charging stage is observed to be similar to the ideal shape. As the machining progresses, the Cu AE is finished and sparks occur between the tool electrode and carbonic layer formed on the workpiece surface. At the stage of ceramic removal, pulses are observed, remaining constant at a peak for a longer period after the capacitor has been fully charged, waiting to release the energy, as shown in Figure 6.

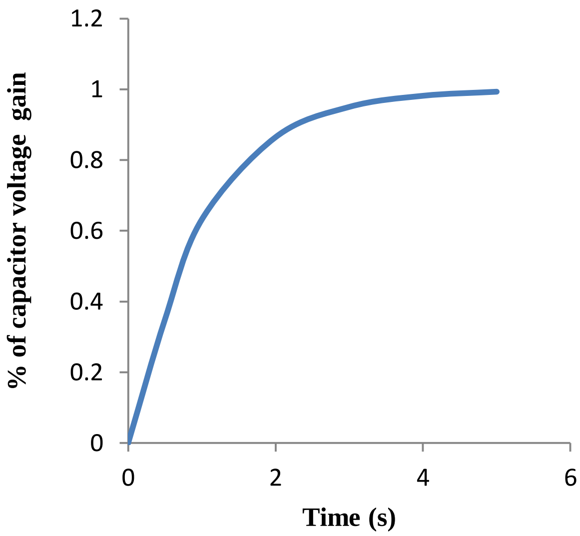

Figure 5. Percentage of capacitor voltage gain with respect to time[25].

It can be assumed that the carbonic layer is yet to attain the sufficient thickness and essential conductivity for the sparks. Once the conditions are fulfilled, the sparks occur. As a result, the ceramic pulses during micro-EDM have longer pulse-off time than regular pulses. An effective pulse in micro-EDM of ceramic material depends on machining conditions such as the dielectric, flushing efficiency, machining depth, feed rate, electrode (material and x-sectional area), assisting electrode (material and thickness), and energy input. The numbers of ineffective pulses such as delayed discharge, short circuit, and open circuit are higher in the micro-EDM of ceramics. The percentage of effective discharges determines *MRR*.

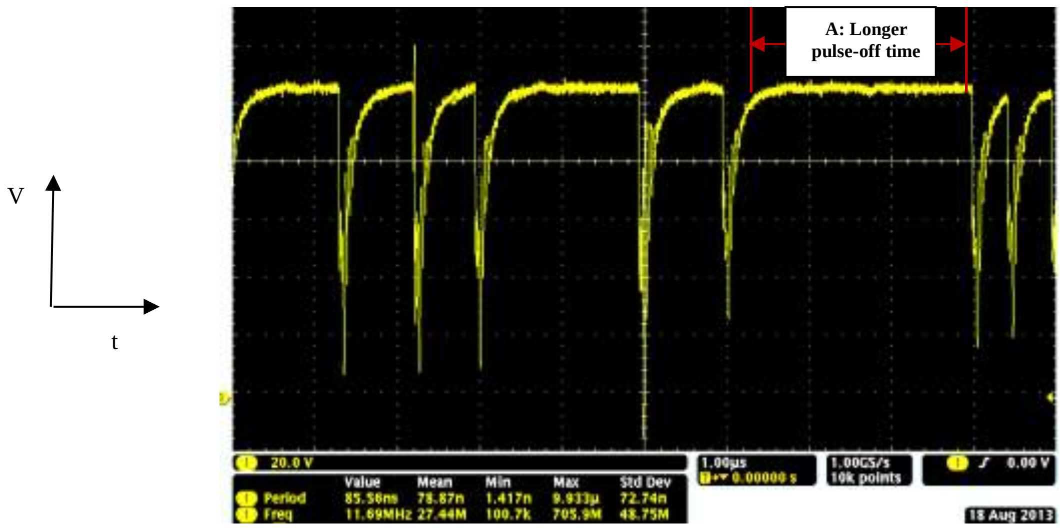

Figure 6. Longer pulse-off time is observed in micro-ED milling of nonconductive ZrO_2 as indicated at by ‘A’ (parameters: C = 0.1 nF and V = 100 V).

MRR and R_a of Micro-channel

MRR in RC-pulse micro-EDM of $ZrO_2$is controlled by capacitance and voltage. The relation between *MRR* and the capacitance and voltage of the process parameters is shown in Figure 7. In the micro-channel fabrication, it is observed that *MRR* increases with the increase of voltage until 100 V and it decreases at voltages higher than 100 V (Figure 7(a)). Similarly, *MRR* increases with the increase of capacitance until 1nF (Figure 7(b)). At capacitances higher than 1 nF no significant material is removed. The reason can be explained by the energy effect of the circuit. In micro-EDM of nonconductive ZrO_2, the formation of the conductive layer plays an important role in continual machining. At lower energy levels, an effective and stable conductive layer is created with a thickness required for the spark. However, at higher energy levels the carbonic conductive layer might have been removed before attaining the necessary thickness. Therefore, material removal decreases drastically at higher capacitances and voltages. *MRR* found in micro-channel machining is about 1.29×10^{-5} mm^3/s with the capacitance of 0.1 nF and voltage of 80 V. *MRR* can be increased up to about 6×10^{-5} mm^3/s in different capacitance and voltage levels. But the minimum surface roughness is observed at lower parameter levels. The average surface roughness of channels and holes is found to be 0.25 µm and 0.2 µm, respectively. One of the micro-channel surface roughness profiles is shown in Figure 8. The difference between the R_a values of channels and holes is perhaps due to the presence of a higher percentage of debris and carbonic particles in the micro-channel which is deposited for longer marching area.

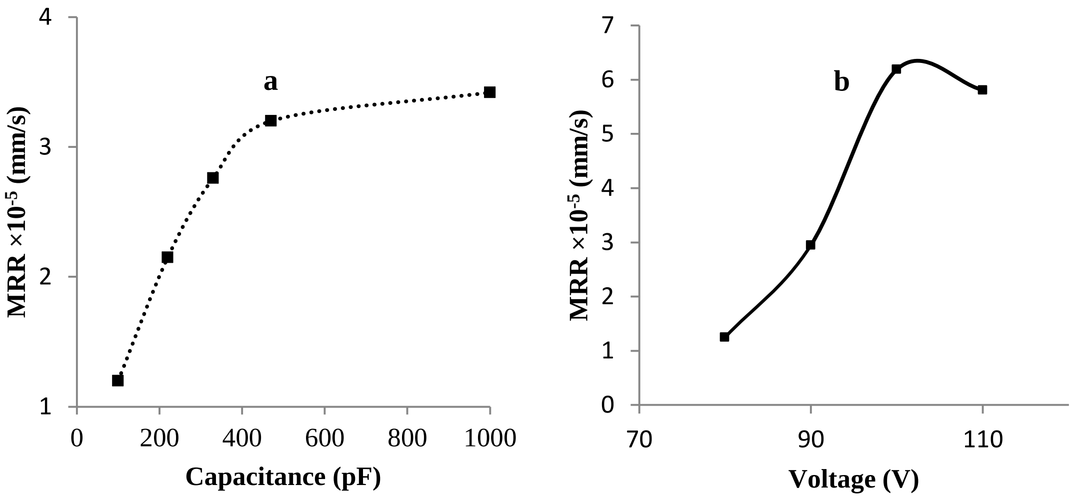

Figure 7. The plot of *MRR* with respect to (a) capacitance at C = 100 pF and (b) voltage at V = 80 V for ZrO_2 when machined by micro-ED milling with a Cu tool electrode and adhesive Cu foil AE in kerosene dielectric.

Figure 8. Surface roughness profile of micro-channel machined on nonconductive ZrO_2 by micro-EDM with a Cu tool electrode and adhesive Cu foil AE in kerosene dielectric (C = 0.1 nF and V = 80 V)

CONCLUSIONS

In this study, a micro-channel in micro-EDM of nonconductive ZrO_2 ceramic is investigated. Machining is conducted using a Cu tool electrode, adhesive Cu foil AE and kerosene dielectric fluid. The following specific conclusions can be drawn from this study:

i) The conductive carbonic layer is created on the workpiece surface disassociating kerosene during the micro-EDM of the nonconductive ZrO_2ceramic. It was found from the experimental investigation that the most significant parameter in micro-EDM of nonconductive $ZrO_2$is capacitance. At higher capacitances (>1nF), the conductive carbonic layer is not stable for significant machining.
ii) Micro-channels are created successfully by using micro-ED milling on ZrO_2. It is observed that the shape is increased both in the longitudinal and radial direction due to initial tool vibration. On the contrary, depth and width are ultimately reduced due to the tool electrode wear.
iii) In micro-channel fabrication, *MRR* increases with the increase of capacitance and voltage. However, stable machining was observed at capacitances lower than 1nF and voltages lower than 110 V.
iv) With the capacitance of 0.1 nF and voltage of 80 V the *MRR* in micro-ED milling of $ZrO_2$is found to be 1.29×10^{-5} mm^3/s. An average surface roughness of channel and hole of ~0.25µmand 0.2µmis obtained, respectively. The micro-channel R_a is found to be higher because of the presence of a higher amount of debris and carbonic particles.

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