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INVESTIGATION OF THE MACHINABILITY OF NON-CONDUCTIVE ZrO_2 WITH DIFFERENT TOOL ELECTRODES IN EDM

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ABSTRACT

Electrical discharge machining (EDM) is a non-conventional process where complex and difficult-to-cut materials can be machined. Adhesive copper foil as an assisting electrode (AE) is used to cover the zirconia (ZrO_2) surface to start the primary spark between the tool electrode and workpiece. Kerosene is dissociated and produces a carbon layer on the workpiece surface when machining of the initial copper foil is completed. Thus machining continues although ZrO_2 is a non-conductive material. In this study, the EDM of ZrO_2 is investigated with graphite, copper and brass tool electrodes. Material removal rate (*MRR*) and surface characteristics are analysed. Experiments are performed by varying the parameters peak current and pulse-on time with different tool electrodes. From the experiments, *MRR* on ZrO_2 has been compared for three different tool electrodes. It is found that the graphite tool electrode performs the highest *MRR* for EDM of ZrO_2. The least *MRR* is obtained by the brass tool electrode. However, better surface quality is observed with the copper tool electrode than EDM with brass or graphite electrodes. This investigation with varying machining parameters and different tool electrodes can be helpful in finding an effective use of the EDM process.

Keywords: Electrical discharge machining; non-conductive ceramics; assisting electrode; material removal rate; conductive layer.

INTRODUCTION

High-density parts are obtainable from non-conductive ceramics with good technical properties related to hardness, dimensional stability, mechanical resistance, wear and corrosion at high temperatures. These ceramics can be applicable mainly in gas turbine blades, defence armour, prosthetic products, heat exchangers, and future generation computer memory products [1]. However, high hardness, intrinsic brittleness, and low fracture toughness are the main problems of ceramic machining. Laser ablation, polishing with diamond suspensions or cutting with diamond tools can be used to process non-conductive ceramics. But these processes are very expensive and time consuming [2-5]. Electrical discharge machining (EDM) is a machining process whereby a desired shape is obtained using electro-thermal energy. Material is removed from the workpiece by a series of rapidly recurring sparks between the tool electrode and workpiece which is submerged in a dielectric fluid and subjected to an electric voltage [6]. EDM can be used successfully in machining of intricate shapes where conventional machining processes are difficult to use [7-9]. In general, EDM is used mainly to machine materials which have electrical resistivity between 100 and 300 Ω-cm to generate electrical discharge between the tool electrode and workpiece [10, 11]. EDM can be applied to the machining of non-conductive ceramics with the assisting electrode (AE) technique [12, 13]. In the AE technique, the non-conductive workpiece surface is covered by a conductive metallic layer or foil or mesh [1, 2]. Initially discharges occur between this conductive layer and tool electrode. Due to the generation of high temperatures in EDM, the dielectric fluid is dissociated and creates a carbonic conductive layer around the discharge area. The conductive debris from tool electrode material also combines with this carbon layer and covers the ceramic surface. This layer is known as the pyrolytic carbon (PyC) layer. Then the discharge is shifted to the ceramic workpiece and materials are eroded from its surface although it is a non-conductive material [14, 15]. The material is removed mainly by spalling, which is the result of alternating thermal load. The EDM process is applied successfully to machine non-conductive silicon nitride, silicon carbide, alumina (Al_2O_3),and zirconia (ZrO_2) by using the AE method [16]. The thickness of the conductive layer applied to the workpiece surface influences the material removal rate(*MRR*) during EDM. The higher *MRR* for micro EDM of ZrO_2 can be obtained by using a 20 µm-thick silver-based varnish layer as AE [17].

The workpiece material, tool electrode, dielectric medium, pulse duration, peak current, polarity, discharge voltage, etc. influence the machining process during EDM of non-conductive ceramics. The material removal is increased due to melting, vaporisation, and thermal spalling with the increase of peak current and pulse duration [18]. Several studies have been conducted to investigate the machining characteristics of non-conductive ceramics. Due to the largest conductive layer thickness, higher *MRR* is obtained when graphite is used as a tool electrode for machining an Al_2O_3 workpiece [16]. ZrO_2 is machined by using two adjacent copper (Cu) electrodes which are separated by a distance plate. It has been found that the tool wear rate is nearly constant below the thickness of the distance plate between 35 to 51 µm [14]. However, most of the studies have been carried using a single tool electrode. During machining of ZrO_2 and other non-conductive ceramics, the rate of occurring unstable machining conditions increases with the increase of the depth of the cut [19]. The conductive layer thickness on ZrO_2 during machining is increased when open circuit voltage increases [20]. The effect of different tool electrodes on *MRR* has not been studied in detail. However, this investigation is desired to study the machinability of ZrO_2 in EDM. Study on maximum *MRR* in EDM of ZrO_2 using different tool electrodes is needed for efficient and effective use of the process. In this study, the effects of different tool electrodes –Cu, brass, and graphite –on *MRR* have been studied in the EDM of non-conductive ZrO_2. Subsequently, optimum parameters to achieve maximum material removal with a better workpiece surface are identified.

EXPERIMENTAL

This study is concerned with *MRR* in EDM of non-conductive ZrO_2 ceramics. Die sinking EDM is used with kerosene dielectric fluid. Square-shaped tool electrodes with the same surface area are used. The materials of the tool electrode are copper (Cu), brass, and graphite. *MRR* is considered for investigation in this study because it is the most important machining characteristic in the context of production. Tool electrode material, peak current and pulse-on time are varied as machining parameters while other conditions are kept constant.

Machine, Electrode, and Dielectric Fluid

The experiments are carried out by using an NC die-sinking EDM machine (FP 60E, EX22, Mitsubishi, Japan).A ZrO_2 ceramic plate (20 mm×15 mm×10 mm) is used as the workpiece in this experiment (Figure 1). Properties of ZrO_2 are given in Table 1. Three different square-shaped electrodes (3 mm × 3 mm) are used for experiments. Cu is commonly used as a tool electrode because of its high electrical conductivity and high melting temperature. Low wear burning is produced by the combination of Cu and certain power supply settings. This electrode has many advantages over brass, such as low wear ratio, low cost, and that it can produce a better surface finish. Graphite is used as an electrode material in EDM, but it is dirty and dusty. Graphite possesses comparatively lower mechanical strength than the other metallic tool electrode materials. It is not as hard and stiff as the metal tool electrodes. Brass is also used as tool electrode because it can be easily machined to a simple shape. Brass has high electrical conductivity and a high melting temperature, too [21].Some properties of Cu, graphite, and brass electrodes are given in Table 2. Kerosene which has a high dielectric strength, low viscosity and high flash point is used as the dielectric fluid in this study. The properties of kerosene are given in Table 3.

Figure1. ZrO_2 workpiece (20 mm × 15 mm × 10 mm).

Table 1. Properties of ZrO_2 workpiece material [18].

Property	Value
Melting temperature (°C)	2720
Thermal conductivity (w/m K)	2
Specific heat capacity (J/g°C)	0.4
Specific gravity (gm/cm^3)	5.68
Electrical resistivity (Ω-cm)	1010
Hardness (Hv)	1270
Thermal expansion coefficient (l/°C)	7.0×10^{-6}

Table 2. Some properties of Cu, graphite, brass.

Property	Value		
	Copper	Graphite	Brass
Thermal conductivity (W/m K)	388	470	109
Melting point (°C)	1083	3650	885–900
Electrical resistivity, ρ (Ω-cm)	1.7×10^{-6}	5×10^{-4}	6.3×10^{-6}
Specific heat capacity (J/ Kg K)	385	711	370
Coefficient of thermal Expansion (°C)	6.6×10^{-6}	1.2×10^{-6} to 8.2×10^{-6}	1.2×10^{-6} to 8.2×10^{-6}
Electrical conductivity, σ (S/cm)	58.5×10^{4}	3×10^{3}	15.9×10^{4}

Table 3. Properties of kerosene dielectric fluid[22].

Property	Value
Dielectric strength (MV/m)	14–22
Dynamic viscosity (g/m-s)	1.64
Thermal conductivity (W/mK)	0.149

Machining Process

The workpiece surface is covered by an adhesive Cu foil as AE. Cu foil is used due to its excellent electrical conductivity and also it is easy to remove after machining. This conductive layer ensures electrical conductivity on the non-conductive workpiece surface that is to be machined. The initial spark occurs between the tool electrode and the AE. The set-up for EDM of non-conductive ZrO_2 with AE is shown in Figure 2. After machining of the AE, conductivity is continued by the dissociation of the kerosene dielectric. Kerosene splits into carbon particles due to the thermal effect of the spark discharges. These carbon particles are fixed on the workpiece surface as a thin black layer and the process is carried on by virtue of this generated carbon layer. The entire constituents of this second layer are still under study [17].

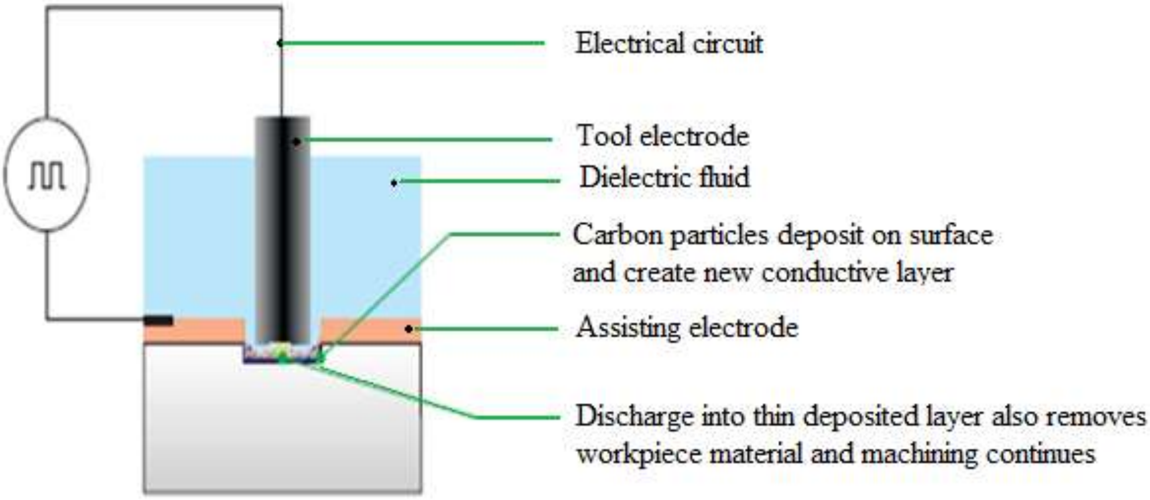


Figure 2. Machining process for ZrO_2 [17].

Tool electrodes are connected with negative polarity when conducting each experiment. Electrode movement is controlled by the motor. The workpiece is carefully clamped to avoid any movement from the base of the tank, where it is submerged in the kerosene dielectric. The schematic illustration of the detail machining process using AE is shown in Figure 3. Acetone is used to clean the workpiece and tool electrodes before machining and also to clean impurities from the workpiece surface after machining. An electronic scale (B204-S Mettler Toledo, Switzerland) is used to take the weight of the workpiece before and after the machining. The machined workpiece surface is analysed with energy-dispersive X-ray (EDX). Machining characteristics, *MRR*, and the surface topography of ZrO_2 are investigated with varying peak current and pulse-on time, keeping other parameters constant. The EDM conditions of this study are summarised in Table 4.

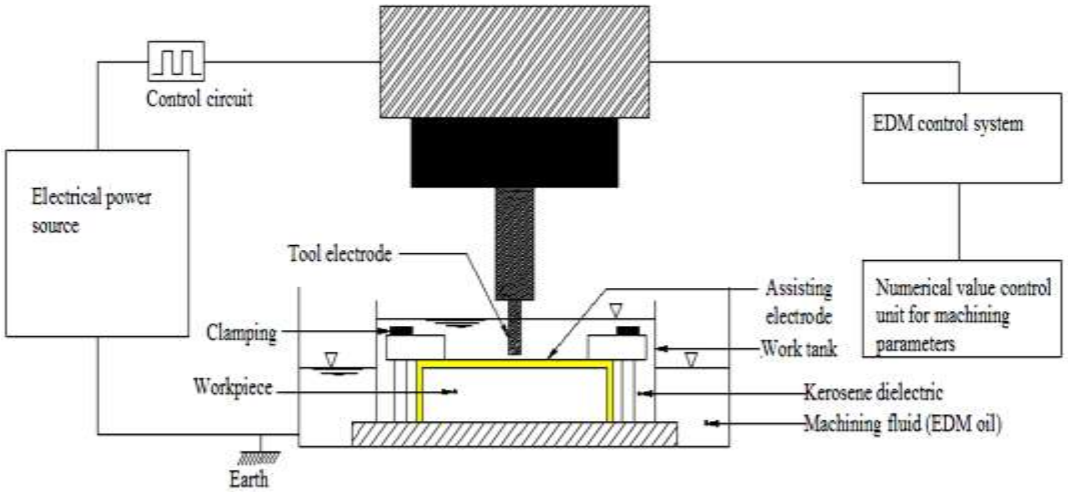


Figure 3. Schematic diagram of experimental set-up for EDM of ZrO_2.

Table 4. EDM conditions.

Machining conditions	Value
Tool electrodes shape (mm)	3 × 3
Depth of cut (mm)	1
Cu foil thickness (mm)	0.06
Electrode polarity	Negative
Peak current, I_p(A)	1.0, 1.5, 2.0
Pulse-on time, T_{on} (μs)	6, 9, 12
Gap voltage, U (V)	10
Pulse-off time, T_{off} (μs)	8

RESULTS AND DISCUSSION

Machinability and Conductive Layer Formation

Experiments are conducted on ZrO_2 in order to investigate the effects of different tool electrodes on *MRR*. The holes of 1.0 mm depth are produced on the workpiece surface during EDM. Stable machining is achieved within the specified range of peak current and pulse-on time. Figure 4 shows the cavity produced on ZrO_2 surface machined by EDM. After commencing the machining process when AE finished, a very thin carbon layer is generated by dissociation of kerosene. Machining advances towards the workpiece surface due to this carbon layer from carbonic dielectric. This layer has a great influence on the material removal from the ceramic surface. Although stable machining is found but the layer thickness is not same on the whole workpiece surface. The SEM micrograph regarding conductive layer thickness is shown in Figure 5. The EDX analysis is conducted on ZrO_2 surface before machining, as shown in Figure 6. The constituents are identified by the peaks with respect to their energy levels. O_2 is found with Zr in this analysis. The EDX pattern of the machined surface of ZrO_2 is illustrated in Figure 7. The main elements in the re-solidified conductive layer are C, O_2, Al, Cl_2, Cu, Zr.

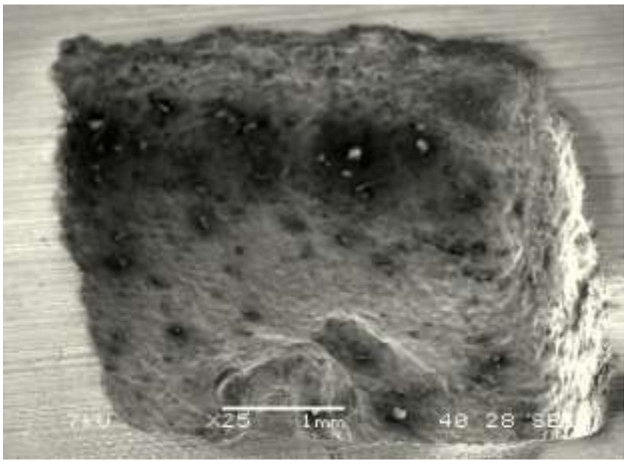


Figure 4. A cavity on ZrO_2 surface by EDM(Parameters: I_p= 1.5 A, T_{on}= 9 µs, U = 10 V, T_{off} = 8 µs).

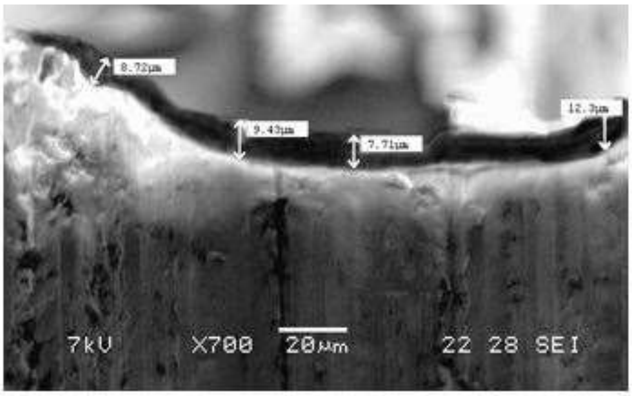
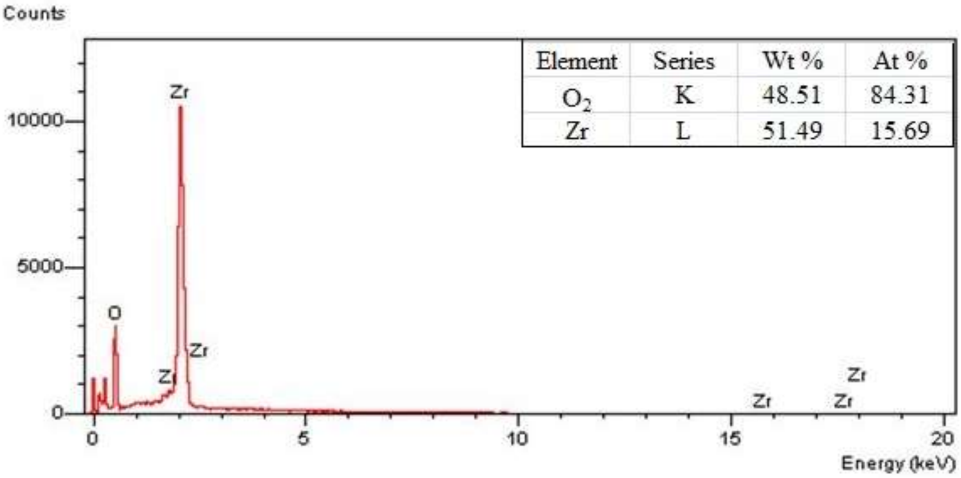


Figure 5. Generated conductive layer thickness on ZrO_2 due to EDM.

Among them a very high C percentage is found. This proves that the principle element of the conductive layer is carbon. The presence of Cu indicates that tool electrode material is transferred to the workpiece surface through the EDM process. Moreover, the existence of O_2 in the layer suggests that oxidisation has taken place in the erosion process during EDM. Similar investigations are observed in previous studies [17, 19, 23].

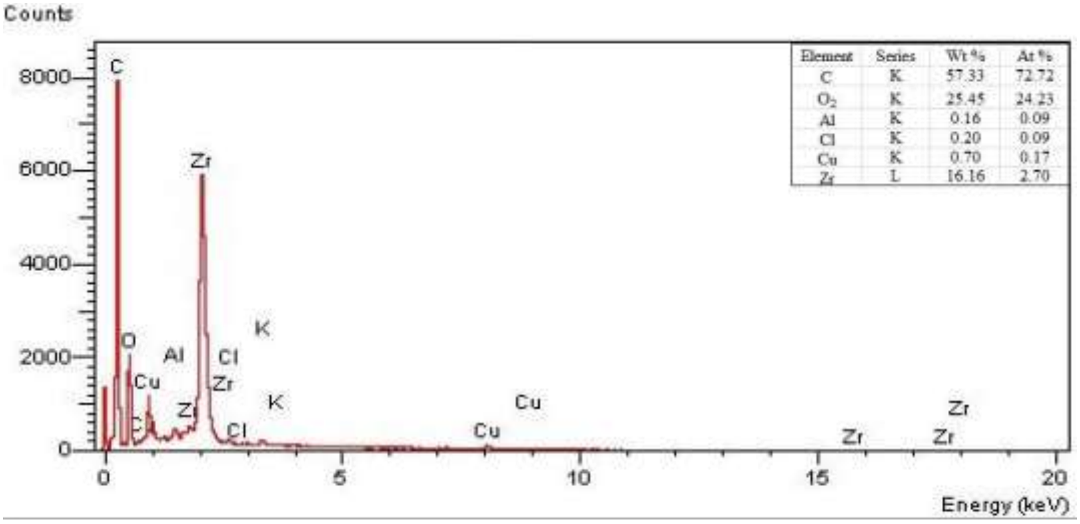
Effect of Tool Electrode Material on *MRR*

Due to conductive layer generation, stable machining is found within the fixed range of peak current and pulse-on time when the other machining parameters are kept constant. *MRR* for ZrO_2 due to different tool electrodes are calculated in this range. The relation between peak current and pulse-on time with *MRR* is depicted in Figure 8 and Figure 9. It is found that *MRR* is increased non-linearly with these three tool electrodes. *MRR* is almost the same for brass and Cu tool electrodes when the peak current is 1 A and pulse-on time is 6 µs. *MRR* increases when Cu is used instead of brass. Compared with brass, the *MRR* of Cu is increased more than twice when the peak current is at 1.5 A and pulse-on time is at 9 µs. This increasing trend is continued when the highest peak current is at 2 A and pulse-on time is at 12 µs. However, the highest *MRR* is found for graphite with negative polarity among the three tool electrodes. Graphite has the highest electrical and thermal conductivity.



Element	Series	Wt %	At %
O_2	K	48.51	84.31
Zr	L	51.49	15.69

Figure 6. EDX spectra analysis of a ZrO_2 surface before EDM.



Element	Series	Wt %	At %
C	K	57.33	72.72
O_2	K	25.45	24.23
Al	K	0.16	0.09
Cl	K	0.20	0.09
Cu	K	0.70	0.17
Zr	L	16.16	2.70

Figure 7. EDX spectra analysis of a ZrO_2 surface after EDM.

The electrical conductivity of the workpiece does not have a significant effect on the EDM surface. In addition, a lower thermally conductive workpiece can produce higher *MRR* [8]. Although electrical and thermal conductivity of material do not affect *MRR* in EDM, the graphite tool electrode increases *MRR* because of the higher thickness of the conductive layer that is produced during machining.

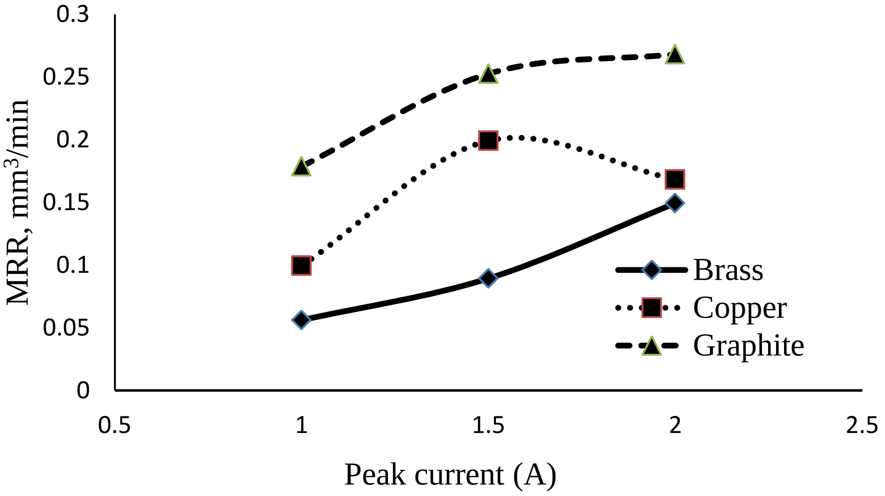


Figure 8. Variation of *MRR* with peak current in EDM of ZrO_2.

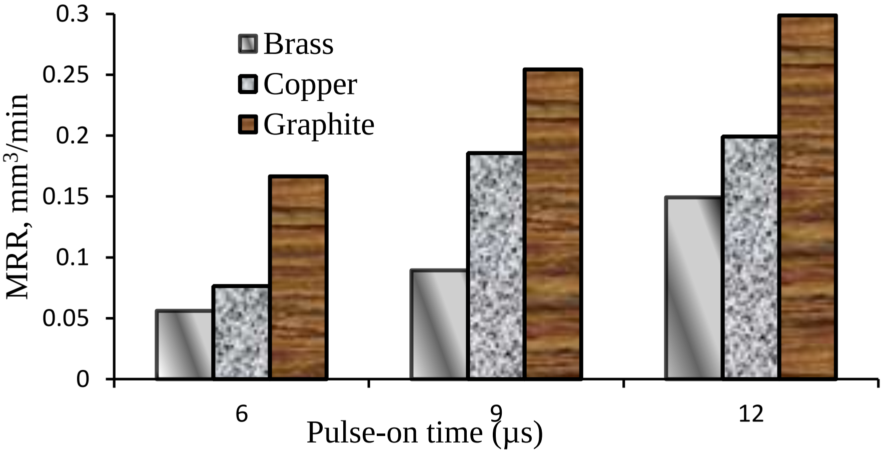
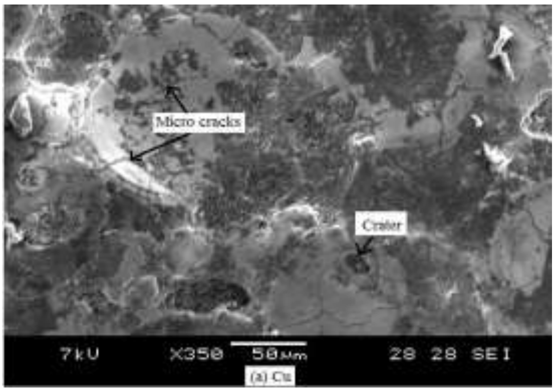
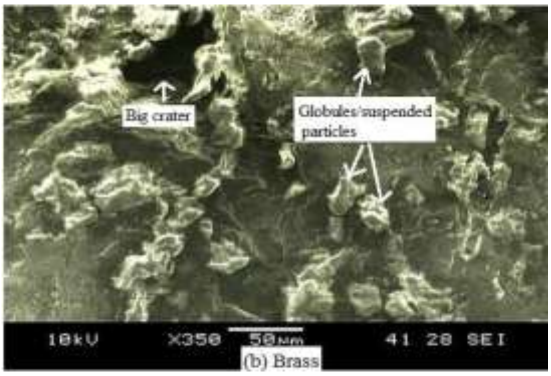


Figure 9. Variation of *MRR* with pulse-on time in EDM of ZrO_2.

Surface Topography of the Machined Surface

The SEM image of the machined surface by EDM presents its response at different machining conditions. The post-EDM surface topography using different tool electrodes is shown in the SEM image in Figure 10. Small cracks and craters are observed in the surface of the workpiece EDM-ed with Cu tool electrode and it appears comparatively smoother than the machined surface with brass and graphite tool electrodes. The SEM images illustrate a lot of globules, micro pits, big and small craters on the machined surface caused by EDM with brass and graphite tool electrodes. Incomplete flushing of the melted materials creates these. During EDM, the molten material generates cracks on the machined surface when re-solidification occurs. With melting and vaporisation, a wide range of materials are removed by spalling. Spalling depends on peak current and pulse-on time.





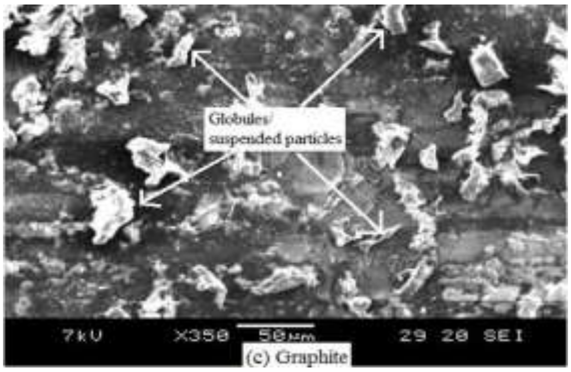


Figure 10. SEM micrographs of EDM-ed surface texture using tool electrodes of (a) Cu, (b) brass, (c) graphite.

CONCLUSIONS

EDM of non-conductive ZrO_2 using AE and Cu, brass, and graphite tool electrodes has been done successfully. During machining, EDM is steady with the rebuilding of the conductive layer from the carbonic dielectric. The conductive layer is generated in different thicknesses on the workpiece surface during machining. Among the tool electrodes, EDM with graphite gives the highest *MRR*. The lowest *MRR* is found for the brass tool electrode. The Cu tool electrode produces smooth surface compared with the other two tool electrodes. Materials are removed by spalling, melting and vaporisation.

Some materials are also removed by oxidisation. Due to the different properties of the tool electrode materials, the EDM parameters are also different for better performance. In this paper the parameters are investigated with different tool electrodes. Further study can be conducted by using parameters such as gap voltage, dielectric medium, pulse-off time, electrode gap distance, etc.

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