

Study of machining non-conducting materials using EDM

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Abstract — Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical spark is generated using electrical energy and material removal occurs mainly due to thermal energy of the spark. There is no direct contact between the tool electrode and the workpiece. Therefore, the process works very efficiently, particularly in the machining of difficult-to-cut materials. Work material to be machined by EDM has to be *electrically conductive*.

However, research and development of non-conductive (ex. ceramic materials), especially suited for electrical discharge machining (EDM), is still limited. Ceramic materials, (e.g. zirconia, silicon nitride or silicon carbide) exhibit excellent mechanical properties but are mostly electrically non-conductive. This can be compensated by an applied, *electrically conductive assisting electrode*. With this modification, the electrical discharge machining of non-conductive ceramic material is enabled.

To initiate the sparks, a conductive layer of adhesive copper is applied on the workpiece surface. Kerosene is used as dielectric medium for creation of conductive pyrolytic carbon layer on the machined surface. Parameters like voltage (V), capacitance (C) and rotational speed (N) are varied to observe the pattern.

During the machining of ceramics, unstable discharges occur. The formation mechanism of the electrical conductive layer on the EDMed surface is much different as compared to other ceramics. In addition to this, the electrically conductive layers are not formed sufficiently to adhere to the EDMed workpiece surface and keep a stable and continuous discharge generation on the ceramics. Graphite is widely used as electrode material in EDM. It is expected that carbon from graphite electrode implant and generate a conductive layer.

The aim of this study is to explore the feasibility and development of an applicable process for processing non-conductive ceramics through EDM, which is specifically used for machining of conducting materials. Also, the effect of various tool electrodes were investigated with graphite, copper and brass tool electrodes on the MRR and surface characteristics of a non-conducting ceramics workpiece.

Keywords — *Conducting materials, Non-Conducting Materials, Ceramics, Tool Electrode*

I. INTRODUCTION

Electrical Discharge Machining (EDM), also known as, Spark Erosion Process is widely used in industrial application and in the field of micro structuring. The main advantage of this process is the ability to structure materials independently of their mechanical material properties. Nowadays especially ceramic materials are becoming more and more interesting for industrial applications. Unfortunately most of these advanced ceramics are electrically non-conductive like, e.g. Al_2O_3 or ZrO_2 . Due to their material characteristics like high hardness, high bending strength and high melting temperature in combination with high brittleness, they are difficult to structure by cutting techniques or laser ablation. Thus they require special tools and techniques for cutting and polishing respectively.

The Electro Discharge Machining process is based on ablation of material through *melting* and *evaporation*. The electrical discharges occur between tool electrode and workpiece in a dielectric medium that separates the two. A voltage is attached to both electrodes and, when the breakdown voltage of the medium is reached, a plasma channel allowing for a current flow is established and a discharge takes place.

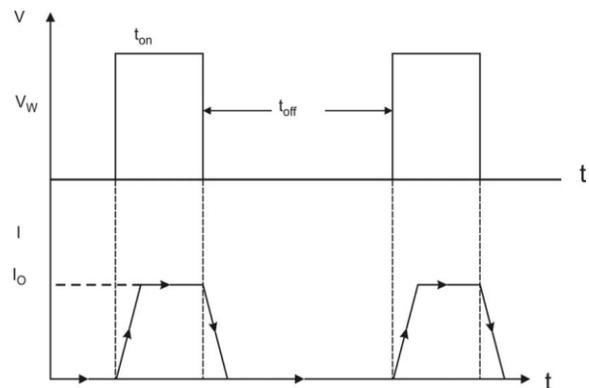


Fig. 1 Waveform used in EDM

This study investigates the feasibility of EDM for processing non-conductive ceramics, which were covered by an assisted conductive material,

usually a copper foil, on the workpiece surface. In this work a novel lacquer based assisting electrode is introduced that is suitable to start a sustaining erosion process and is applied easily by *Doctor Knife* and *Screen Print* techniques. The adhering of conductive material on the surface of the non-conductive ceramics would induce a series of electrical discharges between the tool electrode and the workpiece. Thus, the pyrolytic carbon that cracked from kerosene was formed and deposited on the machined surface to help in initiating the sparks. In this work, the essential EDM machining parameters were varied to determine the effects on material removal rate (MRR), electrode wear rate (EWR), and surface roughness.

Table 1: Overview of main process parameters

Parameter	Value
Open Voltage (in Volts)	200
Current (A)	0.4 – 0.6
Pulse On-Time (µs)	0.7 – 0.9
Pulse Off-Time (µs)	1.5 – 1.7
Gap Voltage (V)	25 – 30

Also, the EDM of Non-Conductive material like ZrO₂ is investigated with graphite, copper and brass tool electrodes. Material removal rate (MRR) and surface characteristics are analysed. Experiments like varying the parameters involving peak current and pulse-on time with different tool electrodes, were observed. It was observed that the graphite tool electrode performs better, having highest MRR for EDM of ZrO₂. 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 paper points out that besides the typical EDM material removal mechanisms, such as melting/evaporation and spalling, other mechanisms can occur such as oxidation and dissolution of the base material.

A major benefit of the electro discharge machining process, due to its electro-thermal nature of ablation, is independency of material hardness and brittleness. The noncontact nature of the process results in a nearly force-free machining, allowing the usage of soft, easy to machine electrode materials even when shaping very hard workpieces. This also enables the machining of fragile or thin workpieces. Additionally, there is no limitation to the angle between the tool and workpiece, so round or irregularly shaped surfaces can be used.

For all those reasons, EDM has been widely used in the generation of micro parts and complex geometries.

1.1 BACKGROUND OF THE ASSISTING ELECTRODE METHOD

Most of the advanced ceramics such as ZrO₂, Al₂O₃, Si₃N₄ are electrically nonconductive where

EDM cannot be directly applicable [1]. A basic process is introduced to apply EDM for processing of nonconductive ceramic materials in which an assisting electrode (AE) layer of electrically conductive material is applied. The sparks initially occur between the tool electrode and the AE layer. After finishing the temporary external layer, a layer of pyrolytic carbon is deposited on the substrate surface disassociating the carbonic dielectric in appropriate conditions.

In other words, the material removal during spark erosion of metals takes place via melting due to the high temperatures caused by the generated sparks [4]. These sparks occur as the tool and the workpiece are connected to a generator and are isolated from each other by a surrounding dielectric.

Presently, TIN coating by PVD process is commonly used as assisting electrode (AE). However, as special equipment for the PVD process is required, this method is non-economical and also difficult to implement. In order to make the assisting electrode more practical, carbon baked layer on ceramics method is more preferred.

Hösel et al. (2009) used a *doctor knife coating* and a *screen printing* process to apply conductive lacquers on a ceramic workpiece. For a minimum thickness of the AE physical vapor deposition of a conductive material such as TiN is used (Tani et al. 2004). As nonconductive ceramics cannot be contacted, an AE will be placed on top of it for electrical contact. The AE provides the required electrical conductivity of the workpiece at the beginning of the machining process [2].

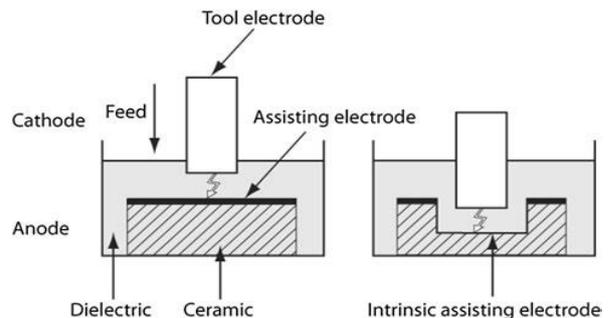


Fig. 2 Basic principle of EDM of non-conducting ceramics with an Assisting electrode

When erosion process starts, the AE will primarily be eroded. Due to the high temperatures generated, the surrounding dielectric fluid is degenerated and creates carbon black out of cracked polymer chains. The carbon black in combination with conductive debris covers the ceramic surface during process and sustains the conductivity (Fukuzawa et al. 1995a, 1997; Mohri et al. 2003). Thus only oils can be used as dielectric, in case that the AE is not supplied continuously. To support the creation of conductive debris carbon black can also be added into the dielectric. The alternating thermal load

of the spark discharges is penetrating the ceramic material and leads to stress induced cracks and thus to the ceramic removal by spalling. Depending on the ceramic material, also removal via melting can occur (see Fig. 3).

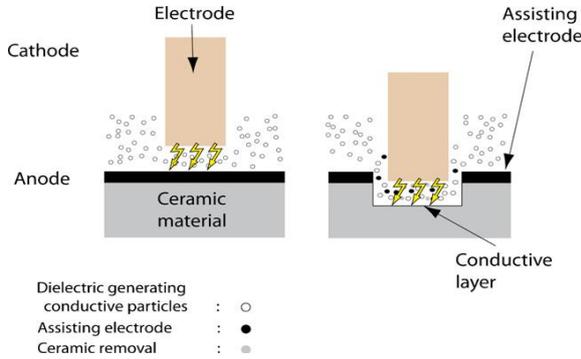


Fig. 3 Principle of the spark erosion process with an assisting electrode on a nonconductive ceramic by a sustaining conductive layer out of dielectric and electrode wear

The research mainly focuses on changing the electrical properties of the ceramic material by creating a compound with dopants. Here TiN, WC or other nitrides and carbides are used. Another approach is to create a conductive compound by making use of spark erosion process in combination with ceramic materials is to embed ceramic particles in a metal matrix. Main disadvantage of above mentioned methods is the modification of the ceramic material. Thus a change in the material properties comes into picture, which cannot be excluded. The material removal of ceramic material during spark erosion differs from standard metal erosion. Here apart from *melting* and *evaporation* also *spalling*, *chemical reaction* and *decomposition* can also take place.

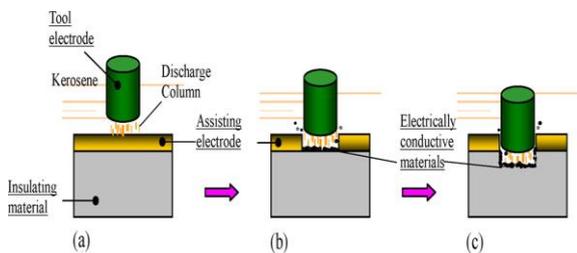


Fig. 4 – Machining process of insulating materials using assisting electrode. (a) Discharge for assisting electrode; (b) transition from assisting electrode to insulating material; (c) discharge for insulating material

The fundamental machining process was assumed as shown in Fig. 4. The discharge of the surface starts from the top of the layer as shown in (a) and creates electrically conductive products on the workpiece as shown in (b). It enters into the

workpiece after the electrode tool passes through the assisting electrode as shown in (c).

Table 2: Physical Properties of Copper Electrode

Physical Properties of Copper Electrode	
Thermal Conductivity (W/m K)	380 - 420
Electrical Resistivity (Ω m)	1.65×10^{-8}
Density (g/cm^3)	8.7 - 9.0

The products made from carbon are mainly from the dissolved components of the working oil during discharge, and from the electrode material. The specific electrical resistance of the electrically conductive layer was $8.1 \times 10^{-2} \Omega\text{cm}$, which was estimated by a special measurement system (Mohri et al., 2003). It was a bit lower than the machinable limit of EDM, so the discharges can continue as far as the generation of this conductive layer.

Table 3: EDM Conditions

	EDM conditions
Discharge current, i_e (A)	1-2
Electrode Polarity	(+,-)
Discharge duration, t_e (μs)	2-4
Pulse interval time, t_o (μs)	32-35
Rotating (RPM)	150-200
Tool Electrode	Cu ($\varnothing 3\text{mm}$)

The assisting electrode acts to make the products on the surface of the workpiece during machining as shown in (b and c) and holds the electrical conductivity during the discharge of surface (c). Machining trials were conducted by many researches, for many insulating ceramics and good results were obtained especially for Si_3N_4 , ZrO_2 and SiC . However, the ceramics of Al_2O_3 are recognized as a challenging machining material for this method as discussed by (Fukuzawa et al., 2004). Additionally *thermally induced spalling*, due to the brittleness of ceramic materials, can occur. Further removal mechanisms are *spalling of a resolidified surface layer* as well as *oxidation* or *decomposition* (Lauwers et al. 2004; Panten 1990).

II. EXPERIMENTAL RESULTS

2.1. Experimental outline

In order to conduct this research a conductive lacquer based assisting electrode (AE) is used which is brought onto the ceramic surface (i.e. non-conducting workpiece) by two coating techniques, *Doctor Knife* and *Screen Printing*. To verify these techniques the conducting layer thicknesses and the conductivity of the applied AEs were determined.

Further investigations were also done to analyse the influence of the dielectric on the relevant

process parameters like Material Removal Rate (MRR, removed ceramic material over time in mm^3/min), Wear Rate (WR, worn tool volume over time in mm^3/min) and Wear Removal Ratio ($\text{WRR} = \text{WR}/\text{MRR} \times 100$, in %) [8].

Further, the influence of the tool electrode material and the process depth on these parameters were also determined. Based on this knowledge channel geometries were generated and characterised by the various researchers to show how non-conducting materials can be easily machined by using EDM.

2.2. Pre-treatment

2.2.1. Applying the Assisting electrode

This study of machining non-conducting workpiece (especially ceramics), focusses on two techniques to apply lacquer based by spark erosion.

The first approach is to create a suspension by adding carbon black into a PMMA (Poly Methyl Methacrylate) based lacquer. The observed particle diameter of 50% of all measured graphite particles (d_{50}) is less than 4 μm . This suspension is applied by doctor knife. The coating is performed manually with a silicone doctor knife.

In the second approach a commercially available conductive lacquer system is used that is suitable for application by screen printing. In this method, a lacquer-based carbon-conductive ink was screen printed on to the surface of non-conductive ceramic workpiece. The screen printing is performed on an EKRA M2 screen printing machine. The workpiece sample were then heated in an oven at $120^\circ\text{C} - 140^\circ\text{C}$ for 2 – 3 hours. Upon heating, the lacquer became conductive and acted as an AE to initiate spark erosion process.



Fig. 5 Left to right: blank, screen printed and doctor knife coated sample 2

2.2.2. Characterisation of applied assisting electrodes

The resulting layer thicknesses of both applied techniques (i.e. Doctor-Knife & Screen Printing) were characterised with a **Laser Profilometer**.

For doctor knife coated AEs the resulting layer thickness ought to be 800 μm . The measurements done by some of the researchers, shows an average value of 356 μm with a standard deviation (σ) of 71 μm . The main reason for this large difference in the thicknesses is due to the evaporation of present diluter that leads to a large volume loss of the lacquer system. It was found that a second covering step reduces σ to 21 μm while the layer thickness nearly gets doubled to around 686 μm .

The coating via screen printing provides layers with a thickness of 30 μm and σ of 3 μm . The results are summarised in Table 4. Additionally, the electrical conductivity is measured with a *Four Pin Probe* to assure the minimal required conductivity. These results show conductivities of 2.06 S cm^{-1} for doctor knife and 1.32 S cm^{-1} for screen printing and are thus meeting the requirements. In Fig. 5 ceramic samples are shown before and after coating.

Table 4: Results of coating techniques for AEs.

	Doctor Knife	Screen Printing
Mean thickness (in μm)	356 (686)	30
Standard Deviation, σ (in μm)	71 (21)	3
Conductivity (in S cm^{-1})	2.06	1.32

III. CONCLUSIONS

The results of the above study shows that it is possible to generate micro channels in a nonconductive materials (like ceramics) when using lacquer based assisting electrode (AE). To apply such AEs two methods were introduced, coating via doctor knife and screen printing. Both methods are suitable to apply a conductive AE on top of a ceramic that is capable of starting a spark erosive process. The screen printing method offers smaller layer thicknesses, of around 30 μm , with higher accuracy and should therefore be favoured. The process characterisation shows that the material removal and wear rates usually depends upon the dielectric and the electrode material.

The choice of the electrode material is influencing the process stability, MRR and WR over depth. Normally, negative polarity of electrodes is selected when using EDM on insulating ceramics due to the need for the generation of a conductive layer during a process (Mohri et al., 1996, 2003; Fukuzawa et al., 1997, 2004; Shin et al., 1998).

Material Removal Rate (MRR) of ceramics can also be improved by employing positive polarity in case where the conductive layer imposed on the surface of workpiece is sufficient.

Copper (Cu) Electrode shows more stable behaviour for erosion depths smaller 500 μm whereas Tungsten Copper (W-Cu) is more stable for depths larger 1 mm. In any case the removal rates are lower as for conventional electrical discharge machining of metals but are in a region of surface finishing. Thus the advantage of this spark erosive method to structure non-conductive ceramics will be found in the generation of micro details in a macroscopic sample. The characterisations of the generated channels show a stable processing in non-conductive zirconia.

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