



รายงานวิจัยฉบับสมบูรณ์

โครงการ ผลกระทบของวัสดุของอิเล็กทรอนิกส์ต่อสมบัติของการกัด
ด้วยเครื่องกัดทางไฟฟ้าบนอลูมินา

โดย นายอภิวัฒน์ มุตะตามระ และคณะ

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เทคโนโลยีสำหรับการกัด(machining)เซรามิกส์รูคหน้าที่มีคุณสมบัติเป็นฉนวนเป็นที่ต้องการในอุตสาหกรรมหลายแขนง ในขณะที่เครื่องกัดวัสดุด้วยไฟฟ้า Electric Discharge Machining (EDM) ได้ใช้อย่างแพร่หลายสำหรับวัสดุที่นำไฟฟ้าได้ เมื่อไม่นานมานี้ เครื่อง EDM สามารถที่จะกัดเซรามิกส์ที่เป็นฉนวนได้หลายชนิด ตัวอย่างเช่น ซิลิคอนไนไตรด์ ซิลิคอนคาร์ไบด์ เซอร์โคเนีย แต่สำหรับคุณสมบัติการสปาร์กเกิดขึ้นอย่างไม่เสถียร การกัดเป็นไปอย่างยากลำบาก กลไกในการสร้างชั้นเหนียวนำไฟฟ้าบนผิวที่ถูกสปาร์กแตกต่างกันอย่างมากเมื่อเทียบกับเซรามิกส์ชนิดอื่น ชั้นเหนียวนำไฟฟ้าถูกสร้างไม่เพียงพอที่จะรักษาความนำไฟฟ้าเพื่อการสปาร์กอย่างต่อเนื่องบนผิวเซรามิกส์ได้ การเลือกวัสดุอิเล็กโทรดที่เหมาะสมเป็นส่วนสำคัญสำหรับผลผลิตและผลกำไรต่อการผลิต ในปัจจุบันนี้อิเล็กโทรดกราไฟต์มีบทบาทอย่างสำคัญในวงการEDM การศึกษานี้ได้สังเกตเห็นว่าคาร์บอนจากอิเล็กโทรด กราไฟต์อาจมีส่วนในการสร้างชั้นเหนียวนำไฟฟ้า การทดลองนี้ใช้อิเล็กโทรดทองแดง กราไฟต์ และทองแดงผสมกราไฟต์ เพื่อเปรียบเทียบผลของการสร้างชั้นเหนียวนำไฟฟ้าซึ่งมีผลต่อสมบัติการ EDM ซึ่งได้เปรียบเทียบกับ อัตราการขจัด สัดส่วนการสึกหรออิเล็กโทรด และค่าความหยาบของผิวงาน อิเล็กโทรดทองแดงผสมกราไฟต์กัดด้วยเครื่องกัดด้วยไฟฟ้าบนอลูมินา 95 เปอร์เซ็นต์ได้แสดงผลอย่างดีเยี่ยม โดยให้อัตราการขจัดสูงอย่างเห็นได้ชัดเมื่อเทียบกับอิเล็กโทรดกราไฟต์และทองแดง ในกรณีเมื่อเลือกขั้วไฟฟ้าเป็นบวกอิเล็กโทรดกราไฟต์ และ ทองแดงผสมกราไฟต์สามารถให้อัตราการขจัดได้สูงกว่าเมื่อเลือกขั้วไฟฟ้าเป็นลบ จากผลการวิเคราะห์ด้วย Energy Dispersive Spectroscopy ไม่สามารถพบธาตุทองแดงบนชั้นเหนียวนำไฟฟ้าทั้งที่สร้างด้วย EDM-3 และ EDM-C3 อย่างไรก็ตามค่าความต้านทานของชั้นเหนียวนำไฟฟ้าที่สร้างด้วย EDM-C3 มีค่าน้อยกว่า EDM-3 อิเล็กโทรด EDM-C3 สามารถลดค่าความหยาบของพื้นผิว

คำสำคัญ : EDM; Assisting electrode; อลูมินา ; กราไฟต์; Copper-infiltrated-graphite

Abstract

Technologies for machining advanced insulating ceramics are demanded in many industrial fields; normally, Electric Discharge Machining (EDM) is utilized for machining electrically conductive materials. Recently, several insulating ceramics, such as Si_3N_4 , SiC and ZrO_2 , have been successfully machined by EDM. As unstable discharges occur during the machining of Al_2O_3 ceramics, inferior machining properties have been obtained. It seems that the formation mechanism of the electrical conductive layer on the EDMed surface is much different as compared to other ceramics. An 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 [3]. Selection of appropriate electrode material is important for productivity and profitability of manufacture. Nowadays, a graphite electrode is an important tool for EDM process. For this study, it is expected that carbon from graphite electrode implant and generate a conductive layer. Copper, graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3) electrodes were used to compare the effects of generation of a conductive layer on alumina corresponding to EDM properties. Material removal rate (MRR), electrode wear ratio and surface roughness are compared. The Electrical Discharge Machining of 95% pure alumina shows that the EDM-C3 performs very well, giving significantly higher MRR than the EDM-3 and copper electrodes. In the case of EDM with EDM-3 and EDM-C3, using positive electrode polarity gives higher MRR than EDM with negative polarity. For EDS (Energy Dispersive Spectroscopy) results, it seems that no element of copper was observed on the conductive layer with an EDM-3 and an EDM-C3. However surface resistivity of a conductive layer created with EDM-C3 is less than with EDM-3. Surface roughness is improved with EDM-C3.

Keywords: EDM; Assisting electrode; Alumina; Graphite; Copper-infiltrated-graphite

หน้าสรุปโครงการ (Executive Summary)
ทุนพัฒนาศักยภาพในการทำงานวิจัยของอาจารย์รุ่นใหม่

1. ชื่อโครงการ (ภาษาไทย) ...ผลกระทบของวัสดุของอิเล็กโตรดต่อคุณสมบัติของการกัดด้วยเครื่องกัดทางไฟฟ้าบนเซรามิกสอลูมินา

(ภาษาอังกฤษ) Effect of Electrode Materials to EDM properties on Alumina Ceramic

2. ชื่อหัวหน้าโครงการ หน่วยงานที่สังกัด ที่อยู่ หมายเลขโทรศัพท์ โทรสาร และ e-mail

ชื่อ ดร.อภิวัฒน์ มุตะตามระ ภาควิชาอุตสาหกรรม คณะวิศวกรรมศาสตร์ มหาวิทยาลัยธรรมศาสตร์
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3. สาขาวิชาที่ทำการวิจัย ...การกัดวัสดุไม่นำไฟฟ้าด้วยเครื่อง EDM.....



5. ระยะเวลาดำเนินงาน2 ปี..... ,

6. ได้เสนอโครงการนี้ หรือโครงการที่มีส่วนเหมือนกับเรื่องนี้บางส่วนเพื่อขอทุนต่อแหล่งทุนอื่นที่ใดบ้าง

☒ ไม่ได้เสนอต่อแหล่งทุนอื่น

☐ เสนอต่อ

7. ปัญหาที่ทำการวิจัยและความสำคัญของปัญหา

ในอุตสาหกรรมปัจจุบันนี้ อลูมินา (Al_2O_3) ถูกใช้อย่างกว้างขวาง ตัวอย่างเช่น การใช้เป็นวัสดุฉนวนของหัวเทียน ฯลฯ ปัญหาที่พบโดยทั่วไปนั้นเมื่อทำการ Sintering แล้ว วัสดุจะมีความแข็งมาก กระบวนการกัดวัสดุที่มีความแข็งมากและไม่นำไฟฟ้า นั้นจำเป็นต้องใช้วิธีการพิเศษอย่างเช่น Laser, Water Jet เป็นต้น วิธีการดังกล่าวต้องลงทุนสูงและเสียค่าใช้จ่ายอย่างมาก

เมื่อประมาณ 10 ปีที่แล้ว วัสดุเซรามิกส์ที่ไม่นำไฟฟ้า อย่างเช่น Si_3N_4 , SiC และ ZrO_2 สามารถที่จะถูกกัดด้วยเครื่อง EDM (Electrical Discharge Machine) โดยใช้ทองแดงเป็นอิเล็กโตรด หลักการของวิธีนี้ใช้วัสดุที่นำไฟฟ้าเคลือบบนวัสดุเซรามิกส์ที่ไม่นำไฟฟ้า หรือ เรียกว่า วัสดุช่วยสปาร์ค (Assisting electrode method) แต่ถึงกระนั้น วัสดุเซรามิกส์บางชนิด เช่น Al_2O_3 ยากที่จะถูกสปาร์คโดยเฉพาะอย่างยิ่ง Al_2O_3 ที่มีความบริสุทธิ์สูงๆ เพราะว่าชั้นวัสดุสำหรับเหนี่ยวนำ

ไฟฟ้า (Electrical conductive layer) ซึ่งถูกผลิตระหว่างกระบวนการ EDM มีลักษณะไม่ค่อยเสถียร ง่ายต่อการหลุดจากชิ้นงาน ทำให้ กระบวนการ EDM ยากที่จะทำให้สำเร็จโดยสมบูรณ์ สำหรับชั้น วัสดุสำหรับเหนี่ยวนำไฟฟ้านั้นมีคาร์บอนเป็นส่วนผสมหลัก โดยที่คาร์บอนนั้นส่วนใหญ่มาจาก ส่วนผสมปกติในน้ำมันEDM และบางส่วนจาก วัสดุช่วยสปาร์ค

ในโครงการวิจัยนี้ ผู้ขอทุนต้องการศึกษาถึงผลกระทบ และข้อได้เปรียบ เมื่อใช้วัสดุที่มีส่วนผสม ของคาร์บอน เป็นอิเล็กโตรด แนวคิดนี้เพื่อให้คาร์บอนจากอิเล็กโตรดสนับสนุนการสร้างชั้นวัสดุ สำหรับเหนี่ยวนำไฟฟ้าระหว่างกระบวนการกัด อันจะส่งผลให้กระบวนการกัดเสถียร พัฒนาอัตรา การกัดได้มากขึ้น และสามารถพัฒนาผิวสำเร็จของชิ้นงาน วัสดุอิเล็กโตรดที่มีส่วนผสมของคาร์บอน นี้อาจจะนำไปสู่ วัสดุอิเล็กโตรดมาตรฐานของการ EDM วัสดุที่ไม่นำไฟฟ้าต่อไป

8. วัตถุประสงค์ของโครงการ

- 1.เพื่อพัฒนาการกัดวัสดุที่ไม่นำไฟฟ้าในกระบวนการ EDM
- 2.เพื่อศึกษากระบวนการสร้างชั้นวัสดุสำหรับเหนี่ยวนำไฟฟ้า (electrical conductive layer)
- 3.เพื่อ ศึกษาผลกระทบของคาร์บอน เมื่อผสมลงไปในวัสดุของอิเล็กโตรด
- 4.เพื่อปรับปรุงผิวสำเร็จของ ชิ้นงาน
- 5.เพื่อเป็นรากฐานสำคัญในการพัฒนาเทคโนโลยีในอนาคต และถ่ายทอดสู่วงการอุตสาหกรรม

9. ระเบียบวิธีวิจัย

อุปกรณ์ที่ใช้ในการวิจัย การวิจัยสามารถดำเนินการโดยใช้เครื่อง EDM ซึ่งมีอยู่แล้วใน ห้องปฏิบัติการ CNC ภาควิชาอุตสาหกรรม คณะวิศวกรรมศาสตร์ มหาวิทยาลัยธรรมศาสตร์ แต่ ต้องเสริมอุปกรณ์พิเศษบางชนิดเข้าไปในตัวเครื่อง.....

....

ขั้นตอน	1-6	6-12	13-19	20-24
1.ติดตั้ง_ดัดแปลง เพิ่มเติมอุปกรณ์ ใน ตัวเครื่อง EDM	↔			
2.จัดเตรียมอิเล็กโตรด	↔			
3.ทำการทดลองEDM		↔		
4.สรุปผลการทดลอง วิเคราะห์ และจัดพิมพ์ รายงาน			↔	
5.ตีพิมพ์ในวารสาร				↔

10. จำนวนโครงการที่ผู้สมัครกำลังดำเนินการอยู่ โดยขอให้ระบุระยะเวลาเริ่มต้นและสิ้นสุดของแต่ละโครงการ แหล่งทุน และงบประมาณสนับสนุนที่ได้รับ เวลาที่ใช้ทำโครงการวิจัยในแต่ละโครงการ เป็นกี่ชั่วโมงต่อสัปดาห์ ทั้งในฐานะหัวหน้าโครงการ ผู้ร่วมโครงการของแต่ละโครงการที่กำลังดำเนินการอยู่

ชื่อโครงการไม่มี.....

ระยะเวลาโครงการปี ตั้งแต่ถึง
.....

แหล่งทุนที่ให้การ
สนับสนุน.....
.....
.....

งบประมาณที่ได้รับ
.....

สถานะผู้สมัคร ☐ หัวหน้าโครงการ
☐ ผู้ร่วมโครงการ

เวลาที่ใช้ทำวิจัยในโครงการนี้กี่ชั่วโมงต่อสัปดาห์.....ชั่วโมงต่อ
สัปดาห์.....

1.1 Introduction

Advanced ceramics, also termed engineering, fine or technical ceramics, have been used as solutions to many scientific problems over the past 30 to 40 years. Some of these problems such as corrosion, erosion, wear, temperature, electrical insulation etc. (or combinations), have been overcome by the advance of technological procedure from a range of materials categorized as oxide or non-oxide ceramics. Those who have found and utilized these solutions have been able to carry out procedures and processes previously impossible, resulting in improved yields strength, life and manufacturing efficiencies of many industrial processes. Owing to their mechanical and physical properties, they are recognized as the too hard to machine. Some of the special machining methods have been applied such as laser, ultra sonic and electrical beam machining. EDM is one of the most applicable methods to machine electrical conductive materials into proper 3 dimensional precise shapes. But many ceramics materials are insulating materials. Recently, insulating materials such as Si_3N_4 , SiC and ZrO_2 etc. have been succeeded to machine by EDM with the assisting electrode method (AEM) that was proposed by Y.Fukuzawa and N.Mohri [1-3]. This method was considered that the surface modification phenomena simultaneously occur during machining process. The EDM machining properties vary with physical thermal properties of workpiece and electrode materials, machining conditions and atmosphere. However, some insulating materials such as oxide insulating ceramics were difficult to machine even if using this method. It seems that the formation mechanism of the electrical conductive layer on the EDMed surface is much different compared with that of other ceramics such as Si_3N_4 , SiC and ZrO_2 etc.

1.2 Purposes of this research

EDM for insulating ceramics of Al_2O_3 were succeeded using on a colloidal carbon baked layer, it is assumed that the dissolute carbon elements assist the adhesion phenomenon on the discharge surface modification.

However, electrically conductive layers are not formed sufficiently enough to adhere on the EDMed workpiece surface to keep a stable and continuous discharge generation on the ceramics [3]. In this study, copper electrode, graphite electrode and graphite infiltrated with copper electrode were used to compare effects of generation of a conductive layer on alumina corresponding to EDMed properties. Effects of electrode polarities were investigated for each electrode materials.

1.3 History of EDM

Electrical Discharge machining (EDM) is developed after World War II, making a die-sinking application. There are two principle types of EDM processes, one is the die sinking and the other is the wire EDM process. The die sinking process was refined as early as the 1940 with the advent of the pulse generators, planetary and orbital motion techniques, CNC and the adaptive control mechanism. Nowadays, to the transistors solid state circuits, not only was it possible to control the Pulse on time, but the pause time or the Off time could also be controlled.

1.4 Background of Surface Discharge Modification Phenomena

At the first trial of the electrical discharge machining on the insulating Si_3N_4 ceramics (specific resistance: $>10^{16} \Omega \cdot \text{cm}$) using the assisting electrode method, the ceramics-metal direct bonded joint or mechanical connected specimen was used as a workpiece. Fig.1.1 shows an arrangement of metal plate for the workpiece on the sinking EDM. The machining was carried out in the working oil with the negative polarity of the tool electrode. The earth was leaded from the connected metal side. As shown in Fig.1.1 (b), the discharge starts from the boundary of the connected metal surface and after a few minutes it expands to the ceramics surface. After the shape of tool electrode is transferred on the

workpiece, the machining proceeds into the ceramics and metal simultaneously. The whole EDMed surface is covered with the black layer which is constructed with the turbo stratic carbon carbonized alloy and tool electrode elements. After the generation of the conductive layer, the electrically conductive products mainly consist of carbon elements that are the result of working oil component dissolution during discharge, and also of tool electrode elements. However, the assisting electrode's components are not observed. The specific electrical resistance of the electrically conductive layer was $8.1 \times 10^{-2} \Omega\text{cm}$. This value was estimated by a special measurement system [3].

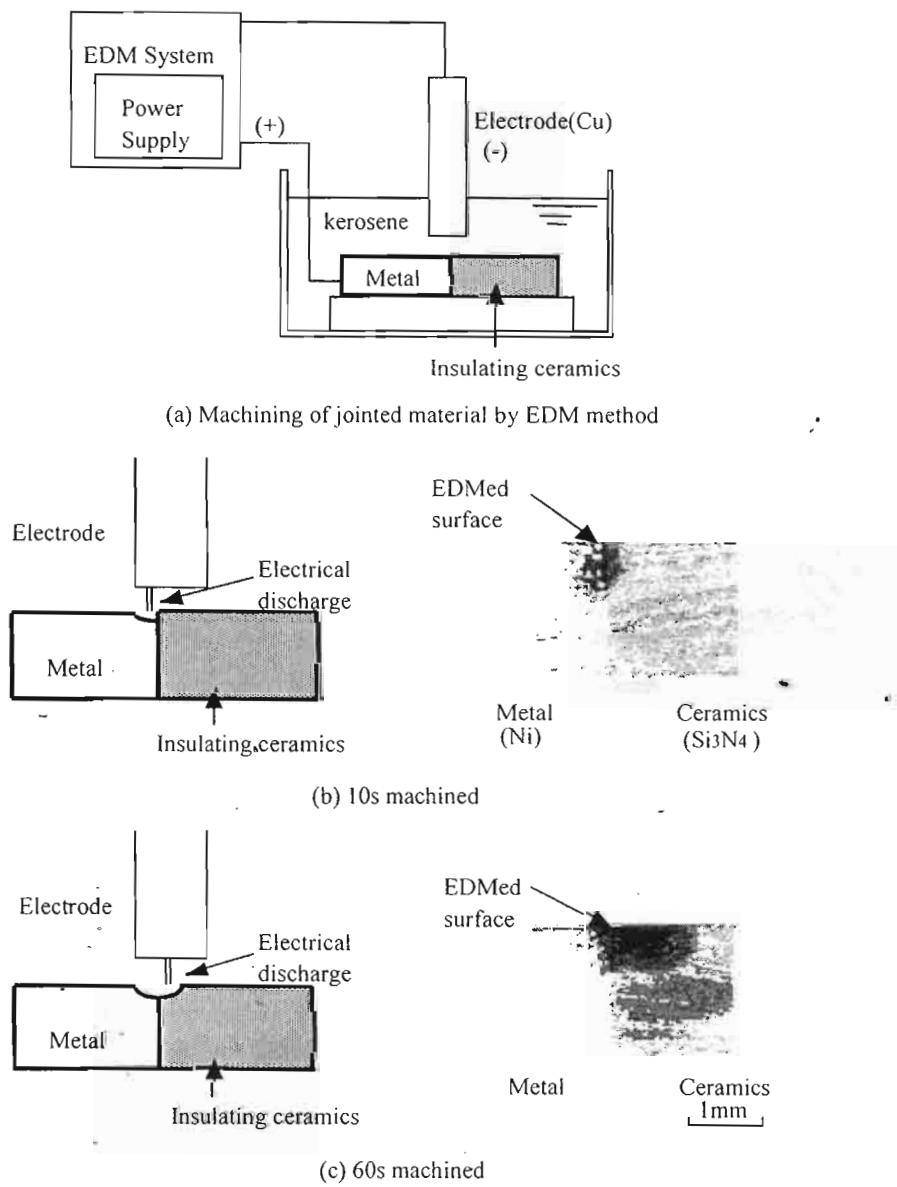


Fig.1.1 Observation of EDM process of ceramics-metal joint.

It was lower than the machinable limit of EDM. Therefore, discharges can be continuous as long as the conductive layer is generated. We call this connected material as an assisting electrode and this new method as an assisting electrode method. Next trial was carried out using the metal plate or metal mesh sheet that were attached tightly on the ceramics surface as shown in Fig.1.2. Machining starts at the attached material and it continues into the insulating ceramics after the tool electrode passes through metal plate. In this case the insulating ceramics also can be machined like the above-mentioned method. When the tool electrode reaches at the boundary between the metal plate and the ceramics, the machining does not proceed for a while which is corresponds to the expanded area of the electrical conductive black layer as shown in Fig.1.1 (b) and(c). The state of this machining is called as a transition region. The continuing time of the transition state is called as a transition time. The transition time depends on the material of assisting electrode. To obtain the shorter machining time of assisting electrode, several thin metal sheets and vaporized layer were used as an assisting electrode. The good machining properties have been obtained using the TiN layer as the assisting electrode.

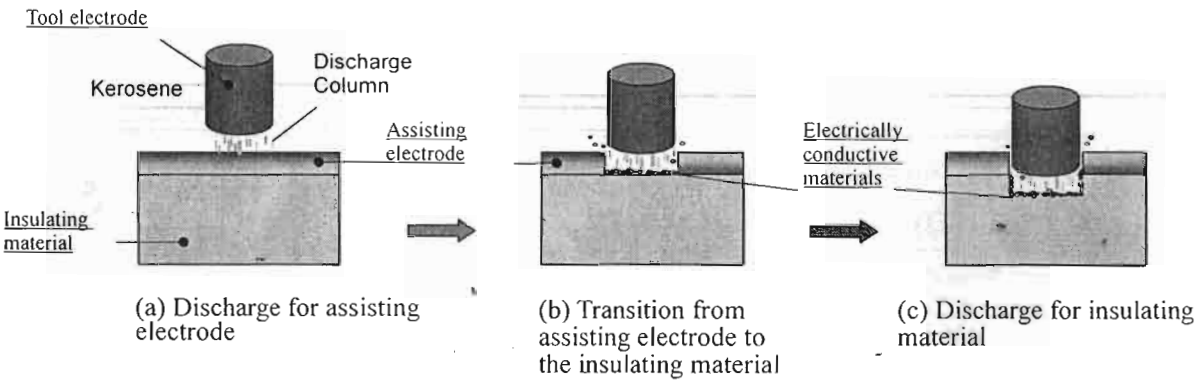


Fig. 1.2 Machining process of insulating materials using assisting electrode

In this method, electrically conductive products are made to adhere on the machined surface during discharge machining in working oil. Using this method many insulating materials such as Si_3N_4 , SiC , ZrO_2 , glass and plastics have been machined to complex shapes in three dimensions.

1.5 EDM process for Al_2O_3 ceramics

Although the oxide ceramics Al_2O_3 is the most widely used ceramics for industrial purposes as the structural materials of comparatively low price is remarkable inferior to other ceramics on the EDMed properties. The reason why the unpleasantly machining properties obtain on the Al_2O_3 ceramics. It is assumed as followed;

1. Thermal conductivity of alumina is rather high as compared to that of silicon nitride
2. The electrical conductive layer is difficult to solidify on EDMed surface.
3. Aluminium carbide of conductive layer is generated on EDMed surface as an unstable product.

Table 1 shows the physical properties for ceramic materials.

Table 1 Physical properties of insulating ceramics.

	Melting point (K)	Thermal conductivity (W/m K)	Specific resistance (Ω cm)
Si_3N_4	2173*	19	$>10^{14}$
SiC	2373*	84	10^3
ZrO_2	2720	2	10^{10}
Al_2O_3 92%	2313	16.7	10^{16}
Al_2O_3 99.5%	2323	29.3	$>10^{14}$
Al_2O_3 99.9%	2323	34	$>10^{14}$
Sapphire	2323	35	10^{16}
Ruby	2323	35	10^{16}
AlN	2723	86	3.1×10^{13}

*Sublimation

1.6 Discharge waveform for insulating ceramics

In EDM of insulating ceramics, the discharge waveforms are divided for 3 patterns as shown in Fig.1.4. One is normal discharge that follows the setup values. Second is long pulse which discharge duration is much longer than setup value. It is generally considered that this particular waveform is generated during machining of high electrical resistance materials. In this method, it is assumed that the long pulses are related to the dissolved carbon components on the surface of the workpiece [1.6]. The other is composed by short or concentrate discharge. Long pulse and concentrate discharge are called for abnormal waveforms. In EDM of insulating materials, they are observed frequently. The main role of removal machining is accomplished by the normal discharge waveforms [1.7].

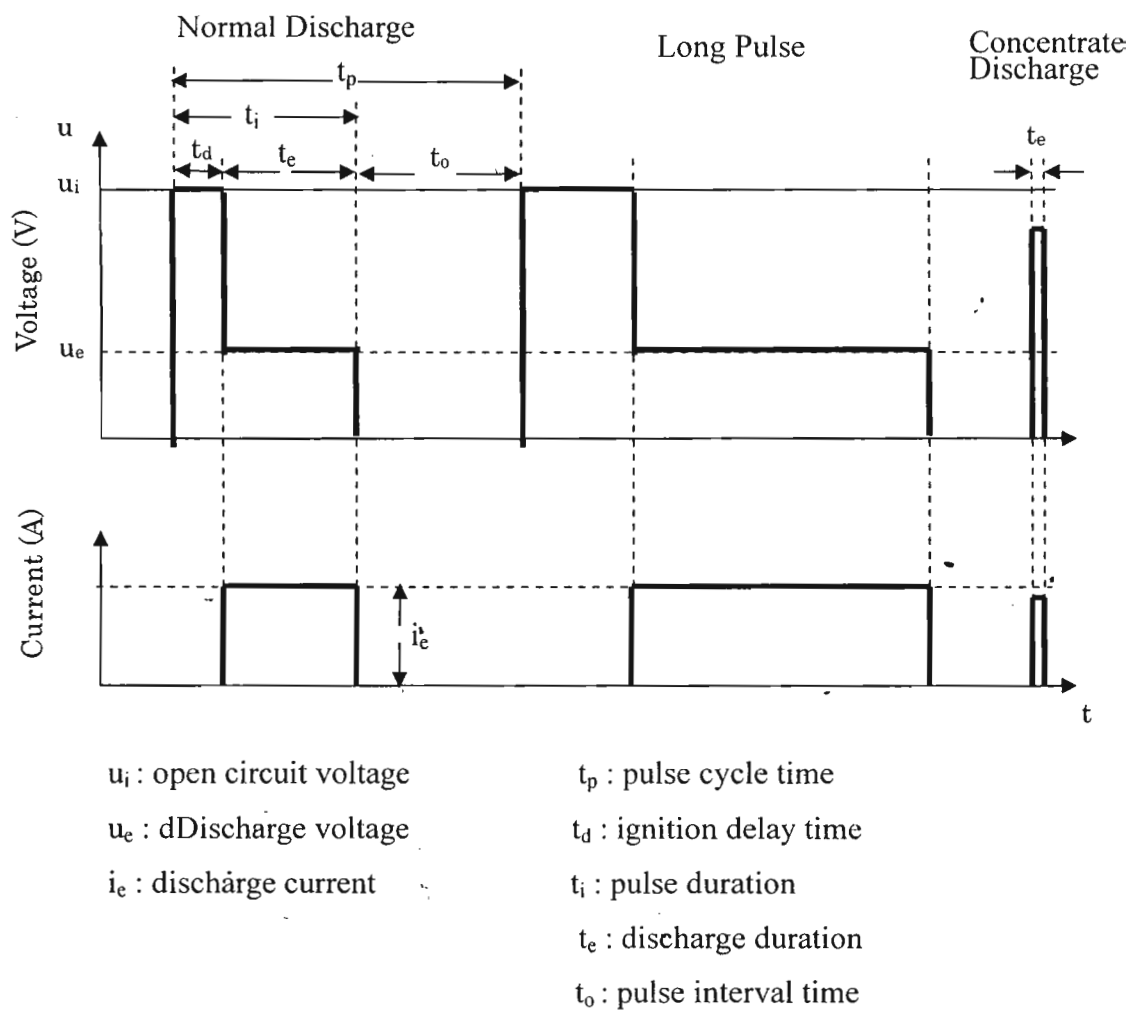


Fig.1.4 Classification of typical discharge waveforms

EXPERIMENTAL PROCEDURE

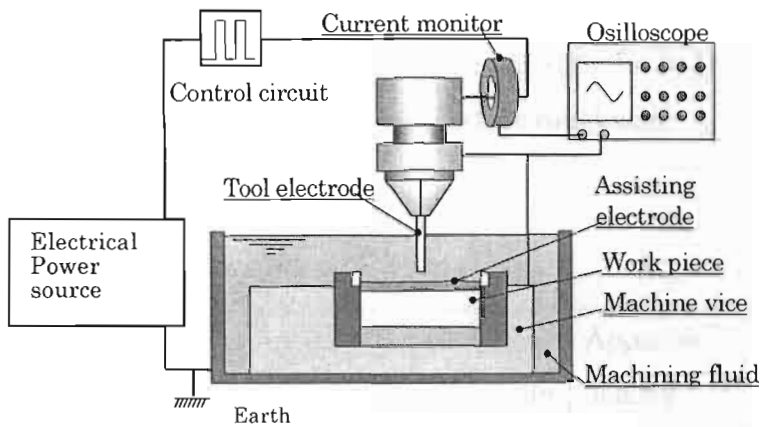


Fig.2.1 Experimental set up for EDM of insulating ceramic

Fig.2.1 shows the schematic illustration of the machining system. A cylindrical copper bar is used for the tool electrode. In order to provide a more suitable assisting electrode, we tried to make the simple method of assisting electrode with a carbon baked on ceramics. In the process of making the assisting electrode, colloidal graphite solution (concentration: 0.1 kg/l) is coated on pre-heated Al_2O_3 ceramics at 473K and maintained at the same temperature for 2 minutes. Discharge waveforms are observed with a current monitor and recorded on a digital oscilloscope. To investigate the effects of the physical properties of the material on discharge properties. The material to be machined was 95% of an alumina. A carbon-baked layer was used as an assisting electrode [3]. Electrodes were compared with normal solid copper electrode and powder electrode which produced by semi-sintering process. The semi-sintered electrodes were bought from POCO Graphite, Inc. POCO's EDM-3 and EDM-C3 had been used for comparisons. EDM-3 is an isotropic ultrafine grain graphite and EDM-C3 is high quality graphite infiltrated with copper. Electrodes were compared with normal solid copper electrode and powder electrode which produced by semi-sintering process. The semi-sintered electrodes were bought from POCO Graphite, Inc.

POCO's EDM-3 and EDM-C3 had been used for comparisons. EDM-3 is an isotropic ultrafine grain graphite and EDM-C3 is high quality graphite infiltrated with copper. Table 2.1 presents the physical properties of electrode materials in this experiment. The diameter of electrode is 3 mm. EDM conditions for alumina are very few to accomplish machining process [1]. The EDM conditions of this research are presented in Table 2.2. The machining properties are evaluated using the removal rate, wear ratio of tool electrode and surface roughness.

Table 2.1 Physical property of electrodes

	Particle size (mm)	Thermal conductivity (watts/m K)	Electrical resistivity (Ohm-m)	Apparent density (g/cm3)
EDM-3	<5	95	1.5×10^{-5}	1.77
EDM-C3	<5	175	3.3×10^{-6}	3.10
Copper (solid)	-	400	1.6×10^{-8}	8.9

Table2.2 EDM Conditions

	EDM conditions
Tool electrode	Cu (Ø3mm)
Electrode polarity	(-) (+)
Discharge current, i_e (A)	1
Discharge duration, t_e (µs)	2
Pulse interval time, t_o (µs)	32
Open circuit voltage, u_i (V)	220
Flushing pressure (MPa)	0.1
Rotating (RPM)	150

RESULTS & DISCUSSION

Normally, negative polarity of electrode is selected when EDM on insulating ceramics due to EDM needs a conductive layer generation during a process. Carbon in working oil easily generate to conductive layer on ceramics' surface [1-3]. However, powder electrodes or semi-sintered electrodes seem that they easily to implant and generate to a conductive layer even if positive polarity is selected for electrode. Figure 3.1 represents the material removal rate (MRR) and electrode wear ratio for each electrode and each polarity.

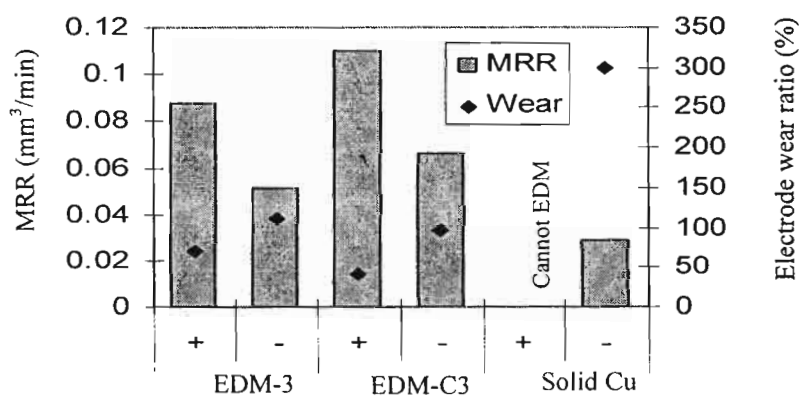


Fig. 3.1. Effect of electrode materials and electrode polarities on the material removal rate (MRR) and electrode wear ratio

The MRR increased when electrodes were used at positive polarity in all cases of semi-sintered electrodes. In case of copper electrode, it cannot be EDMed when positive polarity was selected due to conductive layer was not generated. The highest MRR and minimal wear obtained using EDM-C3 with positive polarity. Copper electrode gives the highest of electrode wear ratio. The results of electrode wear ratio relate to melting point, higher melting point wears less. However, the wear ratio inverts to MRR result. In case of lower MRR, electrode must spend more time for achieve machining. The positive polarity gives better MRR than negative polarity. This result gives a same result as EDM on a

conductive material. The reason can be explained that positive polarity gives better machining than the other due to using positive polarity caused a higher MRR under higher discharge energy [4].

In order to investigate the cross section of EDMed hole, EDM process performed on tightly clamped Al_2O_3 as shown in Fig.3.2.

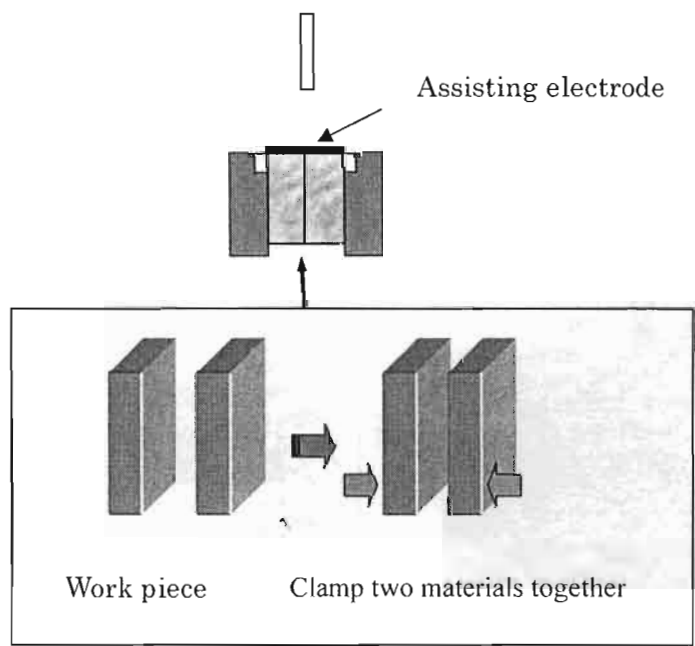


Fig.3.2 Experimental workpiece set up

Fig.3.3 shows SEM of conductive layer created by a) copper solid electrode, b) EDM-3 electrode and c) EDM-C3 electrode. The thickness of conductive layer plays an important role for EDM process.

In case of negative polarity, EDM-C3 gives the thickest for 90 μm of thickness layer followed by EDM-3, 30 μm) and then copper, 25 μm). In case of positive polarity, the trend shows same as negative polarity. EDM-C3 gives the largest of the thickness layer for 60 μm followed by EDM-3 (10 μm). The thickness of the layer relates to the results of MRR in Fig.3.1. The results show that polarity of electrode is more affect than thickness of conductive layer if the conductive layer is enough to generate for sparking.

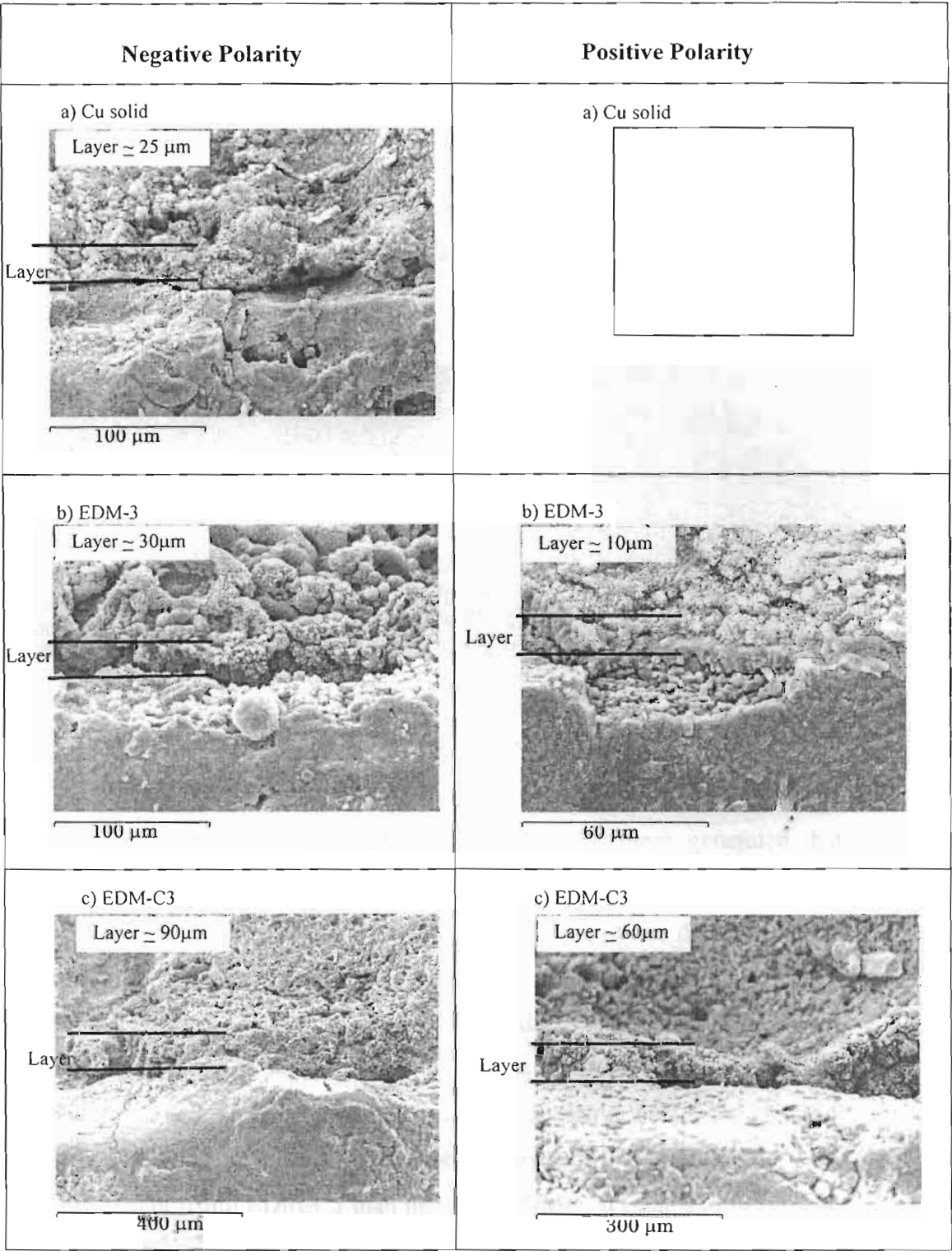


Fig. 3.3. SEM of conductive layer created by a) copper, b) EDM-3 and c) EDM-C3

To investigate the effect of material of EDM-C3 and EDM-3, the experiment was carried out with positive polarity to consider the relationship between a conductive layer generating phenomena through displacement of electrode. Fig.3.4 shows cross-sectional SEM micrograph of holes created by a) EDM-C3 electrode and b) EDM-3 electrode. Fig.3.5 shows electrode shape after EDM process a)Copper b) EDM-3 and c) EDM-C3

a) EDM-C3 electrode

b) EDM-3 electrode

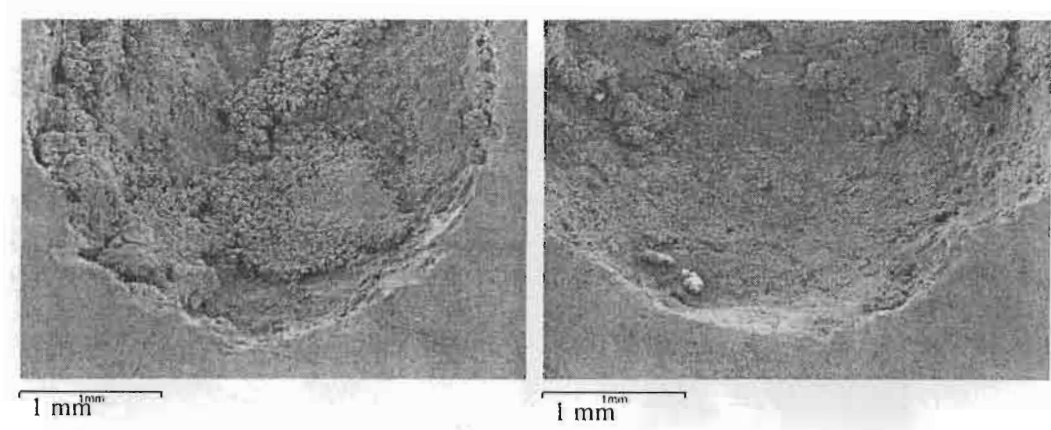


Fig. 3.4 Cross-sectional SEM micrograph of holes created by a) EDM-C3 electrode and b) EDM-3 electrode

Fig.3.4 shows that conductive layer using EDM-C3 was more generated than using EDM-3. Considering the displacements of tool electrodes with two electrodes on Fig.3.6, they can be divided 2 machining states detected on the displacement curves, one is stable machining state and the other is unstable machining state. Stable machining state means the displacement curve is changed within jump stroke, and unstable machining state is rising up of electrode higher than the jump stroke. When short and concentrate discharge occur, the electrode rises up from the workpiece and enlarges the gap distance [4] . The inclination of electrode is greater using EDM-C3 than that with EDM-3. It relates to the number of unstable machining state which more frequently occur using EDM-3. The phenomenon is correspondence to generating little thickness of conductive layer as shown in Fig.3.4. And also both polarities, when EDM process comes to over 3 mm of depth, the unstable often occurs. For this problem, the experiment may change the polarity to negative polarity for creating the conductive layer.

a) Copper



b) EDM - 3



c) EDM - C3



Fig. 3.5 Electrode shape after EDM process

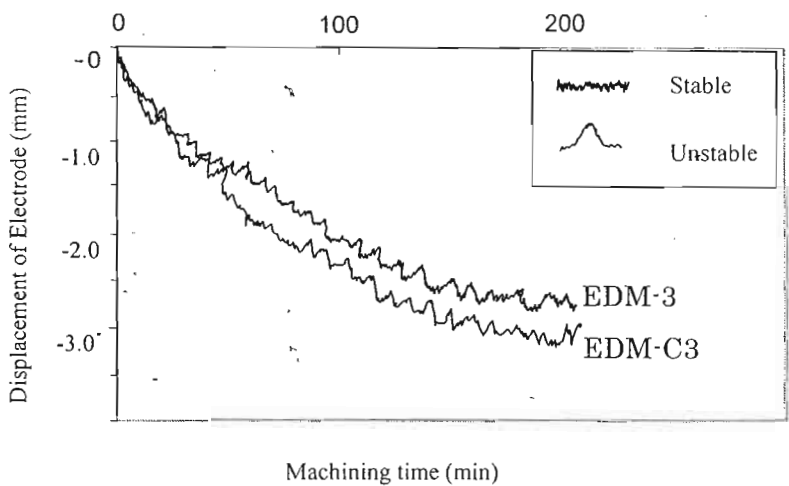


Fig.3.6 Relationship between displacement of tool electrode versus the machining time with electrode $\varnothing$ 3 mm

Fig.3.7 and Fig.3.8 show waveform which obtained from stable and unstable, respectively. Cross sectional of conductive layer produced by EDM-C3 was investigated by EDS (Energy Dispersive Spectroscopy) in order to prove that material of electrode may implant to conductive layer and affect to machining process.

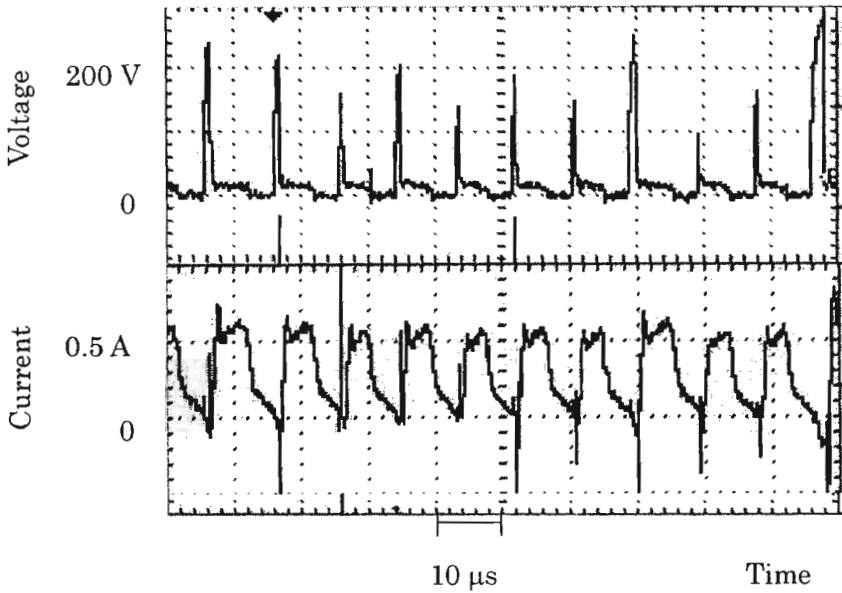


Fig. 3.7 Discharge waveform when stable discharge

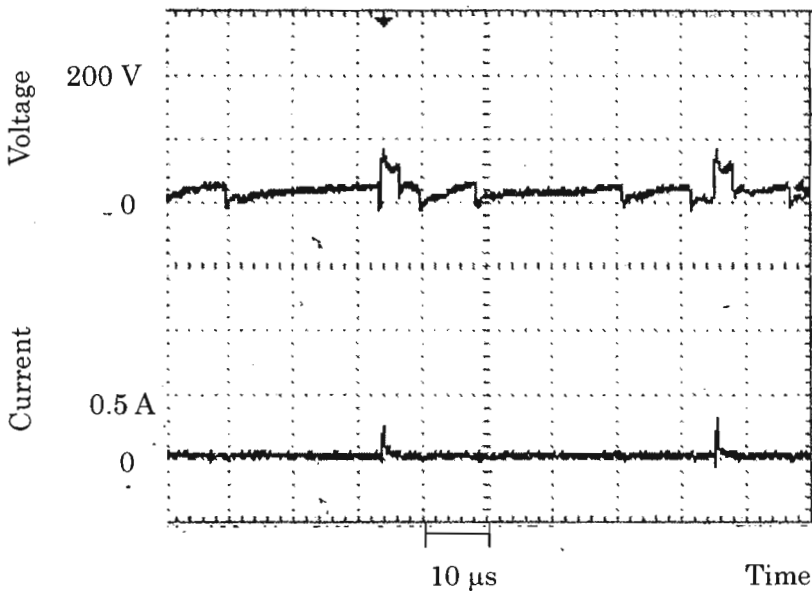


Fig. 3.8 Discharge waveform when unstable discharge

Fig.3.9 shows Energy Dispersive Spectroscopy (EDS) analysis of the conductive layers produced by EDM-C3. Fig.3.10 shows Energy Dispersive Spectroscopy (EDS) analysis of the conductive layers produced by EDM-3. In case of both electrodes, the results are same. The conductive layer is composed of carbon elements that are dissolute from working oil. It seems that an element of copper was not observed on the conductive layer.

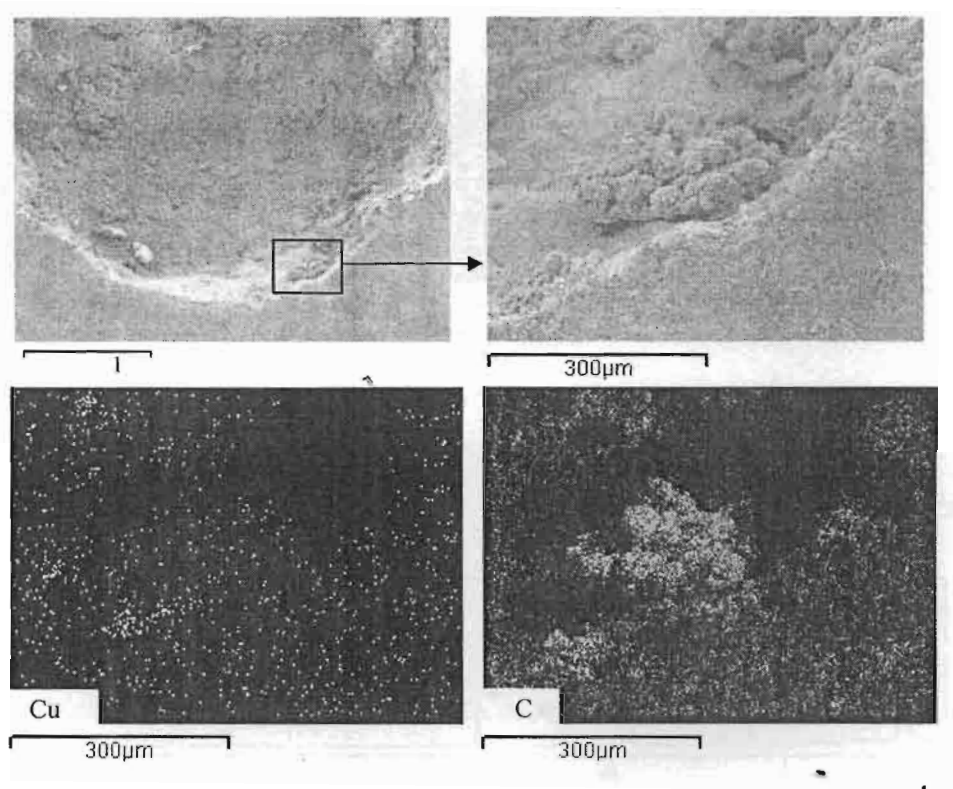


Fig. 3.9. EDS analysis of conductive layer produced using EDM-3

Fig. 3.11 shows X-ray diffraction analysis on Al₂O₃ EDMed surface. Carbon cponponent can be seen on EDM of Alumina. Chemical reaction does not occur, it is thought that fine grain of alumina interlock very good and EDM energy cannot break Al-O bonding. From XRD, result, it show that conductive layer difficult to generate on EDM surface.

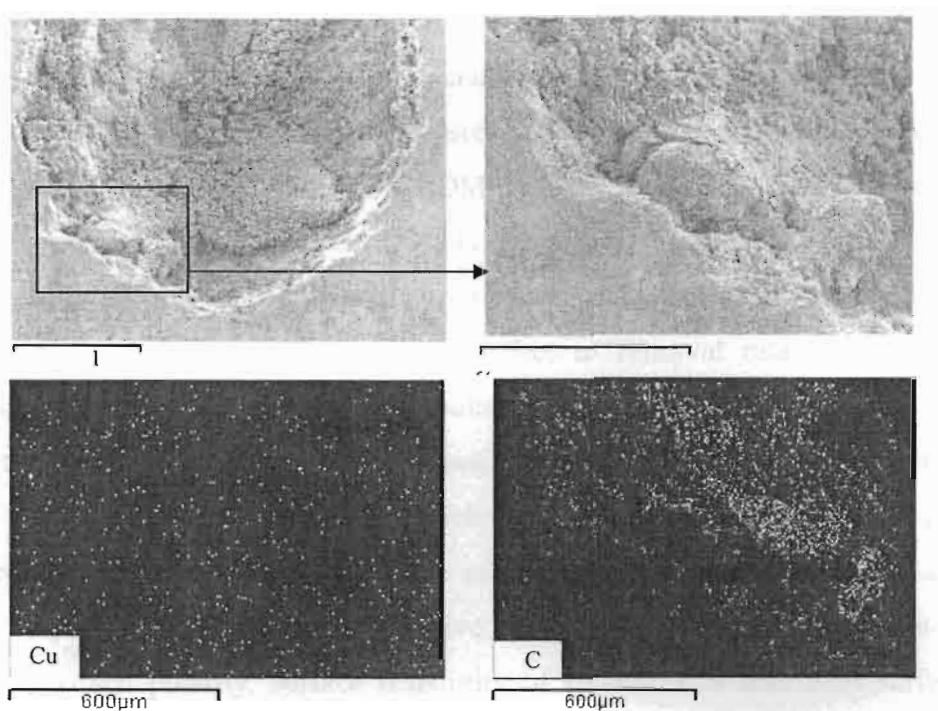


Fig. 3.10. EDS analysis of conductive layer produced using EDM-C3

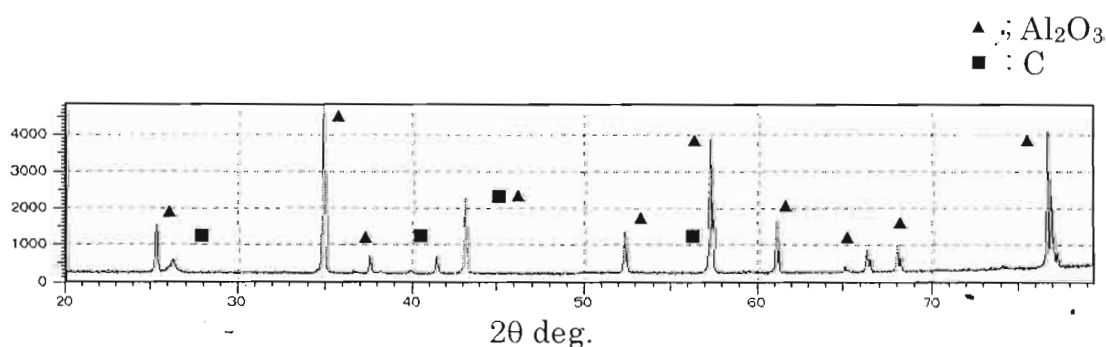


Fig.3.11 X-ray diffraction analysis on Al_2O_3 EDMed surface value

The specific electrical resistance of the electrical conductive layer was measured by Mitsubishi Chemical's resistivity meter model Loresta-GP MCP-T610. Surface resistivity was calculated from electrical resistivity and thickness of conductive layer. "Surface resistivity" is also called "sheet resistance". The unit is " Ω ". However, to distinguish from resistance, it is written

“[Ω/□]” or “[Ω/sq.]” Since surface resistivity varies with the sample thickness, it is often used in such fields as paint and thin films. Table 2 shows electrical resistivity, thickness and surface resistivity for each electrode.

followed by that generated by copper and by EDM-3 respectively. The less electrical resistivity causes the more pulsed discharges. These results relate to removal rate results of EDM-C3 and EDM-3. However the value of electrical resistivity generated with copper electrode is quite same as generated with EDM-3. But the results of MRR, EDM-3 gives much better result than copper electrode. It shows that the thickness of layer seems effect to removal rate results. The calculated surface resistivities of both polarities give same trend of electrical resistivity. Compare the values of surface resistivity in both polarities, the positive polarity gives more values because thicknesses of the layers are less. But influence of electrode polarity give more affect than thickness of the layer and surface resistivity in case of conductive layer can be enough generated. Considering each polarity, surface resistivity of EDM-C3 is less than surface resistivity of EDM-3 in all cases corresponding to the MRR results.

Table 2 Surface resistivity of conductive layer generated with various electrodes

		Negative Polarity		Positive Polarity	
Electrode	Electrical resistivity	Thickness	Surface* resistivity	Thickness	Surface* resistivity
	[Ω· cm]	[μm]	[Ω/□]	[μm]	[Ω/□]
Copper	1.018×10 ¹	25	4.071×10 ³	0	-
EDM-C3	4.924×10 ⁰	90	5.471×10 ²	60	8.206×10 ²
EDM-3	1.491×10 ¹	30	4.971×10 ³	10	1.491×10 ⁴

*Surface resistivity [Ω/□] or [Ω/sq.] = Electrical resistivity x 1/ Thickness

Fig.3.12 shows the relationship between surface roughness and thickness of conductive layer machined by various electrodes and polarities. The surface roughness (Ra values) were evaluated using data obtained from the removed

electrically conductive layer. The layer was removed from the EDMed surface by the shot peening method. The thickness of conductive layer produced by EDM-C3 is the largest follow by that produced by EDM-3 and that produced by copper electrode respectively. These results relate to value of surface roughness, it is observed that EDM-C3 gives low values of surface roughness and the values are quite same as the values produced by EDM-3. Efficiency of discharges depends on the thickness of conductive layer, so pulse discharges easily occur on location with the thick conductive layer and distribute to all area. On the contrary, the surface roughness is generated with irregularly so efficiency of pulse discharges are different at various locations, resulting in a greater surface roughness. Considering the polarity, it shows that positive polarity improved surface roughness. The reason may be explained that on negative polarity, EDM often uses for the surface modified technology [6-7] since large amounts of the carbon in working oil and some electrode material generated to conductive layer causes the location that generated to conductive layer are difficult to control. So pulse discharges occurred different at various locations, results in a greater surface roughness. On the other hand, positive polarity normally is chosen for machining. The surface roughness are control by pulse discharge.

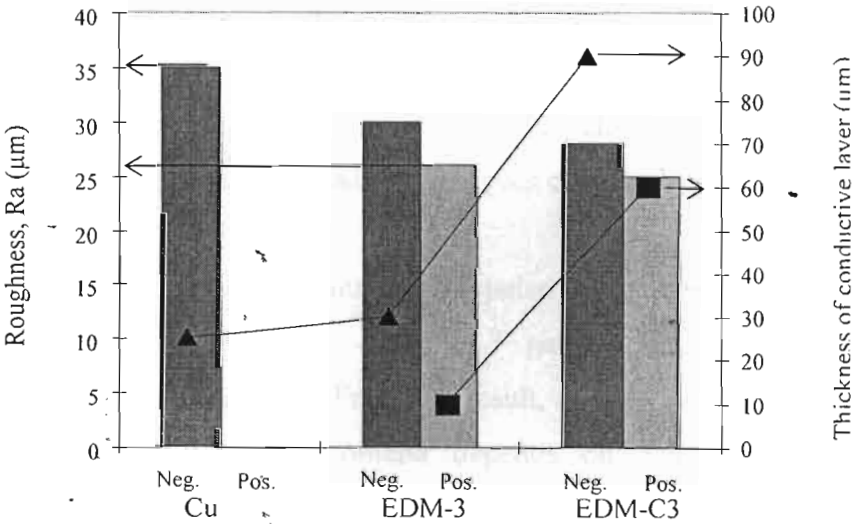


Fig. 3.12. Relationship between surface roughness and thickness of conductive layer machined by various electrodes

In EDM of insulating ceramics, the discharge waveforms are divided for 3 patterns. One is normal discharge that follows the setup values. Second is long pulse which discharge duration is much longer than setup value. It is generally considered that this particular waveform is generated during machining of high electrical resistance materials. In this method, it is assumed that the long pulses are related to the dissolved carbon components on the surface of the workpiece [5]. The other is composed by short or concentrate discharge. Long pulse and concentrate discharge are called for abnormal waveforms. In EDM of insulating materials, they are observed frequently. The main role of removal machining is accomplished by the normal discharge waveforms.

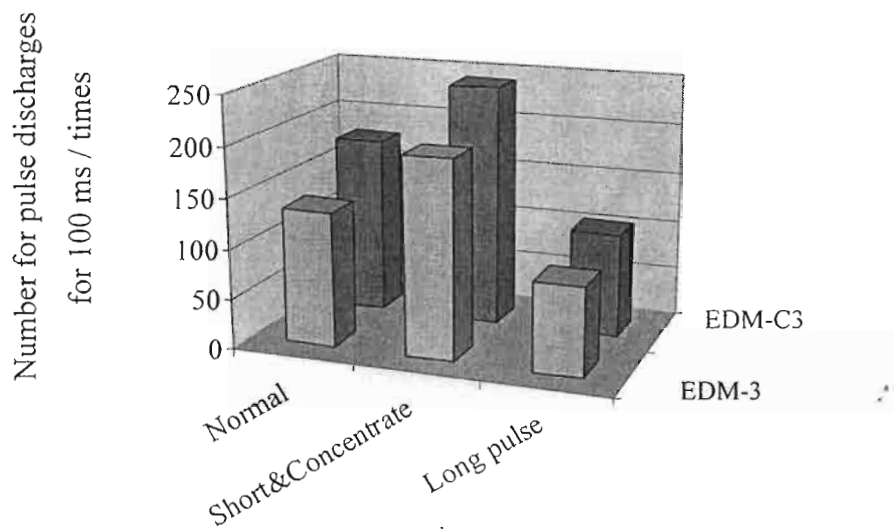


Fig. 3.13. Relationship between number of pulse discharges during 100 ms by graphite electrodes and graphite plus copper electrodes

Fig.3.13 shows relationship between number of pulse discharges and discharge waveform distributions. They were divided 3 patterns, normal, short & concentrate discharge and long pulse. From the result, number of discharges that were concerned with removal phenomena depends on electrodes. Normal discharge, short and concentrate discharge and long pulse are more obtained by EDM-C3 than by EDM-3. It indicates that material of electrode affects the discharge waveform phenomena and discharge frequency corresponding to machining properties. Considering Table 1, EDM-3 is lower thermal conductivity

than EDM-C3. When electrode is lower thermal conductivity material, longer pulse intervals are needed for cooling the gap atmosphere resulting to reduce the discharge frequency (4). The number of normal, short & concentrate discharge affects to efficiency of machining directly.

And number of long pulse discharge affects to conductive layer generation.

CONCLUSIONS AND THE FUTURE PROSPECTS

4.1 Conclusion

For developing processes of EDM of oxide insulating ceramics, generation of a conductive layer on insulating ceramics is one of the most important problems. Using graphite electrode and carbon infiltrated graphite electrode, the following main conclusions can be obtained

1. The conductive layer can be more generated with semi-sintered electrode material.
2. MRR of ceramics can be improved employed positive polarity in case of conductive layer is enough to generate.
3. The EDM-C3 is comparatively a better electrode material as it gives large conductive layer, high MRR and better surface finish.
4. There is no effect of copper from electrode for generation of conductive layer. However the copper element may affect to resistivity of conductive layer.

4.2 The prospects of the future works

The research contains the recommendations for future research of electrical discharge machining of oxide insulating ceramics using the various electrode materials.

In this study we used commercial electrodes. We don't know the composition and condition of sintering. So, we should make electrode ourselves.

Industrial technology of this method should be done to improve the ceramics machining field. And also, I wish to contribute further in this research field.

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Output

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APPENDIXES

STUDY OF ELECTRODE'S MATERIALS ON AN ALUMINA BY EDM

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KEY WORDS : Electrical Discharge Machining, alumina, graphite electrode, assisting electrode

ABSTRACT

As previously reported , several insulating ceramics such as Si_3N_4 , SiC and ZrO_2 have successfully been machined by EDM. As unstable discharges occur during the machining of Al_2O_3 ceramics, inferior machining properties have been obtained as compared to other ceramics. In this study, semi-sintered graphite electrode and copper infiltrated graphite electrode were carried out on 95% of alumina. Graphite and graphite plus copper electrode improved machining rate.

INTRODUCTION

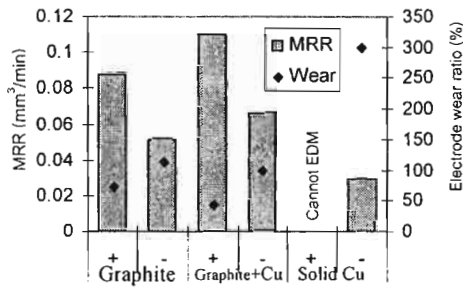
Electrical Discharge Machining (EDM) is recognized as the precision machining process for such hard materials as electrically conductive ceramics and hardened metals. However, recently, insulating ceramics have been successfully machined by EDM using the assisting electrode method (AEM) that the authors proposed [1-2]. Although the oxide ceramics Al_2O_3 is the most widely used ceramics for industrial purposes, electrically conductive layers are not formed sufficiently enough to adhere to the EDMed workpiece surface to keep a stable and continuous discharge generation on the ceramics [3]. In this study, the authors carried out semi-sintered graphite electrode and -copper infiltrated graphite electrode to improve generation of a conductive layer on alumina.

EXPERIMENTAL DETAILS

The material to be machined was 95% of Alumina. A carbon baked layer was used as an assisting electrode[3]. EDM conditions were as follows; $i_c=1\text{A}$, $t_c=2\mu\text{s}$, $t_o=32\mu\text{s}$, rotating= 150 RPM. The solid copper, graphite (EDM-3) and copper graphite (EDM-C3) electrodes of 3 mm diameter from Poco Graphite Inc were used as tools.

RESULTS & DISCUSSION

Fig. 1 represents the material removal rate (MRR) and electrode wear ratio for each electrode.



Normally, negative polarity of electrode is selected when EDM on insulating ceramics due to EDM needs a conductive layer generation during a process [1-3]. However, powder electrodes seem that they easily implant and generate to a conductive layer. Consequently, the MRR was more when electrodes were at positive polarity in all cases of powder electrodes. Because using positive electrode polarity caused a higher MRR under higher discharge energy [4]. And, the MRR was more in the copper plus graphite electrode than in the pure graphite electrode. This might be due to the high specific resistance with the graphite electrode ($540\ \mu\text{Ohm-in}$) than the copper plus graphite electrode ($120\ \mu\text{Ohm-in}$) which decreased the MRR and efficiency.

CONCLUSION

1. The MRR of semi-sintered electrode was more with positive polarity.
2. The copper infiltrated graphite electrode gives the highest MRR.

Acknowledgement

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Effect of Electrode Material on Electrical Discharge Machining of Alumina

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Abstract

Technologies for machining advanced insulating ceramics are demanded in many industrial fields. Recently, several insulating ceramics, such as Si_3N_4 , SiC and ZrO_2 , have been successfully machined by EDM. As unstable discharges occur during the machining of Al_2O_3 ceramics, inferior machining properties have been obtained. The formation mechanism of the electrical conductive layer on the EDMed surface is much different as compared to other ceramics. An 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. For this study, it is expected that carbon from graphite electrode implant and generate a conductive layer. Copper, graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3) electrodes were used to compare the effects of generation of a conductive layer on alumina corresponding to EDM properties. The Electrical Discharge Machining of 95% pure alumina shows that the EDM-C3 performs very well, giving significantly higher MRR and lower electrode wear ratio than the EDM-3 and copper electrodes. In the case of EDM with EDM-3 and EDM-C3, using positive electrode polarity gives higher MRR than EDM with negative polarity. For EDS (Energy Dispersive Spectroscopy) results, it has no element of copper was observed on the conductive layer with both EDM-3 and EDM-C3. However surface resistivity of a conductive layer created with EDM-C3 is less than with EDM-3. Surface roughness is improved with EDM-C3.

Keywords: EDM; Assisting electrode; Alumina; Graphite; Copper-infiltrated-graphite

1. Introduction

Electrical Discharge Machining (EDM) is recognized as a precision machining process for hard materials, such as electrically conductive ceramics and hardened metals [1,2]. However, recently, insulating ceramics have been successfully machined by EDM using the assisting electrode method (AEM) that was proposed in [3,4]. Although Al_2O_3 ceramics are the most widely used ceramics for industrial purposes, 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 [5]. Graphite is widely used as electrode material in EDM, this is due to its good electrical and thermal properties, along with its machinability [6,7]. For this study, it is expected that carbon from graphite electrode implant and generate a conductive layer. In this paper, copper, graphite (Poco EDM-3) and copper-infiltrated-graphite (Poco EDM-C3) electrodes were used to compare the effects of generation of a conductive layer on alumina corresponding to EDM properties. Effects of electrode polarities were investigated for each electrode material.

2. Background of the assisting electrode method

The fundamental machining process was assumed as shown in Fig.1. The discharge starts from the top of the layer (a) and creates electrically conductive products on the workpiece (b). It enters into the workpiece after the electrode tool passes through the assisting electrode (c). 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 [8]. It was lower than the machinable limit of EDM, so the discharges can continued as far as the generation of this conductive layer. The assisting electrode acts to make the products on the surface of the workpiece during machining (b,c) and holds the electrical conductivity during the discharge (c). Machining trials have been applied for many insulating ceramics and good results were obtained 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. [5]

3. Experiments

The material to be machined was 95% alumina. A carbon-baked layer was used as an assisting electrode [5]. Electrodes were compared with normal, solid copper electrodes and powder electrodes which were produced by the semi-sintering process. The semi-sintered electrodes were bought from POCO Graphite, Inc. POCO's EDM-3 and EDM-C3 were used for comparisons. EDM-3 is an isotropic, ultrafine grain graphite and EDM-C3 is a high quality graphite infiltrated with copper. Table 1 presents the physical properties of electrode materials in this experiment. The diameter of the electrode was 3 mm. In this experiment, EDM conditions were as follows; $i_c=1A$, $t_c=2\mu s$, $t_o=32\mu s$, rotation= 150 RPM and used a jump motion. The effect of electrode polarity was investigated.

4. Results and discussions

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 [3,4,5,8,9]. Carbon in the working oil easily generates the conductive layer on the ceramic's surface [8,9]. However, powder electrodes or semi-sintered electrodes seem to easily implant and generate a conductive layer even if positive polarity is selected. Fig. 1 represents the material removal rate (MRR) and electrode wear ratio for each electrode and each polarity.

The MRR increased when electrodes were used with positive polarity in all cases of semi-sintered electrodes. In the case of the copper electrode, EDM cannot be used when positive polarity was selected, due to no conductive layer being generated. The highest MRR and minimal wear were obtained using EDM-C3 with positive polarity. The copper electrode gave the highest electrode wear ratio. The results of electrode wear ratio relate to melting point; materials with higher melting points wear less. However, the wear ratio is inversely proportional to the MRR result. In the case of lower MRR, the electrode must spend more time to achieve machining. The positive polarity gives better MRR than negative polarity. This result is the same as for EDM on a conductive material. This can be explained by the fact that positive polarity gives better machining by causing a higher MRR under higher discharge energy [10]. Fig.3 shows the SEM micrograph of the conductive layer created by a) a copper solid electrode, b) an EDM-3 electrode and c) an EDM-C3 electrode. The thickness of the

conductive layer plays an important role in the EDM process. In the case of negative polarity, EDM-C3 gives the thickest layer, of 90 μm , followed by EDM-3 (30 μm) and then copper (25 μm). In the case of positive polarity, the trend is the same as for negative polarity: EDM-C3 gives the thickest layer, of 60 μm , followed by EDM-3 (10 μm). The thickness of the layer relates to the results of MRR in Fig.2. The results show that polarity of the electrode has more effect than the thickness of the conductive layer if the conductive layer is thick enough to generate sparks. To investigate the effect of the material of EDM-C3 and EDM-3, an experiment was carried out with positive polarity to consider the phenomenon of generating a conductive layer through displacement of the electrode. Fig.4 shows the relationship between displacements of the phenomenon of generating a conductive layer versus the machining time. The displacements of tool electrodes with the two electrodes in Fig.4 can be divided into two machining states detected on the displacement curves; one is the stable machining state and the other is the unstable machining state. The stable machining state means that the displacement curve changes within the jump stroke, while the unstable machining state involves the electrode rising higher than the jump stroke. When short and concentrated discharge occurs, the electrode rises up from the workpiece and enlarges the gap distance [11]. The inclination of the electrode is greater when using EDM-C3 than with EDM-3. The cross-section of the conductive layer produced by EDM-C3 was investigated by EDS (Energy Dispersive Spectroscopy) in order to prove that electrode material may be implanted on the conductive layer and affect the machining process. Fig.5 shows EDS analysis of the conductive layers produced by an EDM-C3 electrode. Fig.6 shows EDS analysis of the conductive layers produced by an EDM-3 electrode. The SEM micrograph in Fig.5 and Fig.6 show that a thicker conductive layer was generated when using EDM-C3 than when using EDM-3. This relates to the number of unstable machining states, which occur more frequently using EDM-3. The phenomenon corresponds to the generation of only a low thickness of conductive layer, as shown in Fig.4. At both polarities, when the EDM process comes to over 3 mm of depth, the unstable state often occurs. To solve this problem, negative polarity may be used for creating the conductive layer.

The EDS results are quite same with both electrodes. The conductive layer is composed of carbon elements that are mainly from the dissolved components of the working oil during discharge. It seems that no element of copper was observed on the conductive layer. The specific electrical resistance of the electrically conductive layer was measured by a Mitsubishi Chemical resistivity meter, model: Loresta-GP MCP-T610. Surface resistivity (also known as sheet resistance), was calculated from electrical resistivity and thickness of the conductive layer. To distinguish it from resistance, it is

written as " $[\Omega/\square]$ " or " $[\Omega/\text{sq.}]\text{'}$ " Since surface resistivity varies with the sample thickness, it is often used in studies of paint and thin films. Table 2 shows electrical resistivity, thickness and surface resistivity for each electrode.

Electrical resistivity of the conductive layer generated by EDM-C3 gives the lowest value, followed by that generated by copper and by EDM-3, respectively. The lower electrical resistivity causes more pulsed discharges. These results relate to removal rate results of EDM-C3 and EDM-3. However the value of electrical resistivity generated with the copper electrode is quite similar to that generated with EDM-3. But EDM-3 gave a much better MRR result than the copper electrode. This shows that the thickness of the layer seems to affect removal rate results. The calculated surface resistivities of both polarities give the same trend of electrical resistivity. Comparing the values of surface resistivity for both polarities, the positive polarity gives greater values because the thicknesses of the layers are less. However, the influence of electrode polarity had a greater affect than thickness and surface resistivity in the case where a conductive layer could be generated sufficiently. Considering each polarity, surface resistivity of a conductive layer created with EDM-C3 is less than with EDM-3 in all cases corresponding to the MRR results.

Fig.7 shows the relationship between surface roughness and thickness of the conductive layer machined by various electrodes and polarities. The surface roughness (Ra values) were evaluated using data obtained from the removed electrically conductive layer. The layer was removed from the EDM surface by the shot peening method. The thickness of the conductive layer produced by EDM-C3 is the largest, followed by that produced by EDM-3 and copper electrodes, respectively. These results relate to values of surface roughness; it is observed that EDM-C3 gives low values of surface roughness which are similar to the values produced by EDM-3. Efficiency of discharges depends on the thickness of the conductive layer, so pulse discharges occur easily in regions with thick conductive layers and then distribute to all other areas. On the contrary, the surface roughness is generated irregularly so efficiency of pulse discharges is different at various locations, resulting in a greater surface roughness. It has also been shown that positive polarity improves surface roughness. The negative polarity of the workpiece, in general, has an inferior surface roughness than that under positive polarity in EDM. The discharge current generated in EDM is composed by ion and electron flows. The proportion of ion flow increases with the pulse duration time, thus, the ion flow impacts violently on the negative workpiece and causes a inferior surface roughness [12].

In EDM of insulating ceramics, the discharge waveforms are divided into three patterns as shown in Fig.8. One is normal discharge that follows the setup values. The second is a long pulse with a discharge duration much longer than the setup value; it is generally considered that this particular waveform is generated during machining of highly electrically resistant materials. In this method, it is assumed that the long pulses are related to the dissolved carbon components on the surface of the workpiece [9]. The other pattern is composed of short or concentrated discharges. Long pulses and concentrated discharges are called abnormal waveforms. In EDM of insulating materials, they are observed frequently. The main role of removal machining is accomplished by the normal discharge waveforms. Fig.9 shows the relationship between the number of pulse discharges and discharge waveform distributions. They are divided into three patterns: normal, short & concentrated discharges and long pulses. From the results, the number of discharges that were concerned with removal phenomena depends on the electrode material. Normal discharges, short and concentrated discharges and long pulses are more readily obtained by EDM-C3 than by EDM-3. This indicates that electrode material affects the discharge waveform phenomena and discharge frequency corresponding to machining properties. Considering Table 1, EDM-3 has lower thermal conductivity than EDM-C3. When an electrode is made from lower thermal conductivity material, longer pulse intervals are needed for cooling the gap atmosphere resulting in reduced discharge frequency [13-14]. The number of normal, short & concentrated discharges affects the efficiency of machining directly, and the number of long pulse discharges affects to conductive layer generation.

5. Conclusions

In the EDM of alumina with different electrode materials, the obtained results are summarized as follows:

1. A thicker conductive layer can be generated with semi-sintered electrode material.
2. MRR of ceramics can be improved by employing positive polarity in cases where the conductive layer is sufficient.
3. The EDM-C3 is a comparatively better electrode material as it gives a large conductive layer, high MRR and better surface finish.

Table 1 Physical properties of electrodes

	Particle size (mm)	Thermal conductivity (watts/m K)	Electrical resistivity (Ohm-m)	Apparent density (g/cm3)
EDM-3	<5	95	1.5×10^{-5}	1.77
EDM-C3	<5	175	3.3×10^{-6}	3.10
Copper (solid)	-	400	1.6×10^{-8}	8.9

Table 2
Surface resistivity of conductive layer generated with various electrodes

Electrode	Electrical resistivity ($\Omega \cdot \text{cm}$)	Negative Polarity		Positive Polarity	
		Thickness (μm)	Surface* resistivity ($\Omega/\square$)	Thickness (μm)	Surface* resistivity ($\Omega/\square$)
Copper	1.018×10^1	25	4.071×10^3	0	-
EDM-C3	4.924×10^0	90	5.471×10^2	60	8.206×10^2
EDM-3	1.491×10^1	30	4.971×10^3	10	1.491×10^4

*Surface resistivity ($\Omega/\square$) or ($\Omega/\text{sq.}$) = Electrical resistivity x 1/ Thickness

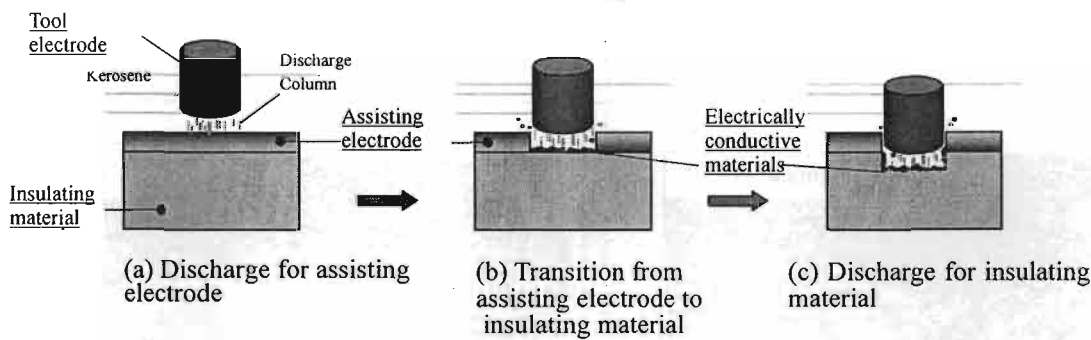


Fig. 1. Machining process of insulating materials using assisting electrode

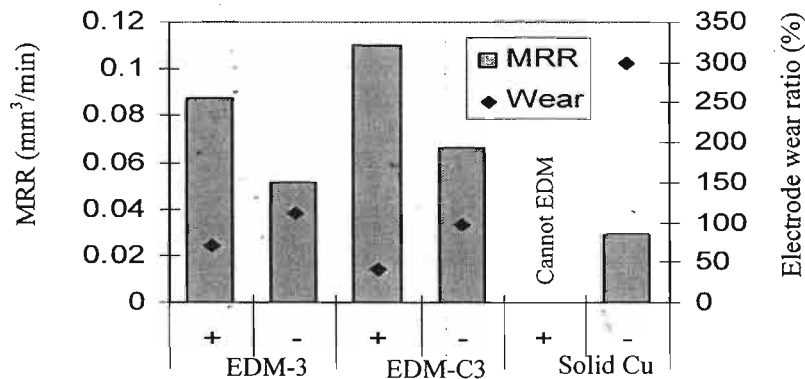


Fig. 2. Effect of electrode materials and electrode polarities on the material removal rate (MRR) and electrode wear ratio

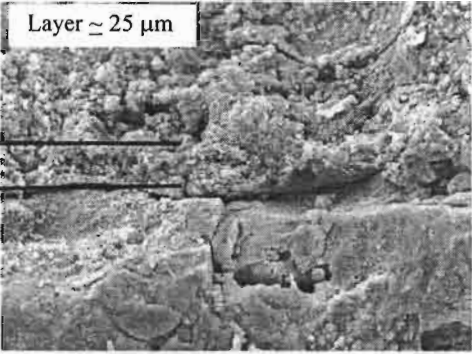
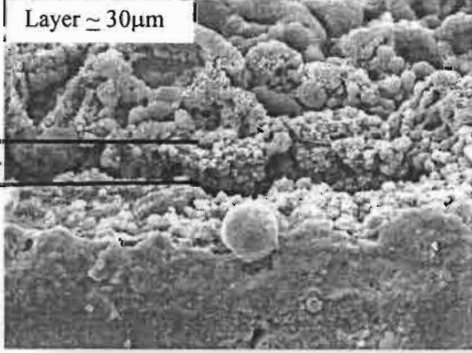
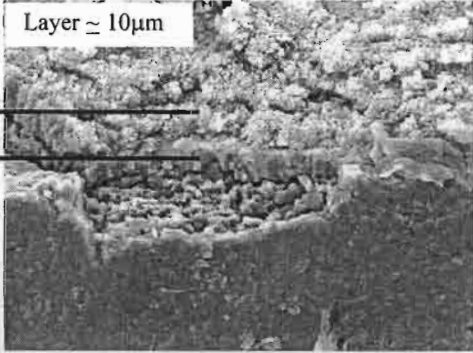
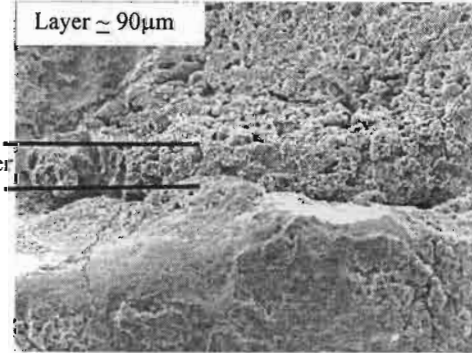
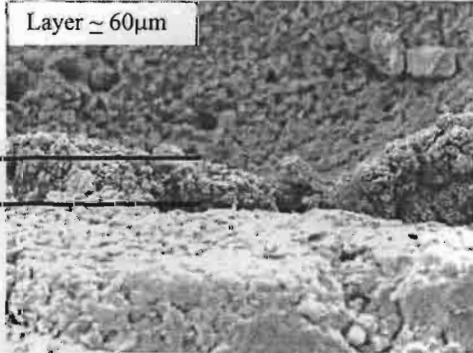
Negative Polarity	Positive Polarity
a) Cu solid Layer $\approx 25\ \mu\text{m}$  100 μm	a) Cu solid CANNOT EDM
b) EDM-3 Layer $\approx 30\ \mu\text{m}$  100 μm	b) EDM-3 Layer $\approx 10\ \mu\text{m}$  60 μm
c) EDM-C3 Layer $\approx 90\ \mu\text{m}$  400 μm	c) EDM-C3 Layer $\approx 60\ \mu\text{m}$  300 μm

Fig. 3. SEM of conductive layer created by a) copper, b) EDM-3 and c) EDM-C3

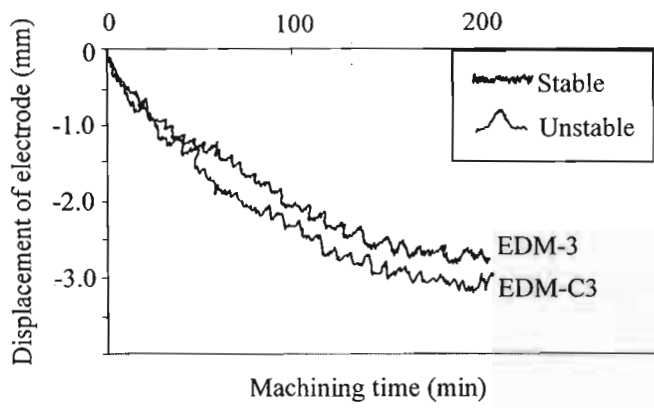


Fig. 4. Relationship between displacement of tool electrode versus the machining time with a) EDM-C3 and b) EDM-3

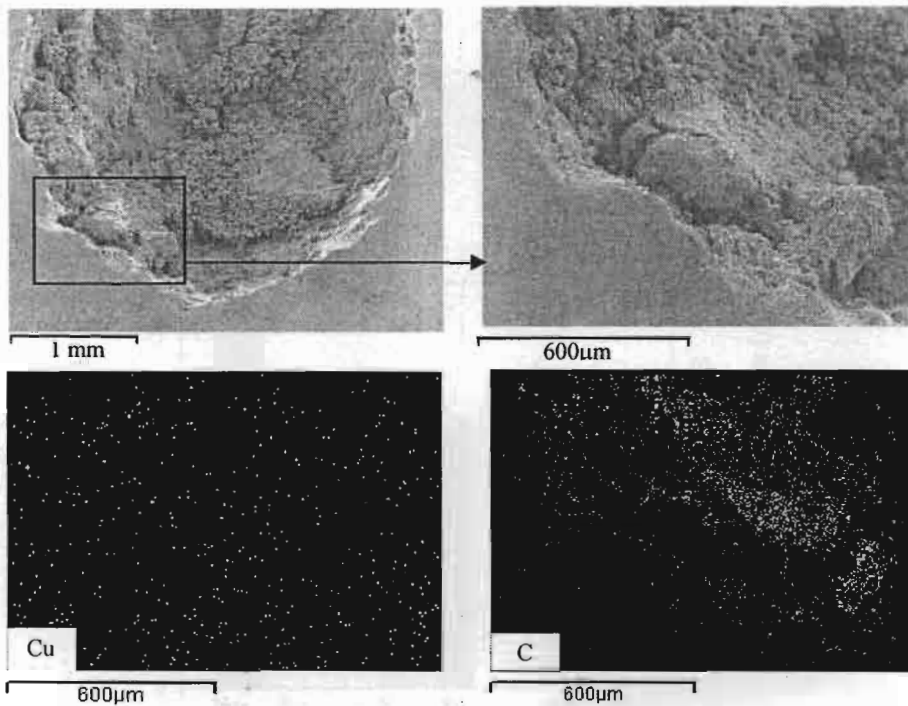


Fig. 5. EDS analysis of conductive layer produced using EDM-C3

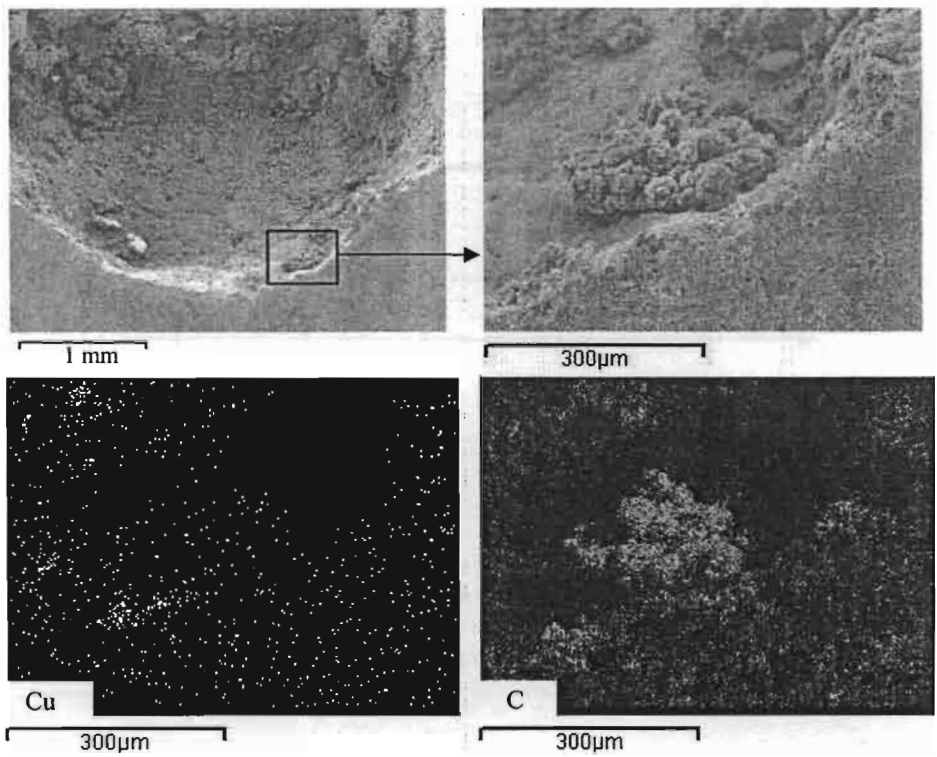


Fig. 6. EDS analysis of conductive layer produced using EDM-3

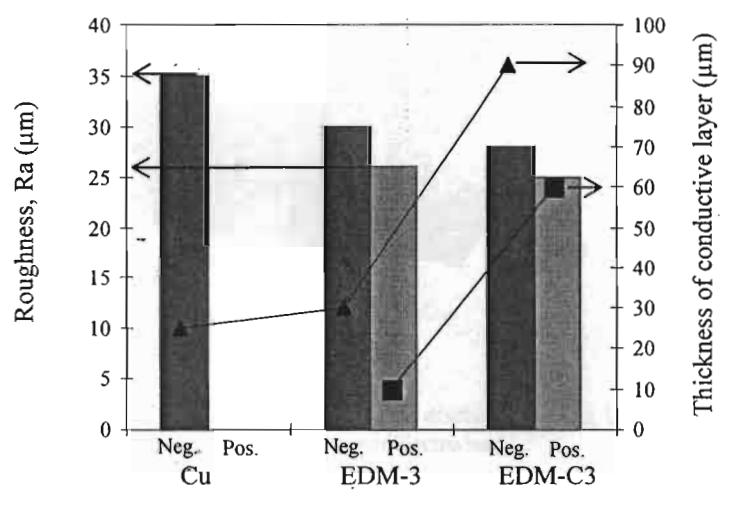


Fig. 7. Relationship between surface roughness and thickness of conductive layer machined by various electrodes

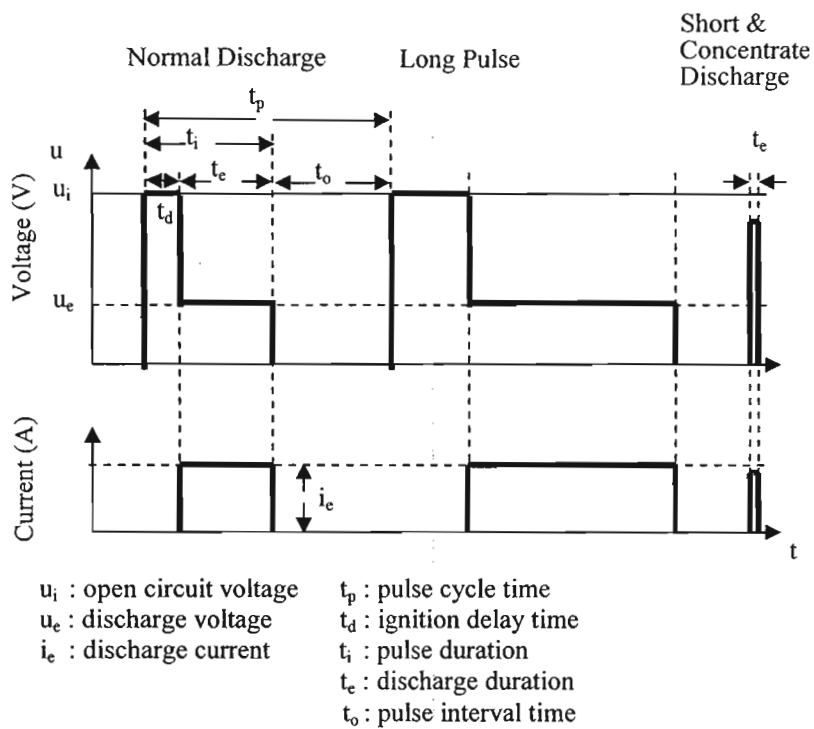


Fig. 8. Classification of typical discharge waveforms

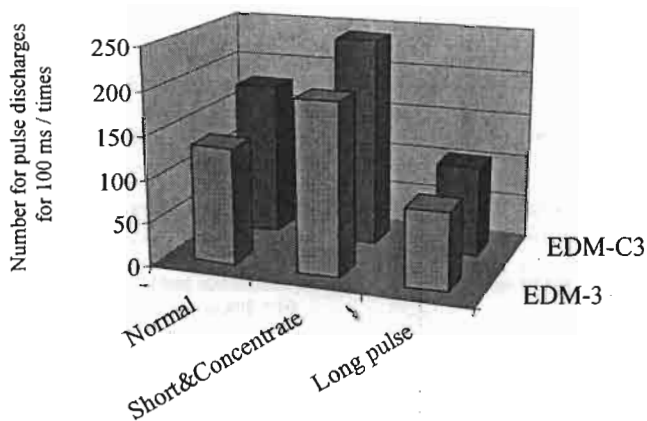


Fig. 9. Relationship between number of pulse discharges during 100 ms by graphite electrodes and graphite plus copper electrodes

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