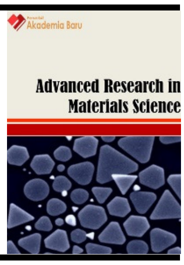
Penerbit Akademia Baru

Journal of Advanced Research in Materials Science

Journal homepage: www.akademiabaru.com/arms.html
ISSN: 2289-7992




# Electrical Discharge Grinding of Polycrystalline Diamond-Material Erosion Rate

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**ARTICLE INFO**

***Article history:***
Received 4 February 2017
Received in revised form 9 March 2015
Accepted 17 March 2017
Available online 3 May 2017

***Keywords:***
Electrical discharge machining, Electrical discharge grinding, Polycrystalline Diamond, Material removal rate, Material erosion rate

**ABSTRACT**

Polycrystalline diamond (PCD) cutting tools is becoming more prevalent in aerospace manufacturing industries due to the emergence of carbon fiber-reinforced plastic-titanium (CFRP/Ti) stack composites, which are now being used for the aerospace mainframes. Excellence mechanical properties of Ti require special tools in which PCD regarded as the best candidate. Ability to retain tools sharpness is an advantage of PCD cutting tools. However, the high thermal conductivity of diamond grains and low electrical conductivity become a challenge in PCD erosion process. This paper investigates the effects of machining polarity, as well as finishing in-feed, to the material erosion rate of PCD by Electrical Discharge Grinding (EDG). The experiment results show the role of carbon plating that happened on PCD surface when using positive polarity for the erosion. Through a scientific methodology and microscopic observation, it was found that the carbon plating phenomenon increased the material erosion rate and lowered the surface roughness value of the machine surface.



## 1. Introduction

The tool electrode wear ratio reported to be lower when workpiece is used as the negative electrode in EDM [1]. Carbon plating of the anode (that is the electrode) is believed to be the reason for the reduction in the electrode wear when using this method [1, 2]. The transformation of diamond into other forms of carbon occurs during the EDM sparking process. The result from the conversion process is the formation carbon ions that are then involved in the anode plating operation. This heat-resolved carbon acts as a shield that protects the electrode from wear [1]. Furthermore, the carbon

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deposited on the anode is also reported decomposed from the dielectric medium [3]. Marafona [4] investigated the effect of so-called "black layer" to the wear ratio of the electrode during electrical discharge machining process (EDM).The black layer that comprises of migrated carbon was found deposited on the positive electrode during the process. They found that the larger amount of the deposited carbon reduced the wear ratio of the electrode used. The "assisting electrode" technology based on "black layer" has been successfully applied in EDM to manufacture insulation material such as ceramics (ZrO2 and Al2O3) [5].

This experiment was designed to investigate the effect of the carbon layer to the erosion rate of the electrical discharge grinding (EDG) process. Unlike the electrode tool carbon plating, an additional layer of carbon on the polycrystalline diamond (PCD) surface does not contribute to better heat conductivity. However, more excellence electrical conductivity of the carbon in comparison with the diamond grains is hypothesized an advantage to the process.

## 2. Methodology

PCD insert tools with different grades were used in this investigation. Table 1 shows the types of PCD used and their composition properties. Two stages of EDG erosion (roughing and finishing) was used as the machining strategy. The roughing procedure was purposely done to obtain the flat surface before the finishing process is sequentially done. The machining parameters are shown in Table 2.

**Table 1**
Properties of PCD[6-8]

| PCD Types | PCD Grain Size (µm) | Diamond Fraction (Vol %) | Cobalt Fraction (Vol %) | PCD to WC layer thickness ratio |
|---|---|---|---|---|
| *CTX002* | *2* | *84.8* | *15.2* | *0.13* |
| *CTB010* | *10* | *89.7* | *10.3* | *0.13* |
| *CTM302* | *2-30* | *91.4* | *8.6* | *0.18* |

**Table 2**
EDG machining parameters

| Operation | Open-Voltage (V) | Wheel rotation speed (rpm) | Current (A) | On-time (µs) | Off-time (µs) | In-feed (mm) |
|---|---|---|---|---|---|---|
| Roughing | 120 | 250 | 12 | 40 | 20 | 0.5 |
| Finishing | | | 1, 3 | 1 | 1 | 0.04 |

The PCD with total cross-sectional area of 23mm2 (7.2mm PCD width and 3.18mm total thickness) was divided into 4 imaginary regions as shown in Figure 1. In this EDG process, commercialize available tungsten-copper wheel with a diameter of 150 mm was acted as the tool electrode and hydrocarbon oil was used as the dielectric. The tool positioning information was used to define the erosion level of PCD. With the high-resolution encoder, the EDM gap control system can achieve the precise position of 0.1µm. As shown in Figure 2, the adaptive scheme of the process was implemented to adjust the feed rate of PCD, to match the erosion rate. The machining time was taken when process starts to erode the specific region until 5µm depth. This continuous erosion enables to the precise interpretation of material erosion rate of PCD with respect to the erosion depth.

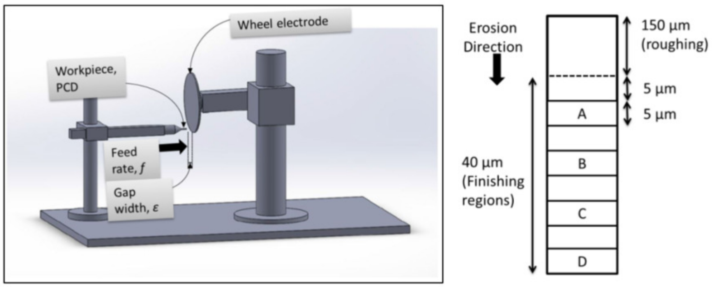


**Fig. 1.** Experimental setup and procedure

**Fig. 2.** Block diagram of the EDM gap control system

As refers to the feeding movement of the PCD, the following equation can be used to calculate the material erosion rate of the process:

$$\dot{m} = \dot{s}A \quad (1)$$

where $\dot{m}$, $\dot{s}$, and A is the volume erosion rate (mm3/s), feed rate, and workpiece cross-sectional area respectively. As a constant cross-sectional value applied, the feed rate value is proportional to the material erosion rate of the process, thus mandates the use of feed rate as the material erosion rate indication.

## 3. Results and Discussion

In negative polarity, the electron flows from the negative electrode (wheel electrode) to the positive electrode (material being eroded) [9]. The positive ions at the same time move in the inverse direction but with much lower acceleration than electrons since the electron is much lighter [10]. Due to the higher kinetic energy of the electron, they earlier collide with the anode and convert their kinetic energy into heat, before the ions reach the other electrode [10]. The theory explains the reason for higher erosion rate in negative polarity implemented in this study. Figure 3 shows the feed rate obtained by different PCD grade used.

**Fig. 3.** Material erosion rate of different PCD types

In this study, 1A current for positive polarity machining was found unable to erode PCD, even for the smallest PCD grade used. The erosion was only happened in few microns depth before the system is stopped feeding the workpiece toward the wheel. The phenomenon was found repeatable, and consistent that caused by the eroded surface morphology of PCD as will be discussed later. Interestingly, nonlinear erosion rates were observed for the other successful erosion. The reduction in erosion rate for positive polarity presumes as presents the normal erosion behaviour. Especially for the first 10µm erosion (region A), the process would be faster as removing only smaller volume of rough residue surface, left by the roughing operation (Figure 4).

**Fig. 4.** Residue surface left by the roughing surface a. SEM image (CTB010) b. Surface profile (CTX002) c. Surface profile (CTB010) d. Surface profile (CTM302)

The graph constructed for negative polarity represents a surprising inverse in trend. Considering the hardest to erode PCD (CTM302), the erosion rate was found fitted well by the one phase decay exponential line pattern as shown in Figure 5 below.

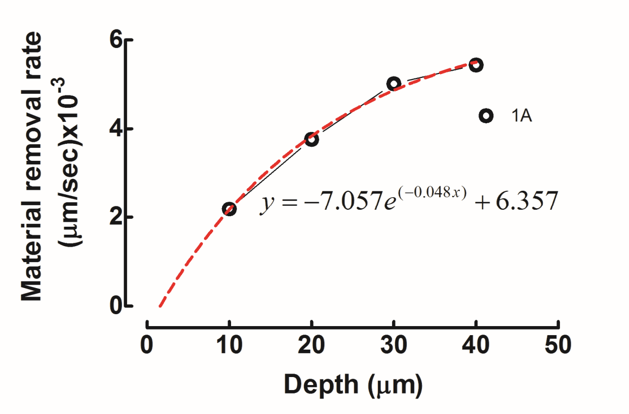


**Fig. 5.** Non-linear regression line fitting

The non-linear line trend indicates the increasing in material erosion rate, where up to 250 percent improvement was recorded. Increasing in material erosion rate at higher in-feed location shows the influence of the carbon plating on the surface. In fact, erosion of the subsequence region was faster than the erosion of the early 10µm depth. As theorized, it was found that the deposition of migrated material on the PCD surface increased with longer machining time implemented whereas it is proportional to the machining depth. Figure 6 shows the deposition of black layer in this continuous erosion process for diamond grain size of 2 – 30µm. It revealed that the thicker the black layer formed, the higher the process removal rate.

**Fig. 6.** The images of carbon layer (black layer) on the eroded surface of CTM302 PCD (obtained by the optical microscope with 100x magnification lens) a. After 10µm finishing in-feed b. After 20µm finishing in-feed c. After 30µm finishing in-feed d. After 40µm finishing in-feed

Especially for large diamond particle size, increasing in machining efficiency could be explained by the increasing in electrical conductivity of PCD through covering the surface of the workpiece, including the exposed large diamond particles with conductive material. The carbon layer acts as the conductor path that connected to the cobalt matrix in which it is useful for the sparking operation. The layer that covered the nonconductive diamond grain would enable the sparking to happen on a particular region. The thermal energy would be supplied towards the diamond grain underneath thus facilitates the erosion process through graphitisation mechanism as mentioned in reference [11]. As shown in Figure 7, the black layer comprises of all PCD's elements (Cobalt, Carbon) and another three additional wheel's elements (Cu, Ca, W). The electrode material that is electrically conductive was migrated to workpiece in the small discharge gap thus increased the electrical conductivity of the PCD. It was believed that the adhered carbon element decomposed from the hydrocarbon dielectric used, in addition to the graphitization process of diamond particles.

As reported in reference [12] there are two kind of residue generally obtained by the EDM process of PCD (diamond particle and deposited metallic film; particularly on the positive electrode). In die sinking EDM without flushing, Pisarcius [13] found that these residues generated the congestion in the gap thus increased the number of inactive pulses (short circuit and arching). The intervention spark phenomenon consequently increased the energy losses and reduced the productivity of the process. Differently, since the dielectric flushing and rotating wheel implemented in this study, more efficient flushing ability could be expected. It thus eliminated or reduced the probability of crystal congestion in the sparking gap.

**Fig. 7.** Elemental composition of the black-layer (The image taken is perpendicular from the eroded surface)

Similar to as discussed in reference [14], porous surface particularly for positive polarity erosion was observed in this investigation (Figure 8).Selective erosion was mentioned happened in positive polarity machining, but it is not well explained [14]. The authors theorised that, the carbon plating is happening on the positive electrode during the positive polarity erosion. On the same time, the sparking is happening in the PCD cobalt region due to better electrical conductivity than the diamond grains. As a result, only the nonconductive diamond grains left on the surface. The cobalt will melt and evaporate while the diamond-to-diamond bonding retains the grains position in a skeleton shape, having a porous look surface. Figure 9 presents the elemental composition of the porous structure. It shows that the top surface is dominated by the carbon element, represents diamond.

**Fig. 8.** Close-up view of the surfaces produced on CTB010 a. Positive polarity b. Negative polarity

**Fig. 9.** Elemental composition of the eroded surface (eroded by positive polarity)

It was also believed that the availability of this black layer would enable the heat to be distributed evenly on the surface, consequently results in smooth eroded surface. During the heating process, the protruded diamond grains underneath the black layer undergoing graphitization. Some portion of graphite dissolves into the molten cobalt before being flushed away by the dielectric. The other portion is solidified; thicken the black layer up to some extent. The process is repeated until the maximum thickness is achieved.

**Fig. 10.** Illustration of the black layer assisted erosion theory

This morphological finding also explains the phenomena of obstructed feeding while eroding with small current in positive polarity. Few microns depth erosion that is happening at the early finishing stage indicates the removing process of highly graphitized residue surface, left by the roughing process. After the completion of the residue structure removal, the skeleton porous structure is developed. At this point, a small current supplied is insufficient to provide enough energy for a spark to reach the high electrical conductive cobalt region, inhibits to further erosion. On the same time, the electrode wheel is obstructed by the protruded grains to achieve the smaller enough gap for sparking.

## 4. Conclusion

In this study the following conclusions were reached:

1. The black layer constitutes of the wheel elements and migration carbon collected by the degeneration of the dielectric fluid and graphitization during the sparking process.
Because of the conductivity of dominated carbon particle, this layer is electrical conductive. The formation of thicker conductive black layer resulted in a significant increase in machining efficiency: an increase of erosion rate of 250% had been achieved with the increase of black layer thickness.
2. The morphological difference of PCD machined with positive and negative polarity also regarded due to the electrical conductive film deposition phenomenon. The availability of the conductive layer eliminates the spark concentration on specific highly conductive region, typically cobalt. The layer facilitates the graphitization process of the diamond grains underneath by thoroughly and evenly heating process of the surface, results in the formation of the smooth surface.

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