Study on Over-erosion in Wire Electrical Discharge Machining of PCD Composite

Changshui Gao, Yi Qiu, Zhuang Liu* and Sheng Wang

School of mechanical and electrical engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

*Corresponding author e-mail: liuzhuang@nuaa.edu.cn

Abstract. This paper has investigated the mechanism of over-erosion in WEDM of PCD composite. The result reveals that the over-erosion phenomenon cannot be avoided in the WEDM of PCD composite during fabrication of micro cutter. The reason of that is due to the different erosion rate of different elements in the composite. The discharge voltage, single-pulse energy and machining gap have influences on the size of over-erosion groove. A set of optimal parameters for minimum erosion groove were obtained through experiments.

1. Introduction

With the development of micro-fabrication, there has been increasing demand for micro milling cutters for many years. Obviously, the quality of micro cutters will significantly affect the process of micro-milling. Polycrystalline diamond (PCD) composite is a type of super-hard material which has been widely used in manufacture of micro-tools due to high hardness, high wear resistance and excellent thermal properties.

For the PCD composite used for manufacturing micro cutter, the material is composed of PCD layer and cemented carbide layer. The cemented carbide layer links to cutter holder by welding process. The PCD layer will be machined as cutter edge having a rotating diameter of 0.5mm or less. Wire electrical discharge machining (WEDM) is a commonly used process to fabricate cutting edge of these cutters made by PCD composite. In the WEDM process, the cutting trajectory of the wire electrode starts from the cemented carbide layer across to PCD layer, as shown in Figure 1(a). With this cutting strategy, the PCD composite can be formed as required size and shape by multiple-layer removal of WEDM, as illustrated as Figure 1(b) [1-2].
In the WEDM of micro end mill, there is a phenomenon of over-erosion often occurred during the process. Severe over-erosion will cause many micro pits in the machining surface and subsequently results in negative effects on the appearance and performance of the micro mill. Therefore, this paper experimentally investigated the over-erosion phenomenon and analysed causes of the over-erosion. The factors affecting the over-erosion were also studied in the work. A set of optimal parameters for small erosion groove was presented as well.

2. The experimental setup

The material selected for the experiment is provided by Element Six company (type: CTB010). As illustrates in Figure 2, the specimen is prepared as a block having thickness \( b \) of approximate 1.1mm. The depth of the over-erosion groove is represented by variable “\( D \)”. Preliminary experiment shows that the value of discharge current and pulse internals influence the machinability significantly. Thus, this paper selected open circuit voltage, single-pulse energy, and machining gap as main factors to study the depth of the over-erosion groove \( (D) \).

A Vollmer QWD 760 WEDM machine was used to perform the experiment, and process conditions were listed in Table 1. Taking into account the experimental objectives and measurement, the wire electrode was designated to cut from side of cemented carbide layer of the composite, as exhibited in Figure 3.

| Pulse voltage | Current | Pulse width | Pulse interval |
|---------------|---------|-------------|----------------|
| 70~250 V      | 1~48 A  | 1~26 \( \mu \)s | 1~5000 \( \mu \)s |

A Vollmer projector was used to measure the depth of the over-erosion groove \( (D) \). The surface topography and elements distribution on machining surface were inspected by a SEM instrument. The machining time was recorded during the process.
3. Results and discussion

3.1. The phenomenon of over-erosion

The over-erosion grooves cannot be avoided in the WEDM of PCD composite, as shown in Figure 4. It often happens during the cutting transition from layer of cemented carbide across to layer of PCD.

![three dimensional picture](image1.png) ![preojection view of over-erosion groove](image2.png)

**Figure 4.** The over-erosion phenomenon

Figure 5 shows the element distribution on the machined surface across two different materials. It can be seen from the figure that the element cobalt (Co) at the surface is significantly increased from nearly 8% to 35% during the transition from cemented carbide area to PCD area. Literature [3] reported that the Co was diffused from PCD side to cemented carbide side in the interface between that two materials during the combination of two materials. As a result, the combination of the interface turns out to be chemical bond of WC-Co-Diamond. Literature [4] investigated Co distribution in PCD material and found that the Co element is often concentrated at the surface of the material. Consequently, a certain amount of Co element has been diffused from PCD side to cemented carbide side. Thus, the conductivity of cemented carbide near the interface is higher than other area due to presence of higher concentration of Co. Table 2 lists physical properties of three types of materials concerning the present work. As a result, the erosion rate becomes larger when cut wire moves into the interface from cemented carbide side to PCD side.

![Element distribution](image3.png)

**Figure 5.** The interface of PCD and cemented carbide
### Table 2. The thermal properties of PCD composite

| Thermal physical constant | Diamond | WC cemented carbide | Co |
|---------------------------|---------|---------------------|----|
| Melting point $T_m$/K     | 1608(phase change) | 3413 | 1765 |
| Boiling point $T_b$/K     | 5100    | 6273 | 3173 |
| Thermal conductivity $\lambda$/W•(m•K)$^{-1}$ | 13.8 | 0.42 | 0.65 |
| Thermal diffusivity $\alpha$/cm$^2$•s$^{-1}$ | 3.114 | 0.114 | 0.187 |
| Density $\rho$/g•cm$^{-3}$ | 3.52 | 15.63 | 8.71 |
| Conductivity $\kappa$/S•m$^{-1}$ | 0 | About $10^5$ | $17.2\times10^6$ |

The cobalt-rich area can be easily eroded because the Co has higher conductivity than other element in the material. Therefore, a single discharge pulse is able to remove a greater volume of the cobalt-rich area which results in larger inter-electrode gap (tens to hundreds of microns). The cutting process will not be interrupted even at this large machining gap. Consequently, an over-erosion groove is formed between the PCD layer and cemented carbide substrates. Obviously, the depth of the over-erosion groove is dependent with the Co concentration and discharge parameters.

3.2. The factors affecting the over-erosion

As exhibited in Figure 6, the WEDM can remove cemented carbide faster than PCD material. This is the basic reason that over-erosion groove is formed. However, the feed rate of the wire will be reduced markedly when the wire is fed into the PCD layer. According to the values recorded by the machine, the feed rate of the wire during cutting PCD layer is only one tens of cutting cemented carbide layer. A relatively much lower feed rate was observed when wire had been cutting into the interface of these two materials.

![Figure 6. The phenomenon of over-erosion](image)

![Figure 7. The relationship of gap and open circuit voltage](image)

The experiments show that the main factors affecting the volume of over-erosion are open circuit voltage, single pulse energy and machining gap. The intensity of electric field increases with the open circuit voltage. A discharge channel will be established when the intensity of the electric field reaches a threshold. In general, machining gap increases with open circuit voltage [5], which means that the higher voltage can remove greater volume of material due to WEDM, as shown in Figure 7.

3.3. Influence of process parameters on the depth of the erosion groove

The depth of the over-erosion grooves was observed by the Vollmer projector, as shown in the Figure 4(b). Fifteen experiments with varied parameters were performed to study effect of these factors on the depth of the erosion groove, as listed in Table 3. The machining results show that the WEDM could not achieve a normal status in some conditions. The first condition is short circuit and in this case the wire
scratched on the workpiece which may result in wire broken. Another condition is that the machining current reaches a relative high level, e.g. higher than 40A, which could also cause wire to be broken.

Table 3. Machining parameters and the depth of grooves

| No. | $U_o$ (V) | $I_p$ (A) | $t_{on}$ (μs) | $t_{off}$ (μs) | $D$ (μm) | Machining stability |
|-----|----------|----------|--------------|--------------|---------|-------------------|
| 1   | 140      | 32       | 8            | 170          | 41      |                   |
| 2   | 180      | 20       | 8            | 170          | 23      |                   |
| 3   | 180      | 30       | 8            | 170          | 50      |                   |
| 4   | 180      | 32       | 12           | 170          | \       | Short circuit     |
| 5   | 180      | 32       | 8            | 100          | \       | Unable to process |
| 6   | 180      | 32       | 8            | 130          | \       | Wire broken       |
| 7   | 180      | 32       | 8            | 240          | 41      |                   |
| 8   | 180      | 32       | 8            | 170          | 47      |                   |
| 9   | 180      | 32       | 4            | 100          | /       | Abnormal status   |
| 10  | 180      | 32       | 6            | 200          | 31      |                   |
| 11  | 160      | 26       | 6            | 200          | 13      |                   |
| 12  | 160      | 28       | 6            | 200          | 11      |                   |
| 13  | 170      | 28       | 7            | 200          | 21      |                   |
| 14  | 180      | 40       | 4            | 150          | /       | Unable to process |
| 15  | 160      | 40       | 2            | 150          | /       | Unable to process |

The over-erosion can be categorized as two types. Figure 8 (a) shows a common shape of over-erosion groove. Figure 8(b) demonstrates another shape of over-erosion groove which was formed in case of large single pulse energy. It can be seen from the Figure 8(b) that not only the cemented carbide but also the PCD have been eroded in the process. The possible reason of that the vibration of the wire causes PCD part to be over-eroded.

Two sets of optimal parameters for small size of over-erosion can be concluded from the experiments. One of them was summarized as open circuit voltage of 160V, peak current of 26A, pulse width of 6μs and pulse interval of 200μs. This set of parameters can reach a groove depth of 11μm. Another set was summarized as open circuit voltage of 160V, peak current of 28A, pulse width of 6 μs and pulse interval of 200 μs. In this case, the over-erosion groove depth was achieved as 13 μm.

4. Conclusion
The over-erosion phenomenon has been experimentally investigated and the causes of that has been analyzed. The fundamental reason of the over-erosion is the different erosion rate of different elements in the composite material. In the PCD composite, element Co has a higher conductivity than others, and this results in higher removal rate for Co-rich area than other area. Also because of this reason, the wire
cutting speed will be reduced when the wire moves across the interface between two materials. Consequently, these reasons cause the over-erosion groove to be formed at the interface during WEDM. Experimental results show that the open circuit voltage, single pulse energy and inter-electrodes gap can significantly affect the size of over-erosion. Finally, two sets of optimal machining parameters have been proposed to reduce the depth of over-erosion groove.

Acknowledgments
This work was financially supported by National Natural Science Foundation of China (Grant no.51675273).

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