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Micro-electrical discharge machining of polycrystalline diamond using rotary cupronickel electrode

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ABSTRACT

Cupronickel was used as the electrode material to fabricate microstructures on polycrystalline diamond by electrical discharge machining (EDM). The electrodes were shaped into tiny rotary wheels driven by the flow of EDM fluid. Results showed that material removal rate was improved by a factor of five compared to conventional electrode materials. Raman spectroscopy and energy dispersive X-ray spectroscopy indicated that graphitization of diamond and diffusion-based chemical reactions between nickel and diamond dominated the EDM process. Effects of electrode rotation rate and discharge energy on the EDM characteristics were clarified. High form accuracy (~0.5 μm/1 mm) and low surface roughness (~0.1 μm Ra) were obtained.

1. Introduction

Polycrystalline diamond (PCD) is an excellent material for fabricating micro cutting/milling/forming tools, micro punches, and key components for micro mechanical systems [1–4]. Owing to its high strength, PCD is extremely difficult to machine by mechanical methods such as grinding and polishing, especially when the workpiece feature size is smaller than 100 μm. In recent years, micro-electrical discharge machining (μ-EDM) of PCD has become a new focus of research [3–5]. In most studies, copper, tungsten, and Cu–W alloy wires were used as electrodes [2–7]. However, the resulting material removal rate (MRR) was quite low, and the consumption of electrode wire was significant, leading to very high production costs.

In this study, a copper–nickel (Cu–Ni) alloy, cupronickel, was adopted as an electrode material for generating microstructures on PCD by EDM. The electrodes were shaped into tiny wheels, the rotation of which was driven by circulation of a dielectric fluid. The material removal mechanisms in the EDM process were investigated by Raman spectroscopy and energy dispersive X-ray spectroscopy analysis, and the optimal EDM conditions were explored. The findings of this study provide a new approach for high-precision and high-efficiency micromachining of PCD and other carbon-based ultra-hard materials.

2. Design of EDM electrode

PCD is a composite of diamond grains sintered with a metallic binder such as cobalt (Co). Conventionally, EDM of PCD is performed at a high discharge energy. In this case, the electrically conductive binder Co is preferentially removed through melting and evaporation, while nonconductive diamond grains dislodge from the surface when overcoming the binding force, as shown in Fig. 1(a). This leads to surface roughening and is not suitable for high-precision machining. To improve surface quality, low energy discharge obtained using a small condenser capacity was found to be effective by way of reduction of the MRR of Co binder and inducement of graphitization of diamond grains [4]. However, this decreased the total MRR of PCD. Therefore, it has become essential to improve the total MRR of PCD, while preventing the dislodging of diamond grains.

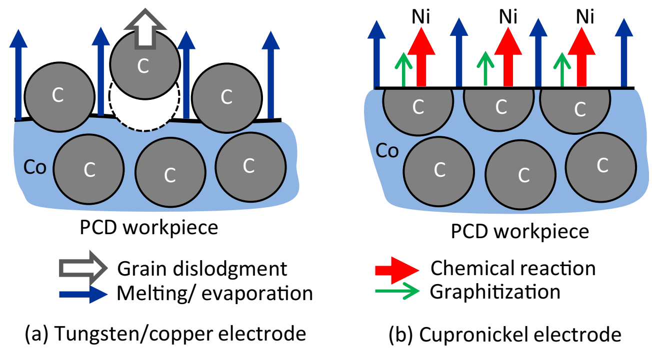

Fig. 1. Surface formation mechanisms of PCD in EDM using (a) conventional electrodes and (b) cupronickel electrodes.

In this study, cupronickel was adopted as the electrode material. It was expected that the Cu in cupronickel would provide a high electrical conductivity for generating discharges, and Ni would assist removal of diamond through chemical reactions. It is known that diamond tools show severe wear when cutting Ni [8]. This is because Ni has a very high affinity for diamond, resulting in thermal and electrical chemical reactions

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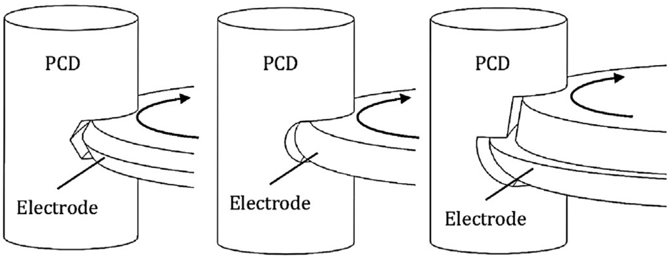


Fig. 2. Schematic of EDM using rotary cupronickel electrodes having various cross-sectional shapes.

when they are in contact. Under high-temperature conditions in EDM, the MRR of diamond grains might be significantly improved by utilizing these chemical reactions between Ni and diamond (C) in addition to diamond graphitization, as schematically shown in Fig. 1(b).

Instead of wire electrodes in wire EDM and block electrodes in die-sinking EDM, rotary wheel electrodes are used in this study, as shown in Fig. 2. Wheel electrodes have the following advantages. (1) The cross section of the electrode can be precisely shaped into arcs, knife-edges, and free-form curves for generating different kinds of microstructures on PCD. (2) Through wheel rotation, debris generated during EDM can be removed effectively from the discharge gap. (3) The wear rate of the electrode is uniform across the wheel surface, which is helpful for accuracy improvement and shape compensation. (4) The service life of wheel electrodes is longer than that of wire electrodes and block electrodes, enabling long-time continuous machining without electrode change. (5) The wheel electrode unit is compact, and can easily be installed for on-machine EDM tool fabrication.

3. EDM system construction and experimental procedures

A prototype μ-EDM system was constructed as shown in Fig. 3. The system includes a workpiece spindle unit, a wheel electrode unit, a dielectric fluid pumping unit, and a DC power source. The workpiece can be rotated at 100 rpm and fed in the vertical direction by a servo-motor. In order to perform vibration-assisted die-sinking EDM for comparison, a set of piezoelectric actuators were equipped on the *Z*-stage to impart vibration to the workpiece at an amplitude of 5 μm and frequency of 2 kHz. PCD rods (diameter 1 mm) were used as the workpiece, which contains fine diamond grains of a mean size of 0.5 μm and a concentration of ~90%, with Co as the binder.

The cupronickel used in the experiment is composed of 30% Ni and 70% Cu (melting point 1210 °C, thermal conductivity 29 W/(m·K)). The as-received material was in the form of a thin plate, from which electrodes were shaped using a lathe into wheels of diameter 16 mm and thickness 0.5 mm. An aluminum millwheel of diameter 14 mm was attached to the electrode shaft so that the rotation of the electrode can be driven by the circulating flow of the dielectric fluid without using additional actuators. In this way, the influence of motor vibration is avoided.

Electrical discharges were generated by an RC circuit where the voltage was 50 V (PCD as anode; cupronickel as cathode), and the capacities of condensers were 50, 500, and 1000 pF. The electrode rotation rate was changed from 70 to 400 rpm by adjusting the output of the fluid circulating pump.

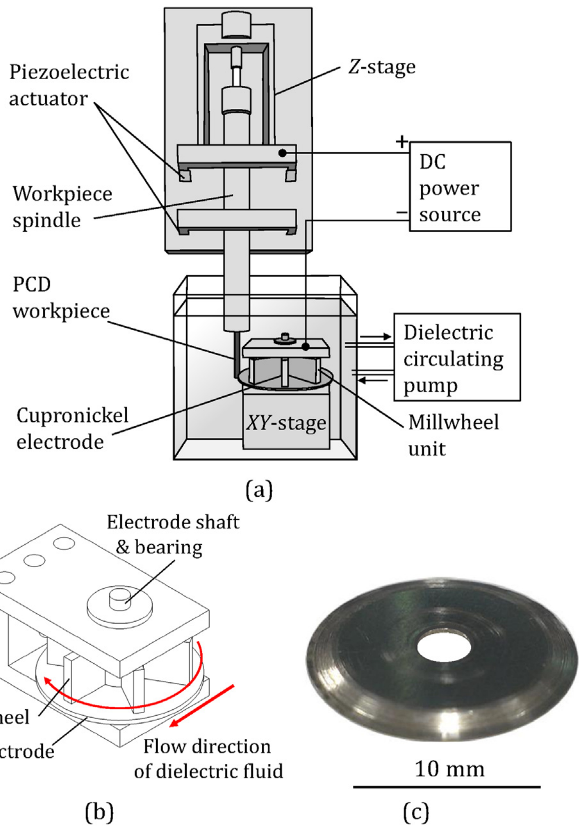


Fig. 3. The developed prototype μ-EDM setup: (a) system diagram, (b) rotary electrode unit, and (c) cupronickel electrode.

4. Results and discussion

4.1. Effect of electrode type/material on MRR

First, the MRR of PCD when using different types of electrodes was investigated and compared. As shown in Fig. 4, in vibration-assisted die-sinking EDM, cupronickel has the highest MRR among the three electrode materials. The MRR when using cupronickel is improved by a factor of five compared with Cu and W. For the same cupronickel material, the rotary electrode has significantly higher MRR than the die-sinking block electrode. In the EDM of type 304 stainless steel, however, there was no significant difference in MRR between cupronickel and copper electrodes. These results demonstrate strongly that the material removal mechanism of PCD in EDM using cupronickel electrodes is distinctly different from that of other electrode materials.

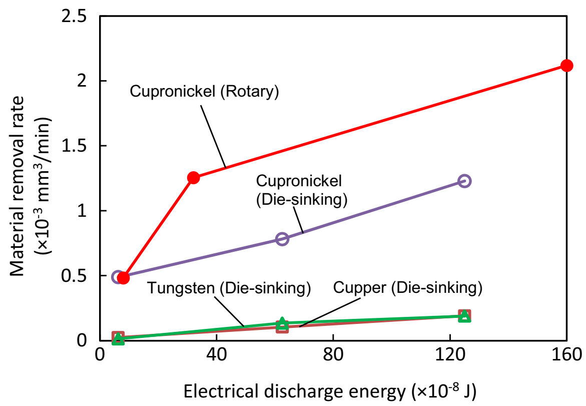


Fig. 4. Material removal rates for different types of electrodes.

4.2. Effect of electrode rotation rate on MRR

Fig. 5 shows the changes in the MRR of PCD with the rotation rate of a rotary cupronickel electrode. The MRR increases with electrode rotation rate in the range of 70–350 rpm, indicating that a high rotation rate contributes to the emission of debris from the discharge gap. At a rotation rate higher than 350 rpm, however, the MRR hardly changes, showing a saturation state where no debris stagnation occurs in the gap.

4.3. Surface topography

Next, surface topography of machined PCD is examined. Figs. 6a and 6b show scanning electron microscope (SEM) images of

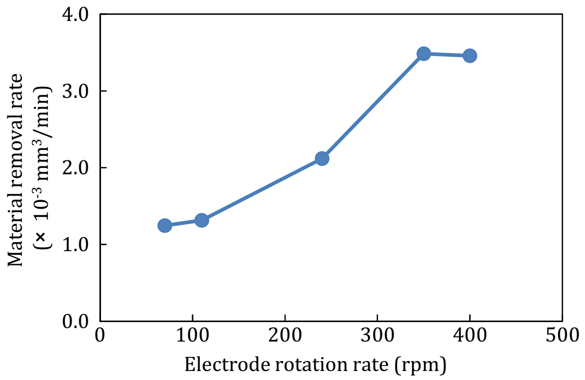


Fig. 5. Change in material removal rate with electrode rotation rate.

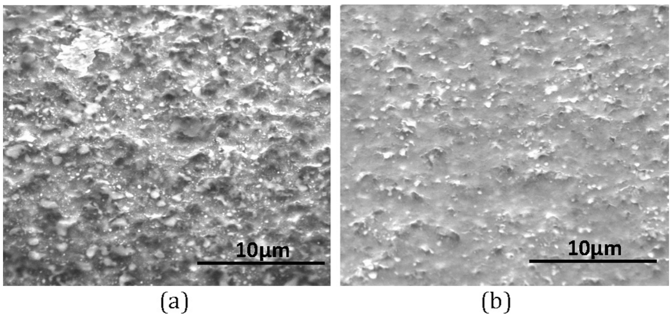


Fig. 6. SEM micrographs of surfaces machined using (a) tungsten block electrodes and (b) cupronickel wheel electrodes.

surfaces machined by a vibrated tungsten block electrode and a rotary cupronickel wheel electrode, respectively. The latter (0.15 μm Ra) is distinctly smoother than the former (0.21 μm Ra). In Fig. 6b, the protrusion of diamond grains from the binder surface is very small, which agrees with the surface formation mechanism shown in Fig. 1b.

Fig. 7 shows changes in PCD surface roughness with electrical discharge energy. By using a low discharge energy, an extremely low surface roughness (~0.1 μm Ra) was obtained.

Fig. 8 shows a three-dimensional surface topography of a microgroove machined using a rotary cupronickel electrode. The deviation between the cross-sectional profile of the groove and that of the electrode is ~1 μm, indicating that the shape of the electrode has been precisely replicated in the PCD workpiece. The longitudinal profile of the groove shows that straightness of the groove is ~0.5 μm over a range of 1 mm.

4.4. Electrode-workpiece interfacial phenomena

To clarify microstructural changes in materials during EDM, both the surfaces of PCD rods and cupronickel electrodes were

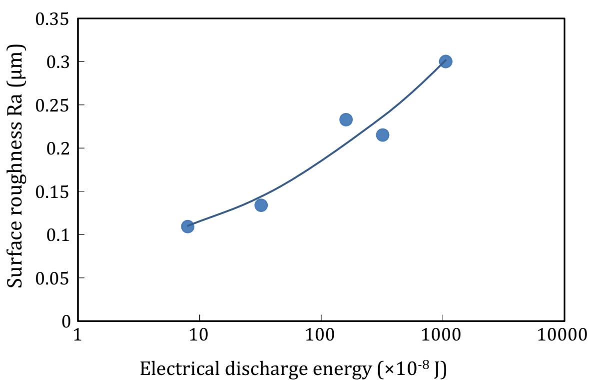


Fig. 7. Change in PCD surface roughness with discharge energy.

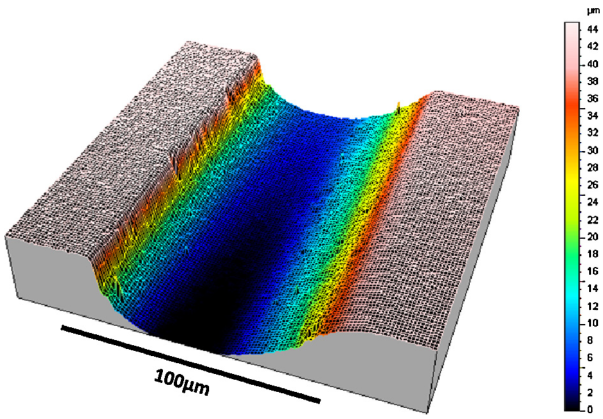


Fig. 8. Three-dimensional topography of a microgroove on PCD machined using a cupronickel wheel electrode.

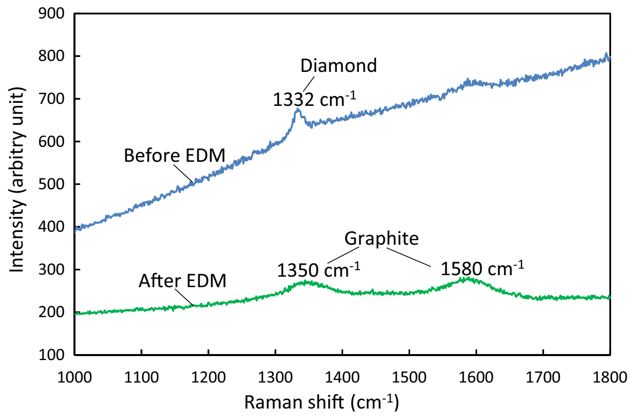


Fig. 9. Raman spectra of PCD before and after EDM.

investigated by laser micro-Raman spectroscopy. Fig. 9 shows Raman spectra of a PCD rod before and after EDM. Before EDM, there is a sharp peak at 1332 cm^{-1} that corresponds to the first order Raman peak of crystalline diamond. After EDM, however, there are two peaks at 1580 cm^{-1} and 1350 cm^{-1}. The peak at 1580 cm^{-1} (G band) indicates crystalline graphite, and the peak at around 1350 cm^{-1} (D band) corresponds to microcrystalline graphite. This result agrees with that from EDM tests using brass electrodes [4], and indicates that graphitization of diamond takes place also in the μ-EDM of PCD using cupronickel electrodes.

In order to examine the interfacial phenomenon between PCD and cupronickel, a cross-section of the cupronickel electrode was analyzed by energy dispersive X-ray (EDX) spectroscopy after the EDM process. Fig. 10 shows the EDX results of the element

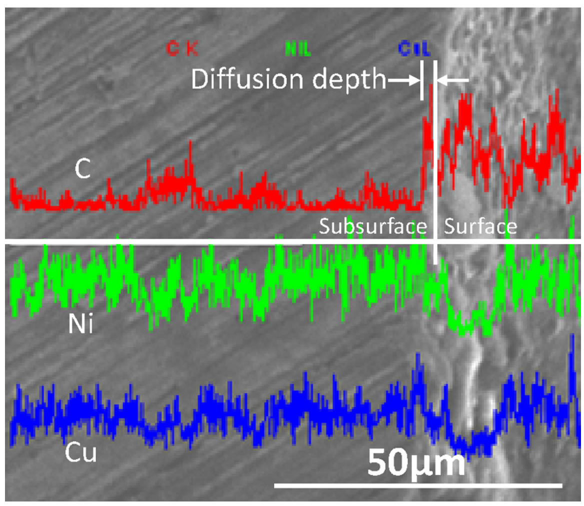


Fig. 10. EDX analysis result of a cupronickel electrode, showing diffusion of the C element from PCD to cupronickel.

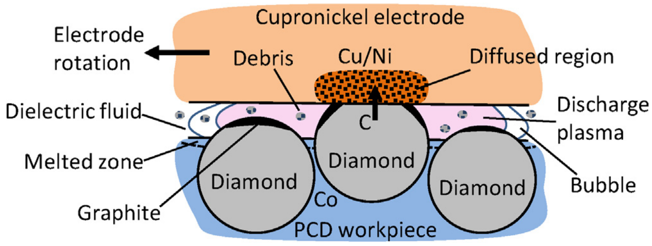
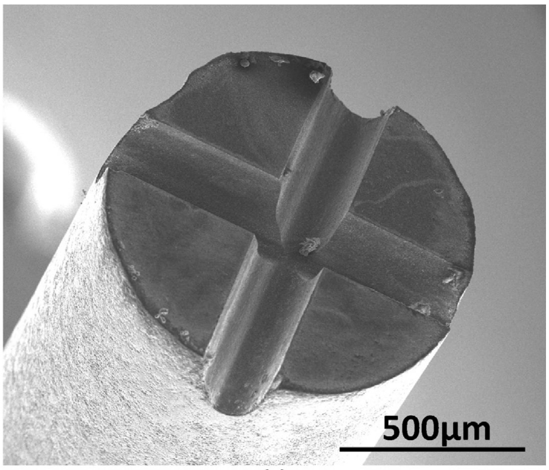


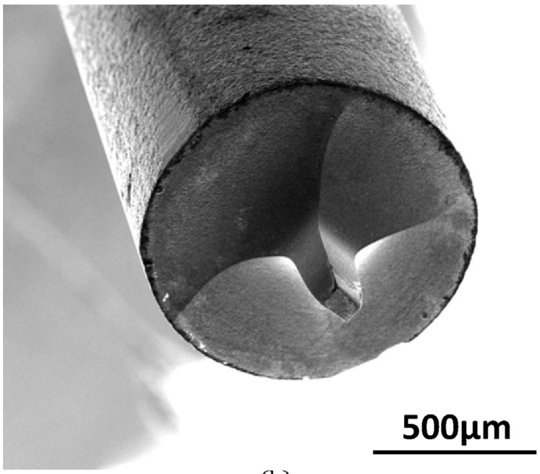
Fig. 11. Schematic model of interfacial phenomena between PCD workpiece and cupronickel electrode in EDM.

concentrations of C, Ni, and Cu. The concentration of C detected in the subsurface region is as high as that on the electrode surface, indicating that the diffusion of C from diamond into cupronickel during EDM is very significant. It can be estimated from Fig. 10 that the depth of diffusion was a few micrometers, similar to that in high-temperature erosion tests [9].

Based on the results of Raman spectroscopy and EDX analysis, a schematic model of the interfacial phenomenon between PCD and cupronickel in EDM is proposed, as shown in Fig. 11. As electrical discharges occur in a very narrow gap for a very short duration, the temperature in the gap is extremely high [10], which causes melting and evaporation of the binder (Co). The high temperature then causes two kinds of material dissipation effects of diamond: graphitization and diffusion-based chemical reaction, with the latter being more significant as seen from the MMR results in Fig. 4. The diamond grains protruding a lot from the binder surface make contact with cupronickel and diffuse to a great extent into Ni, whereas the diamond grains of less protrusion undergo partial surface graphitization. The diffusion of the C element significantly improves the MRR of diamond, while simultaneously enabling the creation of a very smooth surface without grain dislodgement. That is to say, by utilizing the two kinds of interfacial phenomena effectively, an extremely smooth surface may be obtained on PCD at a very high MRR.



(a)



(b)

Fig. 12. Examples of EDM-fabricated microstructures on PCD: (a) crossed microgrooves and (b) a tapered rectangular micro pillar.

4.5. Microstructure fabrication

Finally, microstructure fabrication tests were performed on PCD by μ-EDM using rotary cupronickel electrodes. Fig. 12a is an SEM micrograph of two perpendicularly crossed microgrooves on the top of a PCD rod. The grooves are 200 μm deep and 200 μm wide, having curved cross sections. The ridges of the grooves are very sharp. The groove surface roughness is 0.10 μm Ra, and the flatness of the groove bottom is 0.7 μm/1 mm. Fig. 12b shows a tapered rectangular micro pillar formed from a PCD rod by feeding a rotary cupronickel electrode from four sides. The curved edges of the pin are sharply formed.

These samples demonstrate that the proposed EDM method is useful for precision fabrication of various three-dimensional microstructures on PCD, such as micro cutting/forming/punching tools and micro molds. This method might also be applied to truing and dressing of diamond grinding wheels [11,12], and to the edge truncation of diamond grains. In addition, the findings in this study indicate that besides cupronickel, other alloys such as ferrous metal alloys might also be used for the high-efficiency and high-precision EDM of PCD. This μ-EDM method might also be applied to machining other carbon-based ultra-hard materials.

5. Conclusions

A prototype μ-EDM system was developed for fabricating microstructures on PCD. A wheel-shaped cupronickel electrode was used and was rotated by the flow of EDM fluid. Results show that material removal rate of PCD is improved by a factor of five compared to conventional electrode materials, and surface roughness is reduced greatly. Raman spectroscopy and energy dispersive X-ray spectroscopy analysis show two interfacial phenomena occurring, graphitization of diamond and diffusion-based chemical reactions between Ni and diamond, with the latter tending to be dominant. Increasing the rotation rate of the electrode improved significantly the material removal rate of PCD. Typical microstructures were successfully generated on PCD with high form accuracy and low surface roughness.

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