Catalytic aided electrical discharge machining of polycrystalline diamond - parameter analysis of finishing condition

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Abstract. Polycrystalline diamond (PCD) is regarded as among the hardest material in the world. Electrical Discharge Machining (EDM) typically used to machine this material because of its non-contact process nature. This investigation was purposely done to compare the EDM performances of PCD when using normal electrode of copper (Cu) and newly proposed graphitization catalyst electrode of copper nickel (CuNi). Two level full factorial design of experiment with 4 center points technique was used to study the influence of main and interaction effects of the machining parameter namely; pulse-on, pulse-off, sparking current, and electrode materials (categorical factor). The paper shows interesting discovery in which the newly proposed electrode presented positive impact to the machining performance. With the same machining parameters of finishing, CuNi delivered more than 100% better in Ra and MRR than ordinary Cu electrode.

Keywords: EDM, PCD, Graphitization, Erosion

1. Introduction

PCD is formed by a sintering process that composed diamond particles and metallic binder of cobalt under high pressure and high temperature condition. PCD is typically used as the cutting tools because of its exceptional wear resistance that associated with its extremely hardness and high transverse rupture strength. Nevertheless, this extremely hard material is difficult to be fabricated by conventional method while EDM was found as a suitable method to machine PCD with the ability to produce great surface roughness [1, 2].
In the research relating to the PCD EDM, most researchers focus on parameter optimization to increase the machining performance of material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR). Research on the chemical reaction of the PCD, while using certain electrode to improve the machining performance is very limited.

It was theorized that the nickel composition in the electrode will act as the graphitization catalyst which speed up the EDM erosion process of diamond type workpiece, in this case PCD. As mentioned by Erden et al. [3], electrode material influences the removal mechanism of EDM as the suspended material will naturally produce by the re-solidified electrode material and finally influence the removal characteristic.

As reported by J.Yan et al., more than 500% improvement was achieved by the catalyst electrode Copper Nickel, CuNi in comparison with ordinary electrode of copper, Cu. However the reported investigation is limited to only in Micro EDM application [4]. As different significantly in erosion parameter, the influence of this catalyst electrode in normal EDM is remained uncertain thus require further investigation.

2. Methodology

In EDM, the performance of machining are generally influenced by the parameters selection and types of electrode used. The PCD used in this investigation is limited to CTX002 grade, with the dimension 0.7mm x 0.5 mm for width and thickness respectively (Figure 1). Table 1 shows the properties of the PCD used.

| PCD type | Grain size (µm) | Total of diamond fraction (volume %) | Total of cobalt fraction (volume %) |
|----------|----------------|-------------------------------------|-------------------------------------|
| CTX002   | 2              | 84.8                                | 15.2                                |

![Figure 1. Polycrystalline diamond](image)

Suitable electrode and parameter selection plays an important part to improve the EDM performance. In this study, the performance is defined by the MRR and SR. This study was not only focused on the influence of numerical machining parameter but also the electrode material of Cu and CuNi which was
regarded as a categorical factor in the DOE analysis. Three numerical parameters that were investigated in this research are: pulse-On, pulse-Off and sparking current.

The process was considered as high voltage machining as high peak voltage was fixed at 120V while the depth of cut is fixed to 0.1 mm for every experimental run. Negative polarity was used as found the best for finishing process [7]. The DOE technique of 2-level full factorial design with combination with 4 center points was applied to analyze the process as well as to develop new mathematical model for the respond prediction. The center point analysis is required for the curvature test of the developed model. Table 2 shows the machining parameter used in this investigation. The parameters were chosen as refer to the published article [8] which was mentioned as the parameter that is normally used by the industries.

| Factor | Name         | Unit | Low(-) | Middle | High(+) |
|--------|--------------|------|--------|--------|---------|
| A      | Pulse-On     | µs   | 1      | 3      | 5       |
| B      | Pulse – Off  | µs   | 1      | 3      | 5       |
| C      | Current      | Ampere | 1    | 3      | 5       |
| D      | Electrode    | -    | Cu     | -      | CuNi    |

The experiment is conducted by using a 4-axis SODICK EDM die-sinking machine (Figure 2) with the kerosene as a dielectric fluid. An Ultrasonic cleaning machine was used to clean the electrode and workpiece before and after the EDM process. This cleaning process of using Acetone liquid as the cleaning agent is vital to remove any deposited debris. The surface roughness of eroded surface was measured by Surface Roughness Tester SJ-400 Mitutoyo according to EN ISO 4288. The Material Removal Rate (MRR) was calculated by using the formula (1).

\[ MRR = \frac{Volume\ of\ material\ removed}{erision\ time} = \frac{V(\mu m^3)}{t\ (sec)} \] (1)

![Figure 2. 4-axis SODICK EDM die-sinking](image)
3. Result and Discussion

All the significant factors were determined through Analysis of Variance (ANOVA) with 24 experiments for each response. Augment design were implemented as the model curvature was found significant as stated by the initial ANOVA analysis. Figure 3 and Figure 4 show the post augmented ANOVA for both responses. As indicated by the p-value of lower than 0.05, Figure 3 shows the significant factors for MRR which are single factor B (pulse-on), single factor C (pulse-off), single factor D (electrode material) and several interaction factors.

![ANOVA for material removal rate, MRR](image)

As shown in Figure 4, all single factors considered in this research was significantly influenced the Ra. Although the single factor of B (pulse-on) indicates the p-value of more than 0.05, it should be included into the developed model in order to maintain the hierarchy of some interaction factors involving factor B.
Based on Figure 5 and Figure 6, the R-squared value for both responses were found between 0.8994 and 0.9176 respectively. Close the value to 1 indicates that all significant factors were included into the developed model [9].
Figure 7 shows the 3D surface response graph of MRR for both electrodes with the used of optimized pulse-off parameter of 1µs for both electrodes. Although no different was observed with 5A current used, copper nickel electrode recorded higher MRR of 0.740µm³/s as compared to the copper electrode of 0.324µm³/s at lowest current used. For Ra, the graph as shown in Figure 8 was obtained by the optimize pulse-off parameter which are 2.6µs and 3.3µs for Cu and CuNi respectively. With the range of the investigated parameter, 0.403µm was found as the minimum Ra obtained by Cu electrode while CuNi was obtained more than 100% improvement with the Ra of 0.164µm.

It is known that electrode material will migrate to workpiece in the small discharge gap. As the high frequency sparks occur in a microns size gap, the temperature in the gap is extremely high [4]. Diamond is a metastable phase of carbon, and could convert to graphite at temperature approximately 2273K [8]. With intermediate reactivity of Ni from CuNi electrode, conversion of diamond to graphite can be accelerated. Based on this basic principle, graphite to diamond conversion will happen at lower temperature, with assistance of naturally produced suspended Ni particles which also migrated to workpiece which causes to the graphitization and diffusion-based chemical reaction [4]. These phenomena will then greatly reduce the energy required to erode the surface.

Remarkably, the voltage feedback signal collected by the oscilloscope (Figure 9) from the process in contradiction of the erosion norm in which the higher short circuit (non-energized pulse) tyoically decreases the MRR. In this research, CuNi was offered better performance, but yet short circuiting pulse was frequently appeared. Conversely for Cu electrode, although higher in sparking energy (by means of less short circuit pulse), it does not offer better in the performances. This proved that the diffusion phenomenon that happened while the electrode touching the workpiece (during short circuiting) greatly influenced the erosion performance of Ra and MRR.

Figure 7. Response for MRR obtained by different electrodes a. Cu electrode b. CuNi electrode
For each response, mathematical model or equation was developed with 95% interval of confident. The mathematical model for both response were given by:

\[
MRR = 1.04 + 0.20(A) + 0.22(B) - 0.36(C) + 0.10(D) + 0.1(AB) - 0.2(AC) - 0.11(AD)C^2 + 0.16(ABC) + 0.95(AC^2)
\]

(2)
\[ Ra = 0.68 + 0.17(A) + 0.03(B) + 0.02(C) - 0.03(D) - 0.02(AB) + 5.52E - 3(AC) + 0.06(AD) + 0.01(BC) + 0.04(BD) - 0.02(CD) - 0.23(A^2) - 0.24(B^2) + 0.12(C^2) + 0.06(ABC) + 0.07(ABD) - 0.06(A^2B) - 0.04(A^2D) - 0.2(AB^2) + 0.46(A^2B^2) \] (3)

Confirmation run were conducted to prove the validity of the developed model. Three parameters combinations of experiments were used for both responses as shown in Table 3. As shown in Table 4, the results demonstrated that the model is reasonably accurate for the response prediction as the percentages are below than 15%.

| Run | Current (A) | Pulse-on (µs) | Pulse-off (µs) |
|-----|-------------|---------------|---------------|
| 1   | 5           | 5             | 5             |
| 2   | 5           | 5             | 1             |
| 3   | 1           | 5             | 1             |

| Run | Electrode | Expected Value | Experimental Value | Percentage Error |
|-----|-----------|----------------|--------------------|------------------|
|     |           | MRR (µm³/s)    | Ra (µm)            | MRR (%)          | Ra (%)           |
| 1   | Cu        | 2.761          | 0.722              | 2.811            | 0.713            | 1.81 %           | 1.25 %           |
| 2   |           | 3.247          | 0.485              | 3.262            | 0.483            | 0.46 %           | 0.41 %           |
| 3   |           | 0.324          | 0.960              | 0.333            | 0.980            | 2.78 %           | 2.08 %           |
| 1   | CuNi      | 2.757          | 0.884              | 2.694            | 0.873            | 2.29 %           | 1.24 %           |
| 2   |           | 3.242          | 0.729              | 3.251            | 0.713            | 0.28 %           | 2.19 %           |
| 3   |           | 0.740          | 0.686              | 0.737            | 0.667            | 0.41 %           | 2.77 %           |

4. Conclusion

The influence of copper and copper nickel electrode for MRR and Ra were determined experimentally. In the case of MRR, there is no big difference value recorded by both electrodes at highest peak current used. However, at lower peak current of 1A, better MRR was obtained by the CuNi electrode. Similarly for Ra, the influence of electrode material can be clearly seen at low current used where more than 100% improvement was obtained with the used of CuNi electrode. It can be concluded from this experiment that the electrode that is containing graphitization catalyst material of nickel was contributed to better machining performance (better surface roughness and material removal rate). However, further investigation is required to elucidate the removal mechanism involved which was caused to this improved performance.

Acknowledgement

The authors would like to acknowledge the Ministry of Higher Education (MOHE) Malaysia under Fundamental Research Grant Scheme (FRGS) grant, Vot 1586 and Universiti Tun Hussein Onn Malaysia (UTHM) under Postgraduate Research Grant (GPPS), Vot U805 for financial support.
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