Characterizing the Effects of Micro Electrical Discharge Machining Parameters on Material Removal Rate during Micro EDM Drilling of Tungsten Carbide (WC-Co)

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Characterizing the Effects of Micro Electrical Discharge Machining Parameters on Material Removal Rate during Micro EDM Drilling of Tungsten Carbide (WC-Co)

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Abstract. Micro-dies, molds and miniaturized products can be manufactured using micro EDM process. In this research, EDM machine and on-machine fabricated CuW micro-electrode were utilized to produce the micro holes in WC-16%Co. The effects of voltage, current, pulse ON time, pulse OFF time, capacitor and rotating speed on Material removal rate (MRR) during micro EDM drilling of WC-16%Co was analyzed using fractional factorial design method. ANOVA analysis shows that increasing current, rotating speed, capacitor and decreasing voltage and pulse ON time lead to the amplify in MRR. It was found that out of all the factors, current and capacitor had the most significant effect on MRR, while the effect of capacitor was more than current. Eventually, it can be concluded that micro holes can be produced using EDM machine.

1. Introduction
Tungsten carbide (WC) and its composite (WC-Co) have high strength, hardness, wear and corrosion resistance over large scale of temperatures [1]. Thus, they are suitable materials for manufacturing dies, cutting tools and other special tools and components [1]. EDM process can remove the conductive materials with various strengths, toughness and hardness by take placing spark between the electrode and workpiece submerged in the dielectric [2]. Adding aluminum powder to the dielectric in EDM process helps to augment material removal rate (MRR) and decrease surface roughness [3]. The characteristics of micro EDM and EDM are approximately similar [1]. But in micro EDM, the electrode size, discharge energy and axis movement resolution are at micron range [1]. There are no tool deformation, chatter, mechanical stress and vibration errors in EDM and micro EDM process because of no direct contact and negligible force between electrode and workpiece [1]. Thus, micro EDM is the most effective process for machining of WC [1].

Moreover, Jahan et al. [4] reported that the highest MRR was achieved in micro EDM of WC-10%Co by using CuW micro-electrode among AgW, CuW and W micro-electrodes. In order to achieve higher MRR, lower electrode wear and better surface roughness in micro-EDM of WC, the negative polarity of micro-electrode was suggested [5]. Jahan et al. [6] compared the effect of transistor and RC-type pulse generators during micro-EDM of WC. Their results showed that micro EDM performance relies on discharge energy. It has been stated that controlling the RC-type pulse generator is easier as only voltage and capacitance determine the electrical discharge energy. In RC-type micro EDM, Jahan et al. [4, 6] applied voltage and capacitance (capacitor) as parameters during micro EDM of WC–10%Co and 0.6% others. In addition, in transistor-type micro EDM, they used voltage, resistance, pulse ON time, pulse
OFF time [6, 7] and electrode rotational speed [7] as parameters during micro EDM of WC–10%Co and 0.6% others [6, 7].

Due to the low cost and easy availability of EDM machines as compared to micro EDM and other hybrid machines, it has been used in this research. CuW micro-electrode is used to produce the micro holes in WC-16%Co. There has been less research done on the effects of micro EDM parameters such as voltage, current, pulse On time, pulse OFF time, rotating speed and capacitor on micro EDM drilling of WC-16%Co using any typical EDM. Thus the purpose of this research work is to examine how Material removal rate (MRR) is effected by the micro EDM parameters during micro EDM drilling of WC-Co by the usage of an EDM machine.

![Figure 1. Experimental setup for fabricating micro-electrodes and micro holes EDM drilling](image)

**Figure 1.** Experimental setup for fabricating micro-electrodes and micro holes EDM drilling

2. **Experimental details**

In this research, an AG40L Sodick electrical discharge machine was used to replace the micro EDM machine. Fig. 1 demonstrates the experimental setup for fabricating micro-electrodes and micro holes EDM drilling. CuW material (30%Cu + 70%W) with 1 mm diameter was selected as the raw material for the micro-electrode and WC-16%Co with 0.331 mm thickness was chosen as the workpiece. Copper was selected for the block electrode to fabricate the micro-electrode (Fig. 1) and it was aligned with a dial test indicator with 2 µm accuracy [8]. A WC electrode was used to dress the tapered micro-electrode after micro holes EDM drilling in order to produce a straight electrode [5]. The polarity of the micro-electrode during fabrication and electrode dressing was positive, while negative polarity helped produce the micro holes [5]. Positive polarity was applied on the micro-electrode during micro-electrode fabrication and dressing while negative polarity of micro-electrode assisted in machining micro holes. Oil-based dielectric fluid mixed with aluminum powder at 1.5 g/lit was also used.

![Figure 2. (a) Micro-electrodes with 165.2 µm diameter (b) Micro-electrodes with 169.7 µm diameter](image)

**Figure 2.** (a) Micro-electrodes with 165.2 µm diameter (b) Micro-electrodes with 169.7 µm diameter
Table 1. The levels of machining parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameters</th>
<th>Unit</th>
<th>Level</th>
<th>Level</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Voltage (V)</td>
<td>V</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>B</td>
<td>Current (Ip)</td>
<td>A</td>
<td>0.4</td>
<td>2.7</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>Pulse on time (t_{ON})</td>
<td>µs</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>Pulse OFF time (t_{OFF})</td>
<td>µs</td>
<td>1</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>E</td>
<td>Rotating speed (R)</td>
<td>rpm</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>F</td>
<td>Capacitor (C)</td>
<td>µF</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The through micro holes were produced with two micro-electrodes with 165.2 and 169.7 µm diameter and around 6.8 mm initial length (Fig. 2). These two electrodes were produced on-machine by horizontal moving block electrical discharge grinding (horizontal moving BEDG [HM-BEDG]) [8] based on the experimental setup shown in Figure 1. The micro-electrodes and hole diameters were measured with FESEM. Voltage, current, pulse ON time, pulse OFF time, rotating speed and capacitor were adopted as the parameters to analyze MRR and overcut during micro-EDM drilling of WC-Co using EDM machine. Table 1 shows the machining parameter levels and symbols. MRR was calculated with the following equations [5].

\[
MRR = \left\{ \frac{\pi}{3} \left[ r_{\text{Top}}^2 + r_{\text{Top}} r_{\text{Bottom}} + r_{\text{Bottom}}^2 \right] \times h \right\} \div t
\]  

where \( r_{\text{Top}} \) (mm) is the radius at the entrance side, \( r_{\text{Bottom}} \) (mm) is the radius at exit side, \( h \) is the workpiece thickness, \( t \) (min) is the machining time to make a hole at a particular setting.

The experiments were designed with \( 2^{6-2} \) fractional factorial design and 3 center points consisting of 19 runs including 16 (=2^6-2) and 3 center points. These (resolution IV designs) are designs in which no main effect is aliased with any other main effect or with any two-factor interactions, but two-factor interactions are aliased with each other. The factorial effects defining contrast are \( I = ABEF = ACDF = BCDE \). The alias relationships are as follows:

\( A = BEF = CDF \), \( B = AEF = CDE \), \( C = ADF = BDE \), \( D = ACF = BCE \), \( E = ABF = BCD \), \( F = ABE = ACD \), \( AB = EF \), \( AC = DF \), \( AD = CF \), \( AE = BF \), \( AF = BE = CD \), \( BC = DE \), \( BD = CE \), \( ABC = ADE = BDF = CEF \), \( ABD = ACE = BCF = DEF \).

The three-, four-, five- and six-factor interactions are considered errors. Therefore, the aliased of two-factor interactions are important in this case.

3. Results, Analysis and Discussion

![Figure 3](image-url) (a) worst micro hole (90 V, 5 A, 5 µs, 9 µs, 20 rpm, 0.1 µF) (b) one of the best micro hole (50 V, 0.40 A, 1µs, 1 µs, 0 rpm, 0 µF)
Table 2. ANOVA table for MRR

<table>
<thead>
<tr>
<th>Source</th>
<th>F-Value</th>
<th>Prob &gt; F</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>152.44</td>
<td>&lt; 0.0001</td>
<td>significant</td>
</tr>
<tr>
<td>A-Voltage</td>
<td>18.72</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>B-Current</td>
<td>101.71</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>C-Pulse ON time</td>
<td>11.40</td>
<td>0.0070</td>
<td></td>
</tr>
<tr>
<td>E-Rotating speed</td>
<td>15.87</td>
<td>0.0026</td>
<td></td>
</tr>
<tr>
<td>F-Capacitor</td>
<td>878.59</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>24.22</td>
<td>0.0006</td>
<td></td>
</tr>
<tr>
<td>AF</td>
<td>16.60</td>
<td>0.0022</td>
<td></td>
</tr>
<tr>
<td>Curvature</td>
<td>8.52</td>
<td>0.0153</td>
<td>significant</td>
</tr>
<tr>
<td>Residual</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>15.84</td>
<td>0.0607</td>
<td>not significant</td>
</tr>
</tbody>
</table>

R-Squared = 0.9907  Adj R-Squared = 0.9842
Pred R-Squared = 0.9634  Adeq Precision = 31.929

Figure 3 shows the worst micro holes and one of the best micro-holes were produced as a function of different parameters. The experimental outcomes for MRR were analyzed using Design Expert software. The significance of the models, individual model terms and lack of fit was tested using ANOVA (Analysis of variance). The MRR response for ANOVA validation underwent a Square root transformation [2]. Table 2 demonstrates the ANOVA tables for MRR. If the "Prob > F" value is less than 0.05, it is significant [2]. In this research, A, B, C, E, F, AB and AF were significant model terms for MRR response. Moreover, B and F were the most significant factors. But AB, EF, AF, BE and CD were possibly significant due to aliases.

Insignificant lack of fit is preferable for MRR responses. The results for MRR reveals that an R-Squared value approaching 1 is preferable. Moreover, there were minor differences between Adj. R-Squared and Pred. R-Squared showing that the models had an admissible transaction between input and output parameters. Adeq. Precision greater than 4 is desirable, as it measures the signal-to-noise ratio [2]. Also, residuals had constant variance and normal distribution after using the square root transformation to analyze and model MRR response.

From Figure 4 which captures the response graph for MRR it can be seen that MRR increased with amplifying current, rotating speed and capacitor and decreasing voltage and pulse ON time. The current and capacitor were the most significant factors; however, the effect of the capacitor was greater than the current. Out of all the factors, it was observed that current and capacitor were the most contributing factors with capacitor showing more effect than the current. The voltage controls the discharge gap between the electrode and workpiece, therefore, increasing the voltage augments the discharge gap as well [2]. Appropriate voltage according to current, pulse ON time, pulse OFF time, capacitor and rotating speed results in improved MRR. Figure 4(a) indicates that with voltage greater than 50 V, the amount of MRR decreased as the discharge gap was larger than the suitable range [2] for low amounts of energy in micro EDM [current (0.4 - 5 A), pulse ON time (1 - 5 µs) and capacitor (0 - 0.1 µF) are low]. According to Figure 4(b), MRR augmented with increasing current because of rising amount of spark energy and heat transmitted to the workpiece for melting and vaporization. Figure 4(c) depicts the effect of pulse ON time on MRR. Sparks take place during pulse ON time. The amount of spark energy augments by increasing the pulse ON time [9]. During long pulse ON time, sparks initially get generated between the microelectrode and workpiece, after which some of the sparks generate between the micro-electrode and chip and some between the micro-electrode and workpiece due to the difficulty in removing chips between the micro-electrode and workpiece. The size of chip is decreased by occurring sparks between the micro-electrode and chips. Hence, machining efficiency is deteriorated [9]. The occurring sparks between the micro-electrode and chips cause the chip size to decrease. Thus, machining efficiency is reduced [9]. One more factor that contributes to the inefficiency of machining is the collection of chips inside the micro hole leading to
unstable servo operation. As a result, MRR deteriorated with increasing pulse ON time (Figure 4(c)). Figure 4(d) illustrates that MRR increased by increasing the rotating speed. This is due to the fact that higher rotating speed helped in removing the chips from the distance between workpiece and micro-electrode. According to Figure 4(e), MRR increased sharply by amplifying capacitor because of increasing spark energy transmitted to the workpiece. This reveals that capacitor was the most significant factor for MRR.

Figure 4. Response graphs for MRR (a) Voltage. (b) Current. (c) Pulse ON time. (d) Rotating speed. (e) Capacitor

4. Conclusion
This research has been conducted to investigate the effects of micro EDM drilling of WC-16%Co using a CuW microelectrode and EDM machine. ANOVA analysis shows that increasing current, rotating speed, capacitor and decreasing voltage and pulse ON time lead to the amplify in MRR. It has been observed that current and capacitor contributed the most effect in the increase of MRR. Amongst the two parameters, the effect of capacitor on MRR was greater than that of the current. Thus it can be established that the capacitor contributes the most in increasing the MRR. In the end, it can be concluded that for producing micro holes, EDM is efficient and can be used.

5. References