Modelling the surface roughness behaviour of an EDMed workpiece with different tool electrodes using DoE

M B Ndaliman1,2,3, A A Khan1, M Y Ali1 and M A Mohammad Hambiyah1

1Department of Manufacturing and Materials Engineering, International Islamic University Malaysia, 53100 Kuala Lumpur, Malaysia
2Department of Mechanical Engineering, Federal University of Technology, Minna, Nigeria

E-mail: mbndaliman@yahoo.com

Abstract. Surface roughness of a workpiece is one of the measures used in evaluating the performance of any machining technique. In this paper, the behaviour of a post-EDM roughness of mild steel material subjected to machining with two different electrodes is evaluated through modelling using three machining variables. The variables are peak current, pulse on-time and pulse off-time, while the electrodes used are Cu-TaC compact green electrode and metallic Cu. The investigation was planned and analysed with Design of Experiment (DoE) in which the output response obtained with the two electrodes were compared. Results indicate that the roughness obtained with Cu-TaC electrode is a function of peak current, pulse on-time, pulse off-time with interaction between on-time and off time, whereas that of metallic Cu electrode is related with current and pulse on-time only. Further more, the metallic Cu electrode produced comparatively lower roughness under all the machining conditions. The lowest roughness obtained with Cu-TaC electrode is over 100% higher than that of Cu-electrode.

Keywords. EDM; Surface roughness, Cu-TaC electrode; Metallic Cu electrode; DoE

1. Introduction

The roughness of machined surface expresses the degree of irregularities of it texture. In most production processes finer irregularities of the surface texture are desired. In electro-discharge machining (EDM), many factors contribute to the level of surface roughness attained by the workpiece during machining. These include the machining input parameters, the dielectric fluid and the tool electrode. It is possible to optimize the EDM process input parameters to obtain better surface roughness [1].

Electrode is one of the vital components of EDM, because it is the cutting tool whose form is replicated on the workpiece. Its performance and cost depends on the material, design and fabrication technique used in producing it. The conventional electrodes used in the early days of EDM were mainly metallic or graphite. The most commonly metallic electrode materials were copper, brass, silver, tungsten, copper-tungsten, silver-tungsten and tungsten carbide [2]. The major shortcomings of electrodes are the production difficulty and low cutting speed. The two electrode materials with competitive usage among EDM users are copper and graphite.

3 To whom any correspondence should be addressed.
Practically the choice of EDM electrode material is based on the tool size, type, the work material requirement and the electrode fabrication technique. Other important factors of consideration are the work removal rate, tool’s resistance to wear, the desired workpiece surface roughness, the tool’s machinability and its cost [3]. Research interests have been generated on production tool electrode from such materials like Al, Cr, Cr/Ni, Cu/Co, Cu/Mn, Cu/Sn, Cu/W, Ni, Ni/Co, Ni/Fe, Ni/Mn, Ni/Si, Ti, Ti/Al, TiC/Ni and W/CrC/Cu [4-5] because of their various individual and combine properties. But their fabrication through conventional means can be difficult. This makes the need for alternative design and manufacturing methods of the electrodes to become necessary. The manufacturing process of EDM electrodes is such as an important aspect as it accounts for over 50% of the machining cost depending on their level of complexity in geometry [3]. The more complex geometries are expensive to produce. Though, conventional methods like machining, casting and forming have been used to manufacture electrodes over the years, modern techniques have sprang up for their production. These include the use of powder metallurgy (PM) and rapid tooling.

In their continuous search for better EDM tooling alternatives, researchers have found PM method of electrodes’ fabrication to be faster and more economical. Through this method, large number of EDM tools with even complex geometries can be manufactured in short period of time [6]. The properties of the electrodes can be controlled by regulating the PM process variables like composition, compacting pressures and sintering conditions. These possibilities were established in the mid 1990’s [7-8]. Zaw et al. [9] investigated the performance of sintered ZrB$_2$/Cu and TiSi/Cu. After comparing them with conventional tools (Cu, Gr and CuW), they submitted that both the composite electrodes could not measure up to the standard electrodes under those sintering conditions. However, working with different compositions of the same ZrB$_2$/Cu, Khanra et al. [10] observed that ZrB$_2$-40 wt% Cu gave higher material removal rate (MRR) with reduced tool wear rate (TWR) than pure solid Cu. PM compacted electrodes can be produced from single powder [8, 11-12] or mixture of different powders [13-14]. They are used as green or sintered electrodes in machining. Higher compacting pressures and sintering condition favour the basic machining outputs. Thus, better MRR, lower tool wear and good surface finish for the work material.

In this work, the surface roughness trends of mild steel machined with PM compacted Cu-TaC electrode is modelled with EDM process variables. In addition, its behaviour was compared with the EDM carried out with metallic copper (Cu) electrode under the same conditions. This research is conducted in order to consolidate the performance of the electrode on the steel material since its properties (the electrode) has indicated that it can be used for EDM work [15-16]. Also, previous research results on the electrode’s performance showed that it can reasonably be use in material removal process [17-18]. The input variables of investigation are peak current ($I$), pulse-on time ($t_{on}$) and pulse-off time ($t_{off}$).

2. Design of Experiment (DoE)

The investigation was planned and implemented with design of experiment (DoE). Using two-level full factorial design involving three factors, a total of eight experimental runs were generated. The factors and their levels are presented in table 1. The design matrix alongside the response is presented in table 2. A first-order model (linear relation) was proposed for the output response (Ra) of the study as given in equation (1).

$$\hat{y} = y - e = a_0 + a_1A + a_2B + a_3C + a_4AB + a_5AC + a_6BC$$  \hspace{1cm} (1)

Where $\hat{y}$ = predicted value of the response; $y$ = measured value of the response; $e$ = experimental error; $a_0$, $a_1$, $a_2$, $a_3$ are the model parameters to be estimated using the experimental data; $A$, $B$, and $C$ are peak current, pulse duration and pulse interval respectively; and $AB$, $AC$ and $BC$ are the interaction effects of the variables. The significant ‘a’s to be evaluated and the non-significant ones would be
neglected in the final equations. Design Expert version 6.0.8 [19] software was used to conduct the analysis. Analysis of variance (ANOVA) was utilized to identify the significant model terms. Finally, the models were subjected to diagnostic test to ascertain their adequacy.

Table 1. The input factors and the levels used.

| Factor            | Level-1 (Low) | Level+1 (High) |
|-------------------|---------------|----------------|
| Current, I (A)    | 3.50          | 7.50           |
| On-time, t_{on} (µs) | 6.00          | 7.50           |
| Off-time, t_{off} (µs) | 6.50          | 8.50           |

3. Materials and Methods

The workpiece material used in the investigation is mild steel. The EDM input parameters used in the investigation were peak current (I), pulse-on time (t_{on}) and pulse-off time (t_{off}), while surface roughness is the output variable studied. The Cu-TaC Powder metallurgy (PM) electrode was produced by compaction of the mixed Cu and TaC powders with composition of 25% and 75% respectively in the matrix. Similar investigation was conducted with metallic copper electrode for use in comparison. The EDM was conducted according to the run order presented in Table 2, with kerosene dielectric fluid. The surface roughness of the work material was determined with Mitutoyo SURFTEST Machine (the surface measuring instrument). During this measurement, the average of ten readings was record for each surface in order to obtain the most accurate result. 3-D surface plots showing the behaviour of the Ra for the different machining are presented. The graphical comparison of the performance of the two types of electrodes is also presented.

4. Results and Discussions

The roughness of the surface obtained after the EDM are designated as Ra_{1} and Ra_{2} for the PM and metallic electrodes respectively in table 2. These results were used to model the behavior of response with respect to the input variables.

Table 2. Design matrix with the responses.

| Run No | A: Peak Current (A) | B: On time (µs) | C: Off time (µs) | Ra_{1} (µm) | Ra_{2} (µm) |
|--------|---------------------|----------------|-----------------|-------------|-------------|
| 1      | 7.50                | 6.00           | 6.50            | 21.82       | 11.68       |
| 2      | 7.50                | 7.50           | 6.50            | 23.10       | 18.27       |
| 3      | 3.50                | 7.50           | 6.50            | 19.62       | 12.63       |
| 4      | 3.50                | 6.00           | 6.50            | 18.48       | 8.77        |
| 5      | 7.50                | 6.00           | 8.50            | 21.20       | 9.59        |
| 6      | 3.50                | 6.00           | 8.50            | 17.61       | 8.07        |
| 7      | 7.50                | 7.50           | 8.50            | 22.99       | 15.90       |
| 8      | 3.50                | 7.50           | 8.50            | 19.88       | 12.94       |

4.1. Analysis and the Models

Tables 3 and 4 present the improved ANOVAs of Ra_{1} and Ra_{2} with their statistical significant terms. In table 3, all the input factors are found to be significant as their Prob > F are less than 0.05. Additionally, interaction is found to exist between B and C. This implied therefore that the model with the factors A, B, C and BC as its terms is statistically significant at 5% level of significance. It is also observed from table 4 that the Ra_{2} model has factors A and B as the only significant terms in it. These models obtained on the basis of improved ANOVAs are given in equations (2) and (3).
Table 3. The improved ANOVA of $R_a_1$ with Cu-TaC electrode.

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|--------|----------------|----|-------------|---------|----------|
| Model  | 28.66          | 4  | 7.17        | 341.62  | 0.0003   |
| $A$    | 22.84          | 1  | 22.84       | 1088.93 | 0.0001   |
| $B$    | 5.26           | 1  | 5.26        | 250.69  | 0.0005   |
| $C$    | 0.23           | 1  | 0.23        | 10.73   | 0.0466   |
| $BC$   | 0.34           | 1  | 0.34        | 16.14   | 0.0277   |
| Residual | 0.63         | 3  | 0.021       |         |          |
| Cor Total | 28.73       | 7  |             |         |          |
| $R^2$  | 0.9978         |    |             |         |          |
| Adj $R^2$ | 0.9949      |    |             |         |          |
| Pred $R^2$ | 0.9844     |    |             |         |          |
| Adeq Precision | 47.271     |    |             |         |          |

Table 4. The improved ANOVA of $R_a_2$ with metallic Cu electrode.

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|--------|----------------|----|-------------|---------|----------|
| Model  | 82.65          | 3  | 27.55       | 24.39   | 0.0049   |
| $A$    | 21.22          | 1  | 21.22       | 15.79   | 0.0123   |
| $B$    | 58.48          | 1  | 58.48       | 51.78   | 0.0020   |
| $C$    | 2.94           | 1  | 2.94        | 2.60    | 0.1819   |
| Residual | 4.52         | 4  | 1.13        |         |          |
| Cor Total | 87.16       | 7  |             |         |          |
| $R^2$  | 0.9482         |    |             |         |          |
| Adj $R^2$ | 0.9093      |    |             |         |          |
| Pred $R^2$ | 0.7927     |    |             |         |          |
| Adeq Precision | 13.144     |    |             |         |          |

$Ra_1 = +23.78994 + 0.84487I - 0.97650t_{on} - 2.01950t_{off} + 0.27433It_{off}$  \hspace{1cm} (2)

$Ra_2 = - 12.03519 + 0.81437I + 3.60500t_{on} - 0.60625t_{off}$ \hspace{1cm} (3)

The $R^2$ obtained in machining with the two electrode types are over 0.9 (tables 3 and 4). Also, the Predicted and Adjusted $R^2$ for each of the two electrodes are reasonably close with the difference between them less than 0.20. Finally, their signal-to-noise are greater than 4.0 which is the minimum acceptable value [20]. Based on these statistical features, the models seem adequate to predict the $Ra$ behaviors of the two different electrodes. Further confirmation of the models’ adequacy would depend on the diagnostic tests.

For the model equations to be adequate, the residuals of response should be normally distributed, unstructured (randomly distributed) and with constant variance [20-21]. The normal plots of residuals in figure 1 indicate that they (residuals) approximately follow straight lines. Therefore normality condition is satisfied for the two electrode types. Another condition to be satisfied is that the residual plots against the predicted values should not show any obvious pattern. The fitted values in figure 2 are scattered randomly on display, suggesting that the variances of the original observations are constant for all values. Hence, based on this (constant variance), the models of the data which produced the two plots can be considered adequate.
4.2. Discussions

An observation of table 2 shows that the Ra₁ are generally higher than Ra₂. Thus machining with Cu-TaC electrodes produce rougher surfaces. The highest Ra₁ of 23.10 µm was obtained under extreme machining conditions. Similarly, the highest Ra₂ of 18.27 µm resulted from the same machining conditions. The reason for high Ra₁ could be due to the tendency of the PM electrode to wear faster and deposit lump particles on to the workpiece under these machining conditions. Researches have supported the fact that high I and tₘₚ normally result in increase tool wear [22]. In the case of the Cu-TaC electrode, its high tool wear coupled with material deposition of the work surface would result in irregular profiles on it (workpiece) with a direct consequent on the roughness [13]. Therefore, the PM compact electrodes are associated with rougher surfaces compare to metallic ones [11].

The 3-D surface plots generated by the models for the two electrode type are presented in figures 3 to 5. From the analysis, the Ra of the mild steel was found to be a function of I, tₘₚ, and tₜ₉ with the
interaction effect between $t_{on}$ and $t_{off}$ for the case of Cu-TaC electrode machining. On the other hand, the $Ra_2$ depends only on $I$ and $t_{on}$ with metallic Cu electrode. In figure 3, the contour plot show the values on the lines for the $Ra_1$ behaviour (figure 3a), whereas the trend in the experimental region is illustrated by 3-D response surface (figure 3b). The $Ra_1$ increases with increasing current and pulse on-time. However the influence of on-time on the $Ra_1$ seems to be mild compare to that of the current. Also, the effect of interaction between the pulse on-time and off-time is revealed by figure 4, which show lower $Ra_1$ are obtainable only with combination of low discharge duration at high pulse interval. Under this condition, the contour plot show a low $Ra_1$ of 19.74µm (figure 4a). In practical terms, it implies that machining efficiency would have to be compromised in order to obtain lower roughness with Cu-TaC electrode, since more time would be spent with material removal in the cutting process. The surface roughness obtained with metallic Cu machining increases with increasing $I_p$ and $t_{on}$ and vice versa (figure 5). This is agreement with the normal $Ra_1$ behaviour of copper electrodes [1, 23]. Increasing these variables imply that the discharge intensity would increase at longer striking period on the workpiece. Therefore, the craters on the EDMed surface would increase in number, size and depth, and thus lead to higher roughness.

![Figure 3](image3.png)

**Figure 3.** 3-dimensional plots of $Ra_1$ with $I$ and $t_{on}$: (a) contour plot; (b) surface plot.

![Figure 4](image4.png)

**Figure 4.** 3-dimensional plots of $Ra_1$ with $t_{on}$ and $t_{off}$: (a) contour plot; (b) surface plot.
| A: Peak current | B: Pulse on-time |
|----------------|-----------------|
| 3.50           | 4.50            |
|                | 5.50            |
|                | 6.50            |
|                | 7.50            |

| A: Peak current | B: Pulse on-time |
|----------------|-----------------|
| 6.00           | 6.38            |
| 6.75           | 7.13            |
| 7.50           | 7.90            |
| 9.34           | 10.79           |
| 12.23          | 13.67           |
| 15.12          |                 |

Figure 5. 3-dimensional plots of Ra2 with I and t on: (a) contour plot; (b) surface plot.

The graphical comparison of the experimental runs with the two electrodes is shown in figure 6. The surface roughness curve obtained with Cu-TaC PM electrode can be observed to be clearly higher than that of Cu electrode. The lowest Ra obtained with the Cu-TaC electrode is over 110% higher than the lowest Ra with metallic electrode.

Figure 6. Comparison of the Ra generated by Cu-TaC compacted electrode with that of metallic Cu electrode

5. Conclusions
The following conclusions can be drawn from the investigation.
1. From the results and analysis, the surface roughness of the mild steel machined with Cu-TaC electrode was found to be a function of I, t on and t off with the interaction effect between t on and t off, while metallic Cu electrode depends only on I and t on. Therefore, their models are made up of the terms involving the variables.
2. Direct relationship exists between the surface roughness with current and pulse on-time as variables in both electrode types, though the influence of on-time is mild as compared to that of the current in Cu-TaC machining.

3. As a result of the interaction effect between the pulse on-time and off-time lower roughness are obtainable with combination of low discharge duration and high pulse interval.

4. Machining with Cu electrode produced lower roughness under all conditions compared that of Cu-TaC electrode, with the lowest roughness obtained with the Cu-TaC electrode is over 100% lower than the lowest roughness with the metallic electrode.

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