Statistical Investigation into the Effects of Electro-Discharge Machining Parameters on WC/6%Co Composite-Part 2: Parametric Analysis and Optimization through Desirability Function (DF)

S. Assarzadeh and M. Ghoreishi

Department of Mechanical Engineering, K. N. Toosi University of Technology, P.O. Box: 19395-1999, Tehran, Iran

1. Introduction

Conventional machining of the hard WC/6%Co composite is extremely laborious, burdensome, and time consuming due to its elevated hardness and wear resistance over a wide range of temperatures and working conditions [1]. The effective and economic utilization of EDM process as one of the best alternative machining method for such a material with optimum selection of input parameters needs a thorough understanding of its machinability behavior which in turn can substantially alleviate the difficulties encountered. To that end, in the first part of current research [2], comprehensive mathematical modeling of each of the major responses (MRR, TWR, and Ra) was accomplished through a well organized step-by-step implemented approach aiming to provide a solid foundation to better understand the ED-machinability measures of the chosen cemented tungsten carbide (WC/6%Co, Iso grade: K10). The complementary points in this part are as follow: Firstly, the effects of varying the process input parameters on each performance characteristics, MRR, TWR, and Ra are studied employing the proper form of every developed response equation. To get an in-depth understanding of the WC-6%Co behavior under different EDM conditions, the analysis starts considering the individual main effect plot of each input process factor independent of the other parameters, and then, by 3D surface and its respective 2D contour plot for each pair of significantly interactive parameters when their mutual concurrent contributions are considered. Secondly, the concept of desirability function (DF) was applied to optimize the process performance as maximizing the MRR while minimizing both the TWR and Ra at the same time. Validation experiment has been carried out at the predicted optimal conditions to obtain real output responses comparing each with its corresponding theoretical optimum value. Confirmations errors have also been calculated to verify the correctness of proposed optimization strategy. Details are demonstrated in the following sections.
2. Parametric analysis

To genuinely describe the quality of variation trends of each process response with respect to inputs, it is of great importance to be aware that spark energy is the dominant factor most responsible for the mechanism of material removal in EDM. The amount of discharge energy \( q \) delivered per single discharge assuming a normal pulse (i.e. spark) can be expressed as [3]:

\[
q = \int_{T_d}^{T_{on}} V_{dis}I_{dis}dt \approx V_{dis}I_{dis}(T_{on} - T_d) \approx V_{dis}I_{dis}T_{on}
\]  
(1)

where \( T_d \), \( T_{on} \), \( V_{dis} \), and \( I_{dis} \) represent the ignition delay time, pulse on-time, discharge voltage and current, respectively. The magnitude of ignition delay time in normal pulses is so small compared to pulse on-time [4], so its effects has been neglected for the sake of simplicity. In real EDM conditions, for a sequence of electrical discharges occurring between the two electrodes within the total machining time \( T \), the total discharge duration \( (T_d) \) is given by:

\[
T_d = T \times DC
\]  
(2)

where \( DC \) is the duty cycle (refer to Part 1 [2]). On the other hand, the whole number of discharge pulses \( (N) \) during total machining time can be calculated as:

\[
N = \frac{T}{T_{on} + T_{off}} = \frac{T_{on}}{T_{on} + T_{off}} \times \frac{1}{T_{on}} = \frac{T \times DC}{T_{on}} = \frac{T_d}{T_{on}}
\]  
(3)

Therefore, the total discharge energy \( (Q) \) during overall machining time is given by:

\[
Q = N \times V_{dis}I_{dis}T_{on} \times \frac{T_d}{T_{on}} = V_{dis}I_{dis}T_d = V_{dis}I_{dis}T \times DC
\]  
(4)

This is the total electrical discharge energy delivered into the gap zone which is then shared between the tool and work piece electrodes as well as dielectric liquid. All the following discussions are based on the nature of significant interactive parameters identified in Part 1 of this study [2] and the way influencing process responses in reality along with the aid of this simple relation describing the whole generated electro-thermal energy during sparking, expressed in terms of the selected input EDM parameters.

2.1. Parametric analysis of MRR

Figure 1 shows the main effect plot of each variable on the MRR. As is clear, the MRR increases steadily with the increase of discharge current. Higher levels of discharge currents result in more strong electrical discharges (see Eq. 4) capable of removing a chunk of material from the work piece, hence boosting the rate of erosion [5]. The MRR tends to decrease with the increase of pulse on-time. Despite the usual belief that longer pulse on-times provide much more times for electrical discharging compared to shorter ones, however, in reality, longer pulse durations cause the plasma channel to expand excessively thus lowering the plasma flushing efficiency and electrical discharge density within the gap space with more molten material resolidifying instead of being effectively removed [6, 7]. On the contrary, the main effect of duty cycle displays a reverse tendency. At a constant level of pulse on-time \( (B=0, \text{ or the middle value}) \), increasing duty cycle means lowering the pulse off-time, thereby decreasing the idle time between successive sparks which produces higher discharging frequency leading to higher removal rate. Finally, it can be inferred from the main effect plot of gap voltage that higher MRR is attainable at lower levels of gap voltage. Higher gap voltage provides wider gap distance which in turn results in diminished electrical discharge density and larger electrical resistivity of gap hindering proper transmissivity of sparks [7]. So, the MRR decreases with the increase of gap voltage alone. It should be noted that these results have been acquired considering the effect of each factor independently (keeping the other parameters unchanged), nevertheless, more practically beneficial outcomes are to be revealed when their mutual joint effects are investigated simultaneously as can be obtained by studying 3D surface and 2D contour plots of response measures with respect to each pair of significantly interactive input variables.

The combination effect of discharge current \( (A) \) and pulse on-time \( (B) \) at a constant level (middle value) of duty cycle \( (C) \) and gap voltage \( (D) \) has been shown in Figure 2 (a) and (b) in 3D surface and 2D contour format. It can be concluded that higher MRRs are achievable at the lower right region of contour plot area where the discharge current is at its maximum value while pulse on-time at minimum adjustable levels within the domain of process parameters considered in this research.

This phenomenon can be best attributed to the increased energy density of discharge channel \( (J) \) relative to \( I \) and \( T_{on} \) given by [8]:

\[
J = k \frac{I^a}{T_{on}^b}
\]  
(5)

where, \( a, b, \) and \( k \) are constant coefficients. Although the discharge energy itself is small with a short pulse on-time (Eq. 1), due to a very small discharge channel diameter a higher discharge density is expected. Hence, the higher the discharge current and the lower the pulse on-time the larger is the electrical discharge density. Higher discharge density causes most of the material in the discharge area to be removed in the form of evaporation with thinner recast layer left on the work surface increasing the plasma flushing efficiency [9] and hence the MRR.

Figure 3 illustrates the effect of current \( (A) \) and duty cycle \( (C) \) on MRR. It is understood that while keeping pulse on-time and gap voltage at a certain level, middle level in our case, higher amounts of MRR are achievable mostly in the vicinity specified by both elevated current and duty cycle. At a steady pulse on-time, increased duty cycle implies lower pulse off-time, when combined with elevated discharge currents; higher rates of electrical discharge energy are assured making the MRR as large as possible. Figure 4 depicts the effect of current \( (A) \) and gap voltage \( (D) \) whereas Figure 5 shows the mutual effect of pulse on-time \( (B) \) and duty cycle \( (C) \) on MRR while keeping the other variables at their center levels unvarying. It becomes clear that higher values of current along with lower gap voltage will definitely provide a suitable medium for higher amounts of material melting and evaporation during sparking thanks to enhanced electrical discharge density in a narrower gap region. Lowering pulse on-time and increasing duty cycle conveys greater discharge frequency in which more material can be removed from the work piece in a unit time [10]. This event is clearly visible in Figure 5.
Figure 1. Main effect plots for MRR

(a) Surface Plot of MRR (g/h) vs B (Ton); A (I)

(b) Contour Plot of MRR (g/h) vs B (Ton); A (I)

Figure 2. Response surface plot (a) and contour plot (b) of MRR versus current (A) and pulse on-time (B)

(a) Surface Plot of MRR (g/h) vs C (DC); A (I)

(b) Contour Plot of MRR (g/h) vs C (DC); A (I)

Figure 3. Response surface plot (a) and contour plot (b) of MRR versus current (A) and duty cycle (C)
2.2. Parametric analysis of TWR

Figure 6 shows the four main effect plots of TWR model each of which has been drawn keeping the other factors constant at the middle level. A similar trend is observed compared to the main effect plots of MRR. TWR tends to increase by increasing discharge current and can reach up to about 0.09 g/h alone. This is the highest amount of TWR in these plots which in turn confirms that the discharge current is paramount amongst other parameters in affecting the TWR. It is clear from the main effect plot of pulse on-time that setting longer pulse on-times can favor it as shorter pulse durations will deteriorate tool wear. To better justify this fact, Figure 7 illustrates a schematic view of a single electrical discharge happening between the two electrodes and the formed plasma channel. While keeping constant polarity, during every discharge, accelerated electrons bombard the surface of anode (positive pole: tool) whereas ions aiming to move toward the cathode (negative pole: workpiece) collide the work surface. With small values of pulse duration, a higher number of negatively charged particles, being thousands of times lighter than ions, get the chance of being energized; stroke the positive (anode) tool electrode thereby increasing the rate of electrode material erosion [11]. On the same basis, the rising tendency of TWR with regard to duty cycle can be rationalized. A higher level of duty cycle is equivalent to lower pulse off-time and hence higher pulse frequency which implies greater TWR due to privileged rate of electron collisions with the anode tool surface [10]. On the other hand, selecting lower gap voltage results in larger tool wear rate. The same reason as that mentioned for the MRR can surely be applied here. While keeping other variables unchanged, a narrower gap distance caused by selecting a smaller gap voltage, will give rise to increased electrical discharge density leading to higher rate of tool wear.

The TWR response surface plot and its corresponding contour plot with regard to current (A) and pulse on-time (B) has been depicted in Figure 8. As always smaller TWRs are demanded, they can be reached at lower discharge currents followed by longer pulse on-times (the upper left part of the contour plot). Prolonged pulse duration will give more chance for much heavier positive ions to reach to the target cathode work piece thus occupying most of the plasma channel path not letting excited electrons attacking the anode tool [12]. Besides, at long pulse duration, the released carbon resulting from the decomposition of hydrocarbon-based dielectric liquid, due to high plasma temperature during sparking, attaches to the tool’s surface forming a protective layer against wear, and hence decreasing the TWR perceptibly [13].
Figure 6. Main effect plots for TWR

Figure 7. Schematic drawing of a single electrical discharge

Figure 8. Response surface plot (a) and contour plot (b) of TWR versus current (A) and pulse on-time (B)

Figure 9 shows the effect of discharge current (A) and duty cycle (C) on TWR. It is noticeably revealed that smaller TWRs (less than 0.03 g/h) can be obtained by a special combination of a range of low to medium discharge currents with almost any arbitrarily chosen value of the duty cycle (the end left side of contour plot), and that much smaller TWRs are accomplished moving toward the minimum current (A = -1). This fact, however, cannot be elicited solely by checking the main
effect plots of duty cycle and current as both present the same influence on TWR, increasing each of which makes the TWR to increase progressively. This is undoubtedly due to the strong interactive nature of these two parameters suitably found by the ANOVA of TWR response (refer to Part 1 [2], Table 5). Moreover, the tool electrode suffers more from wear where the current and duty cycle are both chosen at their high levels, a zone located at the upper right part of the contour plot. Increasing duty cycle at a steady level of pulse on-time (the case where Figure 9 has been drawn) means lowering pulse off-time and so increasing the frequency of electrical discharges assuring higher rates of electron attacks on anode tool electrode in a unit time. Similar results have also been reported by Ozgedik and Cogun [13].

Figure 10 (a) and (b) displays the effects of current (A) and gap voltage (D) as surface and contour plot. As can be inferred from the contour plot, low TWRs may be accessible with small currents accompanied by every adjustable level of gap voltage within the current study.

In other words, the coincident effects of these two factors on TWR counteract the effect of gap voltage alone shown in Figure 6, as now a wide range of it can be selected to yield small TWRs provided that the current is kept low enough. This can be attributed to the stronger and more influential effect of current (A) over the TWR as having a much smaller p-value compared to the gap voltage (D) (Table 5, part 1 [2]), covering the effect of gap voltage when considered in a combinatory way.

Figure 11 shows the concurrent effect of pulse on-time (B) and duty cycle (C). It is obviously visible that smaller TWRs can be obtained choosing a higher level of pulse on-time with lower duty cycle. This combination confirms decreased sparking frequency meaning lower amount of electron attack to the positive-polarity tool electrode in a unit time causing less tool wear rate [5].

Figure 9. Response surface plot (a) and contour plot (b) of TWR versus current (A) and duty cycle (C)

Figure 10. Response surface plot (a) and contour plot (b) of TWR versus current (A) and gap voltage (D)
2.3. Parametric analysis of Ra

Figure 12 depicts the main effect plots of the four controllable parameters on Ra. It is understandable that the first two variables, current (A) and pulse on-time (B), have more influential impacts on the Ra than those of duty cycle (C) and gap voltage (D). More specifically, increasing pulse on-time alone, while keeping the other factors constant at their middle levels, can increase Ra from 4 µm up to about 5.7 µm which is a higher difference interval than those created by other parameters. As also clear, altering both duty cycle (C) and gap voltage (D) within their designated intervals considered in this research causes little change on the Ra. This fact was also verified before (see Table 5, Part 1 [2]) as not being significant parameters within 95% of confidence interval, and their main effect diagrams have just been shown here for comparative purposes. In general, the surface quality in EDM depends primarily on the magnitude of electrical discharge energy governed mainly by current intensity and pulse on-time [14, 15]. A prolonged pulse on-time makes discharging action to continue over a longer time duration so that deeper and broader craters are formed over the work surface overwhelming with abundance of resolidified molten material not being ejected effectively which in turn leads to worsened and coarser surface quality [6, 9].

Figure 13 illustrates the joint effects of pulse current (A) and pulse on-time (B) over the Ra. It is apparent that smoother surfaces can be obtained allocating both small values for pulse on-time and discharge current, a situation identified as low energy state. For example, according to the Figure 13 (b), if it is desired to produce a surface having 4.25 µm as Ra roughness, then it is feasible by choosing any arbitrary value for the discharge current within its investigated domain provided that the pulse on-time is allotted to vary from -1 to about -0.5 in coded state (50 µs to 75 µs). However, still smoother surfaces may be achieved by narrowing down their variation ranges toward minimum levels.
Figure 14 (a) and (b) portray the surface and contour plot of Ra with respect to discharge current (A) and gap voltage (D). From this, it is recommended to apply low currents with high levels of gap voltage (the upper left part of Figure 14(b)) at a constant level of pulse on-time to produce more polished work surfaces. Higher gap voltage, while making the gap distance wider facilitating debris removal from the gap space, can help reduce electrical discharge density, altogether with low current intensity collaborate in attaining a superior surface quality [6].

3. Multi-objective optimization of EDM parameters based on desirability function

Metal removal rate is an indicator for productivity while tool wear rate and surface finish account for process economics, precision, and work quality. In particular, tool wear is of paramount concern especially when close tolerances in intricate geometries are needed. The EDM, as a complex and stochastic process, exhibits much difficulty in determining optimal machining parameters for best machining performance. The performance indicators, viz. MRR, TWR, and Ra are conflicting in nature as it is always desirable to have higher MRR with a lower value of surface roughness and tool wear rate at the same time. Due to the presence of a large number of process variables and mutual interactions, the selection of optimum machining parameter combinations to obtain higher MRR and smaller SR and TWR is a challenging task [16-18]. Here, an attempt is made to develop a strategy based on the concept of desirability function for predicting the optimum machining parameter settings generating maximum MRR with minimum SR and TWR all at once.

3.1. Optimization formulation

The mathematical formulation of present optimization problem can be stated as follow:

\[ \text{Max: } F_1(x) = \text{MRR} \]
\[ \text{Min: } F_2(x) = \text{TWR} \]
\[ \text{Min: } F_3(x) = \text{Ra} \]

Subject to: $2 \leq x_1 \leq 8$
\[
\begin{align*}
50 & \leq x_2 \leq 150 \\
40 & \leq x_3 \leq 80 \\
40 & \leq x_4 \leq 80
\end{align*}
\]

where $x_1$, $x_2$, $x_3$, and $x_4$ represent the process input parameters $I$, $T_{on}$, $DC$, and $V$, respectively. It is a four-variable-three-objective optimization statement, each of which has been defined by respective second order regression equations; Equations (13-15) (refer to Part 1 [2]).
3.2. Optimization through desirability function

Popularized by Derringer and Suich [19], the desirability function approach (DFA) is a kind of search-based optimization method capable of handling several response functions simultaneously to find optimal input settings globally. The overall approach is to first convert each response $y_i$ into an individual desirability function $d_i$ that varies over the range:

$$0 \leq d_i \leq 1$$

(7)

If the response $y_i$ is at its goal or target, then $d_i = 1$ (the most desirable case), and if the response is outside an acceptable region, $d_i = 0$ (the least desirable case). There is also a positive number, weight factor $(r)$, associated with the desirability function of each response defining its shape. If the weight is chosen to be less than 1, then the sensitivity of the desirability function is low with respect to the optimal or target value sought for. In other words, if the search algorithm finds a point which is somehow far from the desired optimum or target value, then the decrease in desirability function value will be small in comparison with its maximum amount (unity). Choosing a weight factor higher than one, has the reverse effect, and setting it to one, provides a balanced or medium sensitivity with the shape of desirability being linear [20]. The individual desirability functions are defined according to the goal of optimization and are shown in Figure 15 (a) and (b) for the two cases, maximization and minimization, respectively.

If the objective or target $T_i$ for the response $y_i$ is a maximum value, then:

$$d_i = \begin{cases} 
0 & y_i < L_i \\
\dfrac{y_i - L_i}{T_i - L_i} & L_i \leq y_i \leq T_i \\
1 & y_i > T_i 
\end{cases}$$

(8)

and if the target for the response is a minimum value, then:

$$d_i = \begin{cases} 
0 & y_i < T_i \\
\dfrac{U_i - y_i}{U_i - T_i} & T_i \leq y_i \leq U_i \\
1 & y_i > U_i 
\end{cases}$$

(9)

where, $L_i$ and $U_i$ represent the lower and upper limit values of the response $y_i$, respectively.

![Figure 15. Individual desirability functions for simultaneous optimization: (a) objective is to maximize $y$, (b) objective is to minimize $y$](image)

The individual desirabilities are then combined to form the overall (composite or aggregated) desirability ($D$), another parameter varying between 0 and 1, as the weighted geometric mean of all the previously defined desirability functions, given by:

$$D = \left( d_1^{w_1} \times d_2^{w_2} \times d_3^{w_3} \times \ldots \times d_n^{w_n} \right)^{1/(w_1 + w_2 + w_3 + \ldots + w_n)} = \left( \prod_{i=1}^{n} d_i^{w_i} \right)^{1/(\sum w_i)}$$

(10)

where $w_i$ is the relative importance, a comparative scale for weighting each of the resulting $d_i$, assigned to the $i$th response and $n$ is the number of responses ($n = 3$, in our case). The optimal settings are determined so as to maximize the overall desirability ($D$) by usually applying a reduced gradient algorithm with multiple starting points [21].

3.3. Parametric optimization of the EDM process on WC-6%Co

Based on the developed quadratic mathematical responses (Eqs. 13-15, Part 1 [2]), $d_1$, $d_2$, and $d_3$ are selected as the independent desirability functions for the MRR, TWR, and Ra, respectively. Moreover, the targets are placed on the MRR to become maximized while TWR and Ra to be minimized. Unit weight factor ($r = 1$) and importance ($w_i = 1$) were also assigned for each response. The Response Optimizer option within the DOE module of Minitab statistical software package, release 15, has been used here to search for the best set of optimum input parametric combinations resulting in the most desirable compromise between different responses. Table 1 summarizes the key parameters set to find global optimum settings including constraints of input variables and that of responses’ requirements while Table 2 sorts the first ten optimum settings obtained, in descending order of composite desirability ($D$). The closer the $D$ to 1 the more favorable are the EDM conditions satisfying problem requirements. It can be seen from Table 2 that the most desirable operating conditions correspond to the first row and are discharge current $A = 0.2323$, pulse on-time $B = 0.9895$, duty cycle $C = 1$, and gap voltage $D = -1$ in coded form, equivalent to 5.70 A, 50.53 µs, 40% and 40 V as real values, respectively. Accordingly, the optimized responses are 0.302 g/h, 0.9895, duty cycle $C = 1$, and gap voltage $D = -1$ in coded form, equivalent to 5.70 A, 50.53 µs, 40% and 40 V as real values, respectively. Additionally, the targets are placed on the MRR to become maximized while TWR and Ra to be minimized. Unit weight factor ($r = 1$) and importance ($w_i = 1$) were also assigned for each response. The Response Optimizer option within the DOE module of Minitab statistical software package, release 15, has been used here to search for the best set of optimum input parametric combinations resulting in the most desirable compromise between different responses. Table 1 summarizes the key parameters set to find global optimum settings including constraints of input variables and that of responses’ requirements while Table 2 sorts the first ten optimum settings obtained, in descending order of composite desirability ($D$). The closer the $D$ to 1 the more favorable are the EDM conditions satisfying problem requirements. It can be seen from Table 2 that the most desirable operating conditions correspond to the first row and are discharge current $A = 0.2323$, pulse on-time $B = 0.9895$, duty cycle $C = 1$, and gap voltage $D = -1$ in coded form, equivalent to 5.70 A, 50.53 µs, 40% and 40 V as real values, respectively. Accordingly, the optimized responses are 0.302 g/h, 0.9895, duty cycle $C = 1$, and gap voltage $D = -1$ in coded form, equivalent to 5.70 A, 50.53 µs, 40% and 40 V as real values, respectively. A closer examination of the whole listed settings in Table 2 reveals that although higher MRRs can be obtained, however, those cases are subject to sacrificing both the TWR and Ra as they got higher values than those pertinent to the first solution. Figure 16 illustrates the visual representation of the optimization result. The optimization plot shows the effect of each factor (columns) on the response or composite desirability (rows). Furthermore, each cell presents how the process output varies as a function of one of the process factors while keeping the other parameters unchanged. Also, the vertical lines inside the cells show current optimal parametric settings whereas the dotted horizontal lines represent the current response values. High and low settings of each process design variable can also be observed in this plot denoted by 1 and -1, respectively. The most useful part is the optimal parameter settings required to achieve the process set target criteria, located at the middle row between the high and low row, symbolized by “cur” and expressed in coded form. Finally, the first left column shows the composite as well as each individual desirability, all being unity, along with optimum response values.

Conducting confirmation experiment is the crucial, final, and indispensable part of every optimization attempt. Verification experiment was performed at the obtained optimal input parametric setting to compare the actual MRR, TWR, and Ra with those as optimal responses got through desirability approach. Table 3 summarizes the optimization results along with experimentally obtained responses and their percentage relative verification errors. It should be noted that the errors have been calculated as:

$$
\text{Error} = \left| \frac{\text{Actual} - \text{Optimal}}{\text{Optimal}} \right| \times 100\% 
$$

where Actual is the experimentally obtained response and Optimal is the predicted response from DFA.
As is clear, the amounts of errors are all found to be satisfactory in point of engineering applications, 10.64% as the worst case in predicting TWR, assuring the feasibility, predictability, and effectiveness of the adopted approach.

### Table 1. Constraints and criteria of input parameters and responses

<table>
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<th>Parameter/Response</th>
<th>Goal</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge current (A)</td>
<td>In range</td>
<td>2</td>
<td>8</td>
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<tr>
<td>Pulse on-time (µs)</td>
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<tr>
<td>Gap voltage (V)</td>
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<td>Tool wear rate (g/h)</td>
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<tr>
<td>Surface roughness (µm)</td>
<td>Minimize</td>
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<td>6.589</td>
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### Table 2. Iterative determination of optimum conditions (inputs in coded form)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Current (A)</th>
<th>Pulse on-time (B)</th>
<th>Duty cycle (C)</th>
<th>Gap voltage (D)</th>
<th>MRR (g/h)</th>
<th>TWR (g/h)</th>
<th>Ra (µm)</th>
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<th>d₂</th>
<th>d₃</th>
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<td>4.44991</td>
<td>1</td>
<td>1</td>
<td>0.500078</td>
<td>0.793742</td>
</tr>
<tr>
<td>9</td>
<td>0.997587</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0.27054</td>
<td>0.0564</td>
<td>4.43547</td>
<td>0.705421</td>
<td>0.871967</td>
<td>0.513207</td>
<td>0.680895</td>
</tr>
<tr>
<td>10</td>
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<td>-0.15463</td>
<td>-0.946309</td>
<td>-1</td>
<td>0.28279</td>
<td>0.04136</td>
<td>4.64325</td>
<td>0.827884</td>
<td>1</td>
<td>0.324322</td>
<td>0.645132</td>
</tr>
</tbody>
</table>

Note: The first row in italic is selected as the best compromise solution.

### Table 3. Multi-response optimal points and experimental validation

<table>
<thead>
<tr>
<th>Optimum input setting</th>
<th>MRR (g/hr)</th>
<th>TWR (g/hr)</th>
<th>Ra (µm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>l(A)</td>
<td>l(µs)</td>
<td>l(D)</td>
<td>l(V)</td>
<td>Predicted</td>
</tr>
<tr>
<td>5.7</td>
<td>50.53</td>
<td>40</td>
<td>40</td>
<td>0.302</td>
</tr>
</tbody>
</table>

### Figure 16. Final optimization results

3.4. The interpretation of optimal settings

Making a thorough analysis of the optimum input values can provide a fair basis to justify their estimated amounts in point of physical aspects involved in the EDM process. In the course of optimization through the desirability function approach, a measure of how well the solution has satisfied the combined goals for all responses must be assured. That is D = 1 and the optimum setting providing this could have been able to make a tradeoff between different objective functions. The amount of optimal discharge current has been found to be near to its middle value, providing fair electro-thermal energy so that neither a very low MRR nor an extremely high one is obtained. Along with almost the shortest possible pulse on-time (50.53 µs), the existence of adequate electrical discharge density is assured to help maintaining enough impulsive force expelling much of molten material from crater [22]. Moreover, as was discussed in subsection 2.3, shorter pulse on-times are in favor of smoother surfaces, as the resulted craters’ dimensions (depth and...
diameter) are smaller compared with those created with long pulse durations. Hence, better surface quality is guaranteed. Finally, the optimal values of duty cycle and gap voltage are equivalent to their lowest possible levels considered in the experimental plan as increasing each of which may cause the process performance to deviate from its optimum condition by sacrificing any of the three responses. This effect can be seen in Table 2. Specially, the lowest gap voltage (40 V) provides the narrower gap distance increasing electrical discharge density inside the gap zone helping to improve the MRR.

4. Conclusions

In short, based on an in-depth and comprehensive parametric analysis and optimization of the WC-6%Co EDM-machinability indices, the following principal conclusions can be drawn:

1. In point of main effects analysis, both the MRR and TWR behave the same way though the TWR behaves more nonlinearly. Rising either discharge current or duty cycle results in higher values of stock removal rate and tool wear whereas increasing pulse on-time or gap voltage causes the reverse effect. On the other hand, the work roughness value, Ra, is directly proportional to both the discharge current and pulse on-time while the main effects of other parameters (duty cycle and gap voltage) were found to be almost negligible, changing each of which has minor effect on the Ra.

2. Higher MRRs are always accessible through either enhancing electrical discharge density or rising sparking frequency. These conditions are feasible by lowering the pulse on-time and gap voltage or increasing duty cycle while considering larger discharge currents to confirm greater released electro-thermal energy as a result of sparking.

3. Low amounts of TWRs can mainly be obtained by a combination of lower current levels with prolonged pulse on-times or longer pulse on-times with smaller duty cycles. Decreased discharging frequency resulted from long pulse durations can help protect the anode tool from serious wear as a smaller number of discharges take place within a unite time. In other words, positive ions get enough time with a longer pulse on-time reaching the cathode work piece while occupying much of the path within discharge channel not letting high volumes of electrons bombarding the anode tool.

4. Smoother surfaces can be produced via a combination of either low current intensity with shorter pulse on-time or low current level with higher gap voltage. While keeping the discharge current low enough, the first case produces shallower craters with low diameters while the latter gives rise to wider gap size helping better debris evacuation and lesser deposition of molten products on work surface, hence improving the surface quality in each case.

5. The superior optimum operating conditions which can simultaneously bring out maximum MRR, and minimum TWR and Ra are 5.70 A, 50.53 μs, 40 %, and 40 V as current, pulse on-time, duty cycle, and gap voltage, respectively. Verifying these optimized points, reveals the worst relative error as 10.640 % between the predicted optimal and experimentally obtained value of TWR.

VI. Though the EDM process parameters on WC-6%Co are highly interconnected due to its inherently complex and stochastic nature, however, the approach of RSM coupled with DF can beneficially help identifying process behavior and determining appropriate EDM conditions meeting all performance criteria in a compromise manner.

Scope of future research

The present work will further be followed by a future study focusing on machining characteristics in dry-EDMing WC/6%Co and comparing the results with the present research. The possible outcomes will definitely be of great benefits as there have recently been strong tendencies towards replacing the conventional-EDM with the dry one, a relatively new method claiming to be most effective in point of both process efficiency and environmentally friendly technology. The literature still lacks providing such a comparative work.

References

2. S. Assarzadeh, M. Ghoreishi, Statistical investigation into the effects of electro-discharge machining parameters on WC/6%Co composite- Part 1: Modeling through response surface methodology (RSM), Submitted to the International Journal of Advanced Materials Manufacturing and Characterization, under review.