Performance parameters optimization (multi-characteristics) of powder mixed electric discharge machining (PMEDM) through Taguchi’s method and utility concept

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Electrical discharge machining (EDM) is widely used in the production of dies. This paper describes an investigation into the optimization of the EDM process when silicon powder is suspended into the dielectric fluid of EDM. Taguchi’s method with multiple performance characteristics has been adopted to obtain an overall utility value that represents the overall performance of powder mixed EDM (PMEDM). The four input process parameters, viz., concentration of silicon powder added into the dielectric fluid, peak current, pulse duration and duty cycle, are optimized with consideration of multiple performance characteristics including machining rate (MR), surface roughness (SR) and tool wear rate (TWR). A modified powder mixed dielectric circulation system has been developed. Experiments have been performed on the newly designed experimental set-up developed in the laboratory. The obtained experimental results indicate that the peak current and concentration of the silicon powder suspended into dielectric fluid are most significant parameters. Moreover, the performance of PMEDM has improved over EDM. The predicted optimal values for MR, SR and TWR obtained for PMEDM are 1.22 mm³/min, 0.51 μm and 0.005 mm³/min respectively. The results are further verified by conducting confirmation experiments.

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Electrical discharge machining (EDM) is one of the non-conventional machining processes, which is widely used to produce intricate shapes on any conducting metal and alloy irrespective of their hardness and toughness1. In spite of remarkable process capabilities, the limitations like low volumetric material removal rate and poor surface quality restricted its further applications2. To address these problems, recently, powder mixed EDM (PMEDM) has been emerged as one of the advanced technique in the direction of enhancement of capabilities of EDM2,3. The investigations show that when a suitable material in fine powder form is mixed into the dielectric fluid of EDM, the insulating strength of the dielectric fluid decreases and consequently, the spark gap distance between the electrode and workpiece increases2-6. Enlarged spark gap distance ensures the uniform flushing of debris. As a result, the process becomes more stable thereby improving machining rate (MR) and surface finish. Further, the glossy and smooth surface finish could be achieved by mixing the different additives into the dielectric fluid of EDM2. Mohri et al6. found that an EDM finishing process using dielectric mixed with silicon powder produced a mirror surface of up to 500 cm² area.

The electrical parameters (peak current, pulse duration and pulse off time) and non-electrical parameters (gain, electrode lift time and flushing) of EDM have great effect on process performance7. Besides theses factors, the addition of suitable powder into the dielectric fluid significantly affects the performance characteristics of the PMEDM2. The fine surfaces are produced by addition of graphite and silicon powders into the dielectric oil. Because of significant difference in the thermophysical properties of different powders, it was experimentally found that powder characteristics, such as powder concentration, particle size and particle density, affect the efficiency of EDM3. The performance of PMEDM also depends upon the composition of the workpiece material3. Machining of SKH-54 tool steel in presence of powder particles produces higher MR and discharge dispersion than AISI-01 tool steel.
Literature survey indicates that PMEDM involves a large number of input parameters that affect the quality of the machined component. Therefore, it becomes very important to find out their relative influence on the output characteristics. It is also noted that the quality of the machined component is defined by various output characteristics such as MR, surface roughness (SR), tool wear rate (TWR) and surface hardness. Therefore, the problem of optimization of PMEDM can be considered as a multi-objective optimization problem. The aim of this study is to obtain a single setting (optimal setting) of various input parameters of PMEDM to obtain a single output characteristic as a whole. The multi-criterion methodology based on Taguchi approach and utility concept has been used for optimization.

**Technology of PMEDM**

Powder mixed EDM has a different machining mechanism from the conventional EDM. In this process, a suitable material in the powder form was mixed into the dielectric fluid either in the same tank or in a separate tank. For better circulation of the powder mixed dielectric, a stirring system was employed. For constant reuse of powder in the dielectric fluid, a special circulation system was used. The various powders that can be added into the dielectric fluid include aluminum, chromium, graphite, copper or silicon carbide. The spark gap was filled up with additive particles. When a voltage of 80-320 V was applied between the electrode and the workpiece facing each other with a gap of 25-50 µm, an electric field in the range $10^5$-$10^7$ V/m was created. The powder particles get energized and behave in a zigzag fashion. Under the sparking area, the particles come close to each other and arrange themselves in the form of chain like structures between both the electrodes. The interlocking between the different powder particles occurred in the direction of flow of current. The chain formation helps in bridging the discharge gap between both the electrodes. Due to bridging effect, the insulating strength of the dielectric fluid decreased. The easy short circuit takes place, which causes early explosion in the gap. As a result, a ‘series discharge’ starts under the electrode area. The faster sparking within a discharge takes place, which caused faster erosion from the workpiece surface and hence increased the MR. At the same time, the added powder modifies the plasma channel. The plasma channel becomes enlarged and widened. The sparking is uniformly distributed among the powder particles, hence electric density of the spark decreased. Consequently, uniform erosion (shallow craters) occurred on the workpiece surface. This results in improvement in surface finish.

**Process parameters of PMEDM**

In order to identify the process parameters that affect the performance of PMEDM, an Ishikawa cause-effect diagram is constructed as shown in Fig. 1. The Ishikawa cause-effect diagram (Fig. 1) shows that the following parameters may affect the performance of PMEDM: (i) electrical parameters: peak current, pulse duration, duty cycle and supply voltage, (ii) non-electrical parameters: electrode lift time, working time, nozzle flushing and gain, (iii) powder-based parameters: powder type, powder concentration, powder shape, powder size, powder conductivity and powder density, and (iv) electrode based parameters: electrode material and electrode size.

The following four parameters were chosen for this study: (i) concentration of silicon powder, (A); (ii) peak current, (B); (iii) pulse duration, (C); and (iv) duty cycle, (D).

The ranges of the selected process parameters were decided by conducting the experiments using one variable at a time approach. The selected process parameters, their designated symbols and levels are given in Table 1. Each parameter was studied at three levels.

**Performance characteristics of PMEDM**

To evaluate the performance of PMEDM, the following output characteristics were selected: (i) machining rate (MR), (ii) surface roughness (SR), and (iii) tool wear rate (TWR)

MR is ‘higher the better’ type of quality characteristic, whereas SR and TWR are ‘lower the better’ type. It is required to optimize the performance characteristics of the PMEDM as a whole. A simplified multi-criterion methodology based on Taguchi’s approach and utility concept has been used to achieve the objective of this study.

![Ishikawa cause-effect diagram for PMEDM](image)
The performance evaluation of any machining process or a component depends upon a number of diverse output characteristics. To able to make a rational choice, these evaluations on different characteristics should be combined to give a composite index. Such a composite index represents the overall utility of a product. The overall utility of a component machined by PMEDM is the sum of utilities of each of the performance characteristics.

Thus, if \( X_i \) is the measure of effectiveness of an attribute (characteristic) \( i \) and there are \( n \) attributes evaluating the outcome space, then the joint function could be expressed as:

\[
U (X_1, X_2, \ldots, X_n) = f(U_1(X_1), U_2(X_2), \ldots, U_n(X_n))
\]

where \( U_i(X_i) \) is the utility of the \( i^{th} \) attribute.

It was assumed that the attributes (characteristics) are independent and have no interactions between themselves, and the overall utility function is a linear sum of individual utilities, the overall utility function becomes

\[
U (X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} U_i(X_i)
\]

Depending upon the customer’s requirements, the attributes might be given priorities. The priorities could be adjusted by providing a weight to the individual utility index. The overall utility function by assigning weights to attributes could be written as:

\[
U (X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} W_i U_i(X_i)
\]

where, \( W_i \) is the weight assigned to the attribute \( i \) and the sum of the weights for all the attributes is equal to 1. The utility function is of ‘higher the better’ type. If the composite measure (the overall utility) is maximized, the performance characteristics considered for the evaluation of utility will automatically be optimized (maximized or minimized whichever the case may be).

To determine the utility value for a number of performance characteristics, a preference scale for each performance characteristic was constructed. Later these scales were weighted to obtain a composite number (overall utility). The weighting was done to satisfy the test of indifference on the various performance characteristics. The preference scale may be linear, exponential or logarithmic. The minimum acceptable level for each output characteristic was set at a preference number of 0 and the best available performance was assigned a preference number of 9 (the preference numbers for minimum or best values of characteristics is optimal).

In this study, logarithmic scale was used. Therefore, the preference number \( (P_i) \) is given as:

\[
P_i = A \log \frac{X_i}{X_i'}
\]

where \( X_i \) is the value of performance characteristic or attribute \( i \). \( X_i' \) is the minimum acceptable value of the performance characteristic or attribute \( i \) and \( A \) is a constant. Arbitrarily, \( A \) has been chosen such that \( P_i=9 \) at \( X_i = X^* \), where \( X^* \) is the optimum value of \( X_i \) with assumption that such a number exists.

The next step was to assign weights or relative importance to the performance characteristics. A number of methods exist for the assessment of weights (AHP and conjoint analysis). The weights should be assigned such that the following conditions hold:
The overall utility can be calculated as:

\[ U = \sum_{i=1}^{n} W_i P_i \]  (5)

The multi-characteristic optimization algorithm

The following step-by-step procedure using Taguchi approach and utility concept was used to obtain the multi-characteristic optimization of PMEDM:

(i) The optimal values of the selected performance characteristics have been found separately by using Taguchi’s experimental design and analysis (parameter design).

(ii) Using the optimal values and the minimum levels, preference scales for each performance characteristic have been constructed.

(iii) Weights \( W_i \), \( i = 1, 2, \ldots, n \), were assigned to various output characteristics based on experience and the application of the component such that the sum of weights is equal to 1.

(iv) Using Eq. (5), the utility values for each experiment against each trial condition of the experiment have been found.

(v) The obtained utility values in step 4 were used as a response of the trial conditions of the selected experimental plan.

(vi) The results were analyzed using procedure suggested by Taguchi\(^8\)-\(^10\).

(vii) The optimal settings of the process parameters for optimum utility (mean and minimum deviation around the mean) have been found.

(viii) After considering the optimal significant parameters as determined in step 7, the individual characteristic values have been predicted.

(ix) Number of confirmation experiments has been conducted at the optimal setting and results are compared with the predicted optimal values.

Phase-I: Optimization of an individual performance characteristic

Taguchi’s method was applied to identify the optimum levels of process parameters for each performance characteristic individually. The selection of an appropriate orthogonal array (OA) is a critical step in Taguchi’s experimental design. The OA selected should satisfy the following criterion\(^7\):

Degrees of freedom (DOF) of OA \( \geq \) Total DOF required

Therefore, L\(9\) (3\(^4\)) Taguchi orthogonal array was selected to assign various columns. The experiments were conducted according to the trial conditions specified in L\(9\) (3\(^4\)) OA (Table 2). A total of 27 (= 3 \times 9) experiments (three repetitions at each trial condition) were conducted. The observed values of MR, SR and TWR are mentioned in Table 3.

Analysis and optimal results

Using Taguchi’s analysis and analysis of variance (ANOVA), the optimal settings for MR, SR and TWR were determined separately and the optimal values were predicted. The average values of performance characteristics at each level and against each parameter were calculated and are given in Table 4. Table 5 displays the individual optimal values and corresponding optimal setting of the process parameters for MR, SR and TWR for the experiments performed by PMEDM.

---

\[ \sum_{i} W_i = 1 \]

Table 2 — The L9 (3\(^4\)) Taguchi orthogonal array layout

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Powder concentration (g/L)</th>
<th>Peak current (A)</th>
<th>Pulse duration (μs)</th>
<th>Duty cycle</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>2</td>
<td>1</td>
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<td>3</td>
<td>1</td>
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<td>4</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
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<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
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<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
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</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
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</tr>
</tbody>
</table>

R1, R2 and R3 represent repetitions
Phase-II: Preference scale construction

**Machining rate (MR)**

\[ X^* = \text{optimal value of MR} = 2.89 \text{ mm}^3/\text{min. (ref. Table 5)} \]

\[ X' = \text{minimum acceptable value of MR} = 0.25 \text{ mm}^3/\text{min (assumed that observed values of MR are greater than 0.25 mm}^3/\text{min (Table 3).} \]

Using these values in Eq. (4), the preference scale for MR was constructed as:

\[ P_{MR} = 8.46 \log \frac{X_{MR}}{0.25} \quad \text{(6)} \]

**Surface roughness (SR)**

\[ X^* = \text{optimal value of SR} = 0.4 \mu \text{m (refer Table 5)} \]

\[ X' = \text{minimum acceptable value of SR} = 2.5 \mu \text{m (assumed that observed values of SR are less than 2.5 \mu m (Table 3).} \]

The preference scale for SR was

\[ P_{SR} = -11.30 \log \frac{X_{SR}}{2.5} \quad \text{(7)} \]

**Tool wear rate (TWR)**

\[ X^* = \text{optimal value of TWR} = 0.006 \text{ mm}^3/\text{min (refer Table 5)} \]

\[ X' = \text{minimum acceptable value of TWR} = 0.10 \text{ mm}^3/\text{min (assumed that observed values of TWR are less than 0.10 mm}^3/\text{min (Table 3).} \]

The preference scale for TWR was

\[ P_{TWR} = -7.36 \log \frac{X_{TWR}}{0.10} \quad \text{(8)} \]

**Weights**

The weights to the selected performance characteristics were assigned as given below:

\[ W_{MR} = \text{weight assigned to the MR} = 0.4 \]

\[ W_{SR} = \text{weight assigned to the SR} = 0.4 \]

\[ W_{TWR} = \text{weight assigned to the TWR} = 0.2 \]

The customer’s requirements and priorities were taken into consideration while deciding the weights of performance characteristics. Here, the finishing condition (represented by SR) as well as the efficiency (represented by MR) requirements of the components machined by PMEDM was considered equally important. Therefore, equal weightage was assigned to MR and SR.

**Calculation of Utility Value**

The following relation (overall utility function) was used to calculate the utility values for each trial condition and for each repetition:

\[ \text{Utility Value} = W_{MR} \cdot P_{MR} + W_{SR} \cdot P_{SR} + W_{TWR} \cdot P_{TWR} \]
\[ U(n, R) = P_{MR}(n, R) \times W_{MR} + P_{SR}(n, R) \times W_{SR} + P_{TWR}(n, R) \times W_{TWR} \] …(9)

where, \( n \) is the trial number, \( n = 1, 2, \ldots, 9 \), and \( R \) is the repetition number, \( R = 1, 2, 3 \). The calculated utility values are mentioned in Table 6.

### Analysis of data and determination of the optimal setting of the process parameters

The mean responses and main effects in terms of utility values were calculated and are reported in Table 7a. These results are plotted in Fig. 2. It is clear from Fig. 2 that the third level of concentration of added silicon powder (A_3), the first level of peak current (B_1), the second level of pulse duration (C_2) and the first level of duty cycle (D_1) yields a maximum value of the overall utility function for the PMEDM performance.

The pooled version of ANOVA for raw data (Table 7 b) indicate that the process parameters such as concentration of added silicon powder (A) and peak current (B) are significant at a 95% confidence level. Since the pulse duration (C) and duty cycle (D) are insignificant, any level of these factors may be chosen. However, the second level of pulse duration (C = 100 \( \mu \)s) and first level of duty cycle (D = 0.7) are the best setting from the process stability point of view. The optimal setting of the PMEDM parameters for optimization of MR, SR and TWR is given in Table 8.

### Predicted means (optimal values of performance characteristics)

**Machining rate (MR)**

After utilizing the estimation model of Taguchi approach based on the average values, the performance at the optimum conditions is achieved by using the following equation\(^8-10\):

\[ Y_{opt} = \text{Average performance} + \text{Contribution of significant factors at optimum level} \]
The 95% confidence interval of confirmation experiments (CI_CE) was calculated by using the following expression:

\[
\text{CI}_{CE} = \pm \sqrt{F_{a} (1, f_{e}) \times V_{e} \left( \frac{1}{n_{eff}} \right)}
\] …(10)

where, \( F_{a} (1, f_{e}) \) is the F-ratio at a confidence level of \((1-\alpha)\) against DOF one and error degree of freedom \( f_{e} \) \( n_{eff} = \frac{N}{1 + \left( \frac{d.o.f. \ of \ all \ factors \ used}{\text{in \ the \ estimate \ of \ mean}} \right)} \)

For MR:
- \( N \) (total number of trials) = 27, \( R \) (number of repetitions) = 3, \( n_{eff} = 5.4 \) (calculated), and \( F_{0.05} (1, 4) = 7.71 \) (tabulated f-value) and \( V_{e} = \text{error variance} = 0.10 \).
- Therefore, \( \text{CI}_{CE} = \pm 0.37 \)
- The predicted optimal range is 0.84 mm³/min. < MR < 1.60 mm³/min.

**Surface roughness (SR)**
- The predicted mean of the SR (using Table 9) is

\[
Y_{opt} = \overline{A_3} + \overline{B_1} - \overline{T} = 0.51 \mu m
\]

The 95% confidence interval of confirmation experiments (CI_CE) was calculated by using the following values in Eq. (10):
- \( N \) (total number of trials) = 27, \( R \) (number of repetitions) = 3, \( n_{eff} = 5.4 \) (calculated), and \( F_{0.05} (1, 4) = 7.71 \) (tabulated f-value) and \( V_{e} = \text{error variance} = 0.015 \).
- Therefore, \( \text{CI}_{CE} = \pm 0.14 \)
- The predicted optimal range is 0.36 µm < SR < 0.66 µm

**Tool wear rate**
- The predicted mean of the TWR (using Table 9) is

\[
Y_{opt} = \overline{A_3} + \overline{B_1} - \overline{T} = 0.005 \text{ mm}^{3}/\text{min}.
\]

The 95% confidence interval of confirmation experiments (CI_CE) was calculated by using the following values in Eq. (10):
- \( N \) (total number of trials) = 27, \( R \) (number of repetitions) = 3, \( n_{eff} = 5.4 \) (calculated), and \( F_{0.05} (1, 4) = 7.71 \) (tabulated f-value) and \( V_{e} = \text{error variance} = 0.00017 \).
- Therefore, \( \text{CI}_{CE} = \pm 0.01 \)
- The predicted optimal range is 0 mm³/min. < TWR < 0.015 mm³/min.

**Confirmation Experiments**
- Three confirmation experiments were conducted at the optimum setting of the process parameters. The values of the performance characteristics, viz., MR, SR and TWR were recorded and are given in Table 10. However, the overall average values are reported here:
- MR = 1.06 mm³/min; SR = 0.40 µm; TWR = 0.007 mm³/min.

<table>
<thead>
<tr>
<th>Table 8 — Optimal setting of process parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder concentration* (A3, third level)</td>
</tr>
<tr>
<td>Peak current* (B1, first level)</td>
</tr>
<tr>
<td>Pulse duration (C2, second level)</td>
</tr>
<tr>
<td>Duty cycle (D1, first level)</td>
</tr>
<tr>
<td>* Significant at 95% confidence level.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 9 — Average values of performance characteristics at optimum level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levels</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>A3</td>
</tr>
<tr>
<td>B1</td>
</tr>
<tr>
<td>*The above average values are taken from the Table 4.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10 — Observed values of performance characteristics (confirmation experiments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial No.</td>
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<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
</tr>
<tr>
<td>Overall average</td>
</tr>
</tbody>
</table>
It is clear from Table 10 that the average as well as individual characteristic values are well within the 95% CI_{CE} of the optimal range. The summary results and comparison with the single characteristic optimization are given in Table 11.

**Conclusions**

Based on the experiments performed on a newly developed experimental set-up developed for PMEDM, the following conclusions have been drawn:

(i) A simplified model based on Taguchi’s approach and utility concept was used to determine the optimal setting of the parameters for a multi-characteristic process. The model was used to predict an optimal setting of the parameters of PMEDM to achieve its optimum performance.

(ii) The optimal setting of input process parameters for individual characteristic is:

- MR = A_3, B_3, C_2, D_1
- SR = A_3, B_1, C_2, D_1
- TWR = A_3, B_1, C_2, D_1

(iii) The optimal settings of input process parameters for overall utility is A_3, B_1, C_2, D_1.

(iv) The percentage contributions of each parameter to the overall utility index for PMEDM is given as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>% Contribution on overall utility value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder concentration</td>
<td>84.01</td>
</tr>
<tr>
<td>Peak current</td>
<td>8.84</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>4.20</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>2.95</td>
</tr>
</tbody>
</table>

(v) The concentration of added silicon powder and peak current are the most influential parameters on overall utility value.

(vi) With a different set of weights, a different set of optimal parameters for the output characteristics will be obtained. The optimal set of process parameters predicted would be closer to the optimal set predicted for that characteristic which has been assigned the largest weight.

(vii) The model could be extended to any number of performance characteristics provided preference scales for the characteristics are available.

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**References**