Optimization of micro-EDM with multiple performance characteristics using Taguchi method and Grey relational analysis

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This study presents optimization of multiple performance characteristics [material removal rate (MRR), tool wear rate (TWR), and overcut (OC)] in micro electrical discharge machining (micro-EDM) using Taguchi method and Grey relational analysis. Machining process parameters selected were pulse-on time, discharge current, and gap voltage. Based on ANOVA, pulse-on time is found the most significant factor, which affects micro-EDM process. Optimized process parameters simultaneously leading to a higher MRR, lower TWR, and lower OC are then verified through a confirmation experiment. Validation experiment shows an improved MRR (12.88%), TWR (14.57%) and OC (6.1%) when Taguchi method and grey relational analysis were used.

Keywords: Grey relational analysis, Micro-EDM, Multiple performance characteristics, Taguchi method

Introduction

Electrical discharge machining (EDM), a thermo-electric process, erodes material from workpiece by a series of discrete sparks between workpiece and tool, both submerged in a dielectric fluid. Micro-EDM process is an appropriate machining method for manufacturing accurate and complex 3D micro-features in production of difficult-to-make structures (fuel injection nozzles, micro compressor, miniature gas turbine, spinneret holes for synthetic fibres, electronic and optical devices, micro-mechatronic actuator parts and micro-tools). Taguchi method optimizes only a single performance characteristic. Handling multiple performance characteristics by Taguchi method requires further research effort. For micro-EDM process, material removal rate (MRR) is a higher-the-better performance characteristic whereas tool wear rate (TWR) and overcut (OC) are a lower-the-better performance characteristic. Hence, optimization of multiple performance characteristics is more complicated than optimization of a single performance characteristic.

Theory of grey system makes use of grey relational generating and calculates grey relational coefficient (GRC). Grey relational analysis (GRA) has found wide application areas for determining optimal parameters for different machining processes. With GRA and analysis of variance (ANOVA) of grey relational grade, optimal combination of process parameters has been predicted.

In this study, machining process parameters (pulse-on time, discharge current and gap voltage) were optimized by grey relational grade obtained using GRA for multiple-performance characteristics (MRR, TWR, and OC) under given machining conditions.

Experimental Section

Machining Parameters Selection and Performance Evaluations

A scheme of experiments was performed using ELECTRONICA make EDM machine with brass electrode (diam, 500 µm) for machining workpiece made of 304 stainless steel. De-ionized water was used as dielectric medium. On the basis of preliminary experiments conducted by using one variable at a time approach, range of discharge current, pulse-on time, and gap voltage were selected (Table 1). Micro-EDM characteristics (MRR, TWR and OC) were considered
as output responses for through micro-hole machining. MRR (mg/min) was calculated as workpiece removal weight over machining time. As during EDM process, both workpiece and tool electrode is eroded simultaneously, TWR is expressed as the ratio of tool wear weight to machining time. OC of machined micro-hole was calculated by subtracting diameter of tool electrode from diameter of machined micro hole. Use of $L_9$ orthogonal array (OA), which has 3 columns and 9 rows, handle three, three-level process parameters. Hence, only 9 experiments are needed to study entire machining parameter space using $L_9$ OA (Table 2). Each experiment was replicated thrice.

### Results and Discussion

#### Grey Relational Analysis (GRA) for Experimental Results

<table>
<thead>
<tr>
<th>Data Pre-processing</th>
</tr>
</thead>
</table>

Data pre-processing is a process of transferring original sequence to a comparable sequence. For this, experimental results are normalized in the range between zero and one. Depending on characteristics of data sequence, there are various methodologies of data pre-processing available for GRA\textsuperscript{16}. MRR, a dominant phenomenon in micro-EDM, decides machinability of material under consideration. For larger-the-better characteristic like MRR, original sequence can be normalized as

$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad \ldots(1)$$

where, $x_i^*(k)$ and $x_i(k)$ are sequences after data pre-processing and comparability sequence respectively, $k=1$ for MRR; $i=1, 2, 3, \ldots, 9$ for experiment numbers 1 to 9.

To obtain optimal cutting performance, smaller-the-better quality characteristic has been used for minimising both TWR and OC. When smaller-the-better is a characteristic of original sequence, then original sequence should be normalised as

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad \ldots(2)$$

where, $x_i^*(k)$ and $x_i(k)$ are sequence after data pre-processing and comparability sequence respectively, $k=2$ and 3 for TWR and OC; $i=1, 2, 3, \ldots, 9$ for experiment numbers 1 to 9. All sequences after data pre-processing using Eqs (1) and (2) are presented in Table 3.
The deviation sequence \( \Delta_{0i}(k) \) is deviation sequence of reference sequence \( x^*_0(k) \) and comparability sequence \( x^*_i(k) \) as:

\[
\Delta_{0i}(k) = |x^*_0(k) - x^*_i(k)| 
\]

Deviation sequence \( \Delta_{0i} \) can be calculated using Eq. (3) as

\[
\begin{align*}
\Delta_{01}(1) &= |x^*_0(1) - x^*_1(1)| = |1.00 - 0| = 1.00 \\
\Delta_{01}(2) &= |x^*_0(2) - x^*_1(2)| = |1.00 - 1.00| = 0.00 \\
\Delta_{01}(3) &= |x^*_0(3) - x^*_1(3)| = |1.00 - 0.8595| = 0.1405 \\
\end{align*}
\]

So, \( \Delta_{0i} = (1.00, 0.00, 0.1405) \)

Similar calculation was performed for \( i = 1 \) to 9 and results of all \( \Delta_{0i} \) for \( i = 1 \) to 9 are presented in Table 4.

<table>
<thead>
<tr>
<th>Expt. no.</th>
<th>Material removal rate (MRR)</th>
<th>Tool wear rate (TWR)</th>
<th>Overcut (OC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference sequence</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>1</td>
<td>0.0000</td>
<td>1.0000</td>
<td>0.8595</td>
</tr>
<tr>
<td>2</td>
<td>0.2974</td>
<td>0.9215</td>
<td>0.8403</td>
</tr>
<tr>
<td>3</td>
<td>0.5938</td>
<td>0.8810</td>
<td>1.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.4218</td>
<td>0.2671</td>
<td>0.7382</td>
</tr>
<tr>
<td>5</td>
<td>0.5599</td>
<td>0.2451</td>
<td>0.9570</td>
</tr>
<tr>
<td>6</td>
<td>0.8419</td>
<td>0.1724</td>
<td>0.5738</td>
</tr>
<tr>
<td>7</td>
<td>0.5445</td>
<td>0.3324</td>
<td>0.5617</td>
</tr>
<tr>
<td>8</td>
<td>0.8680</td>
<td>0.0296</td>
<td>0.1535</td>
</tr>
<tr>
<td>9</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Computing Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG)

GRC expresses relationship between ideal and actual normalized experimental results. GRC is given as:

\[
\xi_i(k) = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{0i}(k) + \zeta \Delta_{\text{max}}} 
\]

where \( \Delta_{0i}(k) \) is deviation sequence of reference sequence \( x^*_0(k) \) and comparability sequence is \( x^*_i(k) \), \( \zeta \) distinguishing or identification coefficient. If all parameters are given equal preference, \( \zeta \) is taken as 0.5. GRC for each experiment (Table 5) can be calculated using Eq. (4).

After obtaining GRC, the GRG is computed by averaging GRC corresponding to each performance characteristic. Overall evaluation of multiple performance characteristics is based on GRG, given as

\[
\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) 
\]

where \( \gamma_i \) is GRG for \( i \)th experiment and \( n \) is number of performance characteristics.

Higher GRG (Table 5) represents that corresponding experimental result is closer to ideally normalized value. Experiment 3 has the best multiple performance characteristics among nine experiments because it has highest GRG. In present study, optimization of complicated multiple performance characteristics of micro-EDM of 304 stainless steel has been converted into optimization of a GRG. Mean of GRG for each level of machining parameters and also total mean of GRG for nine
experiments is calculated (Table 6). Mean of GRG for each parameter is shown by horizontal line (Fig. 1). Basically, larger is GRG, closer will be product quality to the ideal value. Thus, larger GRG is desired for optimum performance. Therefore, optimal parameter setting (Table 6) for better MRR and lesser TWR and OC is \((A_1, B_3, C_1)\). Optimal level of process parameters is the level with the highest GRG.

**Analysis of Variance (ANOVA)**

Fisher’s \(F\) test\(^{19}\) determines machining parameters that have a significant effect on performance characteristic. Usually, change of machining parameter has a significant effect on performance characteristic when \(F\) is large. ANOVA for GRG is presented in Table 7. Pulse-on time is dominant parameter that affect GRG (Fig. 2) and hence contributes in improving MRR and reducing TWR and OC\(^{20,21}\). Thus when pulse-on time increases for a fixed frequency, discharge energy becomes high and increases MRR, and also remove extra material at the entry side of hole, which in turn increases OC.

**Analysis based on SEM Micrographs**

SEM pictures (Fig. 3) reveals that when pulse-on time increases, OC also increases\(^{22}\). Optimal process

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**Table 5—Calculated grey relational grade GRG) and its order in optimization process**

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Grey relational coefficient (GRC)</th>
<th>Grey relational grade (GRG)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MRR (\xi_1) (1)</td>
<td>TWR (\xi_2) (2)</td>
<td>OC (\xi_3) (3)</td>
</tr>
<tr>
<td>1</td>
<td>0.3333</td>
<td>1.0000</td>
<td>0.7806</td>
</tr>
<tr>
<td>2</td>
<td>0.4158</td>
<td>0.8643</td>
<td>0.7579</td>
</tr>
<tr>
<td>3</td>
<td>0.5518</td>
<td>0.8077</td>
<td>1.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.4637</td>
<td>0.4056</td>
<td>0.6563</td>
</tr>
<tr>
<td>5</td>
<td>0.5318</td>
<td>0.3984</td>
<td>0.9208</td>
</tr>
<tr>
<td>6</td>
<td>0.7597</td>
<td>0.3766</td>
<td>0.5398</td>
</tr>
<tr>
<td>7</td>
<td>0.5233</td>
<td>0.4282</td>
<td>0.5329</td>
</tr>
<tr>
<td>8</td>
<td>0.7912</td>
<td>0.3400</td>
<td>0.3713</td>
</tr>
<tr>
<td>9</td>
<td>1.0000</td>
<td>0.3333</td>
<td>0.3333</td>
</tr>
</tbody>
</table>

**Table 6—Response table for grey relational grade (GRG)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Machining parameters</th>
<th>GRG</th>
<th>Main effect (max-min)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Pulse-on time</td>
<td>0.7235(^*)</td>
<td>0.5614</td>
<td>0.5171</td>
</tr>
<tr>
<td>B</td>
<td>Discharge current</td>
<td>0.5693</td>
<td>0.5991</td>
<td>0.6336(^*)</td>
</tr>
<tr>
<td>C</td>
<td>Gap voltage</td>
<td>0.6257(^*)</td>
<td>0.5776</td>
<td>0.5986</td>
</tr>
</tbody>
</table>

\(^*\)Levels for optimum GRG

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**Fig. 1—Effect of micro EDM parameters on multi-performance characteristics**

**Fig. 2—Contributions (%) of factors on grey relational grade (GRG)**

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parameters are found as pulse-on time at level 1, discharge current at level 3, and gap voltage at level 1. Pulse-on time is the most significant factor (Figs 1 & 2) that affects GRG. Metal removal is directly proportional to the amount of energy applied during pulse-on time. Energy applied during on-time controls peak amperage and length of pulse-on time. Pulse duration and pulse-off is called pulse interval. If pulse duration is longer, then more workpiece material will be melted away. Then, it will have a broader and deeper hole than using shorter pulse duration. Even though hole has rough surface finish, extended pulse duration will allow more heat sink into workpiece and hence recast layer will be larger and heat affected zone will be deeper (Fig. 3).

**Confirmation Test**

Confirmation test has been carried out to verify the improvement of performance characteristics in micro hole drilling of 304 stainless steel using micro-EDM. Optimum parameters are selected for confirmation test (Table 8). Estimated GRG $\hat{\gamma}_i$ using optimal level of machining parameters can be calculated as

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\gamma_i - \gamma_m)$$  \(\ldots(6)\)

where $\gamma_m$ is total mean of GRG, $\gamma_i$ is mean of GRG at optimal level, and q is number of machining parameters that significantly affect multiple-performance characteristics.

Using Eq. (6), predicted MRR, TWR, OC and GRG for optimal machining parameters are obtained (Table 8), which shows comparison of experimental results using initial (OA, A,B,C) and optimal (grey theory prediction design, A,B,C) machining parameters. MRR is accelerated from 15.0381 to 17.2614 mg/min, TWR is
decreased from 15.9469 to 14.6241 mg/min and OC also decreased from 118 to 115.8 μm. Corresponding improvement in MRR is 12.88%, TWR 14.57% and OC 6.1% respectively. It is clearly shown that multiple performance characteristics in micro-EDM process are greatly improved through this study.

Conclusions

GRA based on Taguchi method’s response table has successfully evaluated feasibility of micro hole drilling in EDM of 304 stainless steel. Optimal machining parameters have been determined by GRG for multiperformance characteristics (MRR, TWR and OC). From response table of average GRG, following largest value of GRG was found for: pulse-on time, 100 μs; discharge current, 4 A; and gap voltage, 20 V. These are the recommended levels of controllable process factors when better MRR, lesser TWR and OC are simultaneously obtained. ANOVA of GRG for multiperformance characteristics revealed that pulse-on time is the most significant parameter. Based on SEM picture, it is observed that when pulse-on time increases, MRR and OC increases. Based on confirmation test, improvement in performance characteristics were found as follow: MRR, 12.88; TWR, 14.57; and OC, 6.1%. Thus performance characteristics of micro-EDM process (MRR, TWR and OC) are simultaneously improved together by using GRA.

References