Optimization of process parameters on machining rate and overcut in electrochemical micromachining using grey relational analysis

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This paper investigates the effect and parametric optimization of process parameters for Electrochemical micromachining (EMM) of 304 stainless steel using grey relation analysis. Experiments were conducted using machining voltage, pulse on-time, electrolyte concentration and tool tip shapes as typical process parameters. The grey relational analysis was adopted to obtain grey relational grade for EMM process with multiple characteristics namely machining rate and overcut. Analysis of variance was performed to get the contribution of each parameter on the performance characteristics and it was observed that electrolyte concentration and tool tip shape were the most significant process parameters that affect the EMM robustness. The experimental results reveal that, the conical with rounded electrode, machining voltage of 9V, pulse on-time of 15ms and electrolyte concentration of 0.35mole/l is the optimum combination for higher machining rate and lesser overcut. The experimental results for the optimal setting show that there is considerable improvement in the process.

Keywords: Grey relational grade, Electrochemical micromachining, Tool tip shape, Machining rate, Overcut

Introduction

Micromachining technology finds many applications in aerospace, bio-technology, electronics, optics, biomedicine and mechanical engineering. To meet these requirements various micro manufacturing methods have been developed. Among the various methods, electrochemical micromachining (EMM) appears to be a potential micromachining technology for advantages such as no tool wear, good surface finish, and no heat affected layer. EMM is a process of removing material similar to electroplating. The workpiece is dissolved according to Faradays laws of electrolysis. In this process, the workpiece to be machined is made as anode and the tool is made as cathode of an electrolytic cell with a salt solution being used as an electrolyte. On the application of a potential difference between the two electrodes with availability of adequate electrical energy between the tool and the workpiece, the positive metal ions leave the workpiece.

EMM process is a complex process and it is very difficult to determine the optimal machining parameters for improving the output quality. The optimization of process parameters is vital for the achievement of higher productivity, which is the preliminary basis for survival in today’s dynamic market conditions. Optimal quality of the workpiece in EMM can be generated through combinational control of various process parameters. To select the appropriate process parameters, several researchers developed mathematical models based on statistical regression techniques to establish the relationship between the machining performance and the machining parameters. Particle swarm optimization algorithm has been used to optimize electrochemical machining parameters like tool feed rate, electrolyte flow velocity and the applied voltage in order to improve dimensional accuracy, material removal rate and machining cost. Multi-objective optimization of current, voltage, feed rate and gap was done for improving material removal rate and surface roughness using multiple regression models and artificial neural networks. Senthilkumar et al have developed mathematical model
based on RSM approach for correlating the material removal rate and surface roughness with predominant process parameters. Munda et al established a comprehensive mathematical model using pulse on/off ratio, machining voltage, electrolyte concentration, voltage frequency and tool vibration frequency on the material removal rate and the radial overcut through response surface methodology (RSM).

Although, researchers have optimized the process, there is no systematic study reported considering the tool tip shape as a one of the control factors. In EMM, the dissolution rate of the workpiece decreases as the machining depth increases due to the difficulty of maintaining the flow of electrolyte deep inside the micro hole. In addition to this, bubbles confined in the machining gap interfere with electrolyte diffusion. Since inadequate diffusion of electrolyte changes the machining conditions, the machining rate decreases significantly with increasing depth. Researchers worldwide are developing innovative methods to overcome the problem of electrolyte diffusion. In this study conical with rounded and truncated cone tip shapes with same geometric specification are considered. The process parameters such as machining voltage, pulse on-time, electrolyte concentration and tool tip shape are optimized considering the multiple characteristics machining rate and overcut by using Grey Relation Analysis (GRA).

Selection of Control Factors

The experimental factors were selected based on the above literature review includes factors possibly affecting the machining rate and overcut in general. Like in the reviewed literature, this study included pulse on-time, machining voltage and electrolyte concentration as a control factors. Tooling information such as tool tip shape and tool electrode diameter is also important. Hence, the influence of the pulse-on time, machining voltage and electrolyte concentration on the machining rate and overcut for the different tool electrode tip shapes like flat tip, conical with rounded tip, truncated cone tip and wedged electrode tip have been investigated experimentally. Based on the studies conducted, the machining rate and overcut are significantly influenced by the tool electrode tip shapes. The flat tip gives lower machining rate due to insufficient flow of electrolyte and higher overcut due to the stray current at the sharp edges. The truncated cone tip electrode produces the highest machining rate compared to the flat-tip electrode. The conical with rounded tip electrode produces holes that had lesser overcut when compared with flat tip electrode. Wedged electrode produces elliptical hole for same machining conditions compared with other three tip shapes. The wedged side supplies sufficient amount of electrolyte solution and other side it restricts the flow, resulting in improper machining. Therefore, from this four tip shapes, conical with rounded and truncated cone tip shapes with same geometric specification are considered for the study.

Experimental Procedure

The EMM set-up used for conducting the studies is shown (Fig. 1). The set-up basically consists of various elements, such as mechanical machining unit, tool electrode feeding system, inter-electrode gap control system, electrolyte supply system and pulsed power supply system. The tool electrode feed mechanism, with
resolution of 2 µm along Z-axis is designed with stepper motor and 8051 microcontroller. The set-up maintains the initial set gap (40 µm) constantly throughout the machining by providing appropriate control signals to the stepper motor with the help of microcontroller unit. The 304 stainless steel of 200 µm thickness is used as a workpiece. In the case of stainless steel, its mechanical strength and chemical resistance can be controlled by adjusting the alloys composition. Because of strong resistance to corrosion, it is largely employed for production medical equipment. The basic tool electrode is made up of stainless steel of Φ 452 µm and the tip shapes were shown (Fig. 2). The side walls of the tool electrode are coated with a bonding liquid. The tool electrode is made as a cathode and workpiece is made as anode. The workpiece is placed in sodium nitrate (NaNO₃) electrolyte. (Table 1) shows the machining parameters and their levels used for the experiments. The experiments were conducted at 50 Hz frequency and a machining current of 0.8 A. The machining performance is evaluated in terms of machining rate and overcut. Machining rate is defined as amount of material removed (in thickness direction) per unit machining time. Overcut (radial overcut) of the machined micro-hole has been considered as machining accuracy criteria. It is the difference between the radius of the machined hole and the radius of the tool electrode. The micro-hole diameter is measured with the help of an optical microscope. Machining time is noted for each experiment. In EMM, higher machining rate and lower overcut are desired.

Orthogonal array selection
The orthogonal array is selected based on the degrees of freedom (DOF). In this study, an L₁₈ mixed orthogonal array is used. The experimental combinations of the machining parameters using the L₁₈ orthogonal array are presented (Table 2). Each of the experiments has been conducted twice. Machining rate and overcut are the two responses considered in this study. In EMM, higher machining rate and lower overcut are desired. Therefore, the machining rate is the higher-the-better performance characteristic and the overcut is the lower-the-better performance characteristics.

Grey Relational Analysis
In this section, the use of the orthogonal array with the grey relational analysis for determining the optimal machining parameters is reported step by step. Optimal machining parameters with considerations of the multiple performance characteristics are obtained and verified.
Data preprocessing

Grey data processing must be performed before Grey correlation coefficients are calculated. A series of various units must be transformed to be dimensionless. In order to find grey relational grade usually, each series is normalized by dividing the data in the original series by their average. Let the original reference sequence and sequence for comparison be represented as \( x_i^0(k) \) and \( x_i^1(k) \), \( i=1, 2, \ldots , m; k=1, 2, \ldots , n \), respectively, where \( m \) is the total number of experiments to be considered, and \( n \) is the total number of observed data. Data preprocessing converts the original sequence to a comparable sequence. Several methodologies of preprocessing data can be used in GRA, depending on the characteristics of the original sequence\(^{19} \). If the target value of the original sequence is “the-larger-the-better”, then the original sequence is normalized as follows

\[
x_i^+(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)}
\]  

(1)

If the purpose is “the-smaller-the-better”, then the original sequence is normalized as follows

\[
x_i^-(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}
\]  

(2)

Grey relational coefficients and Grey relational grades

Following the data preprocessing, a Grey relational coefficient can be calculated using the preprocessed sequences. The Grey relational coefficient is defined as follows.

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

(3)

Where \( \Delta_{0i}(k) \) is the deviation sequence of the reference sequence \( x_i^0(k) \) and the comparability sequence is \( x_i^+(k) \). \( \xi \) is the distinguishing coefficient, \( \xi \in [0,1] \). A Grey relational grade is a weighed sum of the Grey relational coefficients, and is defined as follows.

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

(4)

Here, the Grey relational grade \( \gamma_i \) represents the level of correlation between the reference and comparability sequences.

Results and Discussion

The experimental results for the machining rate, and overcut are listed (Table 2). Basically, the machining rate belongs to the “larger-the-better” methodology that is Eq. (1) which is employed for data preprocessing whereas smaller value of the overcut are desirable and hence it belongs to “smaller-the-better” methodology, that is Eq. (2) which is employed for data preprocessing. The values of the machining rate, and overcut are set to be the reference sequence \( x_i^0(k) \), \( k = 1–4 \). Moreover, the results of eighteen experiments are the comparability sequences \( x_i(k) \), \( i=1, 2, \ldots , 18; k = 1–4 \). (Table 3) lists all of the sequences after implementing the data preprocessing using Eqs. (1) and (2). The reference and the comparability sequences are denoted as and respectively. Also, the deviation sequences \( \Delta_{0i}(k) \), \( \Delta_{\max}(k) \) and \( \Delta_{\min}(k) \) for \( i = 1–18; k = 1–4 \) can be calculated. The distinguishing coefficient \( \xi \) can be substituted for the Grey relational coefficient in Eq. (3). If all the process parameters have equal weightage, \( \xi \) is set to be 0.5. The Grey relational grade is calculated based on the Eq. (4). (Table 4) lists the Grey relational coefficients and the grade for all eighteen comparability sequences. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Experiment 4 has the best

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Machining Rate (µm/sec)</th>
<th>Overcut (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000</td>
<td>0.2548</td>
</tr>
<tr>
<td>2</td>
<td>0.0874</td>
<td>0.6616</td>
</tr>
<tr>
<td>3</td>
<td>0.1760</td>
<td>0.8783</td>
</tr>
<tr>
<td>4</td>
<td>0.2506</td>
<td>0.9924</td>
</tr>
<tr>
<td>5</td>
<td>0.1457</td>
<td>0.4753</td>
</tr>
<tr>
<td>6</td>
<td>0.1352</td>
<td>0.9125</td>
</tr>
<tr>
<td>7</td>
<td>0.0967</td>
<td>0.4487</td>
</tr>
<tr>
<td>8</td>
<td>0.1678</td>
<td>0.9582</td>
</tr>
<tr>
<td>9</td>
<td>0.1865</td>
<td>0.9810</td>
</tr>
<tr>
<td>10</td>
<td>0.3345</td>
<td>0.7376</td>
</tr>
<tr>
<td>11</td>
<td>0.2075</td>
<td>0.2243</td>
</tr>
<tr>
<td>12</td>
<td>1.0000</td>
<td>0.1293</td>
</tr>
<tr>
<td>13</td>
<td>0.1212</td>
<td>0.9125</td>
</tr>
<tr>
<td>14</td>
<td>0.1900</td>
<td>0.1000</td>
</tr>
<tr>
<td>15</td>
<td>0.1294</td>
<td>0.0038</td>
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<tr>
<td>16</td>
<td>0.1434</td>
<td>0.8365</td>
</tr>
<tr>
<td>17</td>
<td>0.1329</td>
<td>0.0837</td>
</tr>
<tr>
<td>18</td>
<td>0.7145</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
multiple-performance characteristics among eighteen experiments because it has the highest grey relational grade as shown (Table 4).

This investigation employs the response table of the Taguchi method to calculate the average Grey relational grades for each factor level, as illustrated (Table 5). Since the Grey relational grades represent the level of correlation between the reference and the comparability sequences, the larger grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence.

Based on this study, a combination of the levels can be selected so that it can provide the largest average response. In (Table 5), the combination of A1, B2, C3, and D3 shows the largest value of the Grey relational grade for the factors A, B, C, and D, respectively. Therefore, it is observed that the conical with rounded electrode, machining voltage of 9V, pulse on-time of 15ms, and electrolyte concentration of 0.35mole/l is the optimal parameter combination of the EMM operations. Based on the optimum condition, the conical with rounded electrode aids to remove the debris near the machining zone resulting in higher machining rate and lesser overcut. At higher pulse on time (15ms) and electrolyte concentration (0.35mole/l) the proper flushing of debris eliminates the micro sparks and improves the machining rate and overcut. (Fig. 3) shows the Grey relational grade graph and the total mean of the Grey relational grade are indicated in line.

**Analysis of Variance (ANOVA)**

The grey relational grades obtained from the experimental values are statistically studied by ANOVA to inspect the effects of each machining parameter on the observed values and to clarify which machining parameters significantly affects the observed values. In addition, the F-test has been used to determine which process parameters have a significant effect on the performance characteristic. (Table 6) shows the calculated F-values for machining rate and overcut respectively to determine the relative significances of different control factors. The results of the F-test clearly indicate that the electrolyte concentration and tool tip
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shape have statistically significant effect on machining rate and overcut at the 95% confidence level. This could be attributed to the fact that increases in electrolyte concentration, increases the number of ions associated in the machining process. This increase in number of ions increases the current density between the tool electrode and the work piece. Additionally, the shape of tool electrode provides proper supply of electrolyte solution to the work piece surfaces during EMM. According to faradays law of electrolysis, the metal removal rate depends on current density distributed on the work piece surface during EMM. The current density distribution under the bottom and along the sidewall of the tool electrode is based on the tool tip shape and electrolyte conductivity. Therefore, the tool tip shape and the electrolyte concentration are found to be the significant factor that influences the machining rate and overcut. Percentage contribution (%C) indicates the relative power of a factor to reduce variation. For a factor with a higher percent contribution, a small variation will have a great influence on the performance. The percent contribution of the machining parameters on the machining rate and overcut shown (Table 6), reveals that electrolyte concentration and pulse on-time have the maximum influence on machining rate and overcut.

Confirmation Test

Confirmation test has been carried out to verify the improvement of performance characteristics while EMM of 304 stainless steel. Optimum parameters are selected for the confirmation test as given (Table 5). The estimated grey relational grade using the optimal level of the machining parameters can be calculated as

\[
\eta = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m)
\]  

Fig. 4 — Optical microscope picture of machined micro hole with conical rounded electrode at : a) 8V/7.5ms/0.23 mole/l; and b) 9V/15ms/0.35 mole/l.

Where \( \eta_m \) is the total mean of the grey relational grade, \( q \) is the number of significant parameters, \( \eta_i \) is the mean of the grey relational grade at the optimal level. The obtained process parameters, which give higher grade relational grade, are presented (Table 7). The predicted machining rate, overcut and grey relational grade for the optimal machining parameters are obtained using the Eq. (7) and also presented in (Table 7). Table 7 also shows the comparison of experimentally obtained machining rate and overcut (trial 1 of the OA) and experimentally obtained machining rate and overcut at optimum EMM process parameters. It can be seen that the overall performance of EMM process has been improved. Though the improvement in overcut is not significant, machining rate has been significantly improved from 0.0865 to 0.1445. Fig. 4 a & b shows the optical microscope picture of the machined micro hole with conical rounded electrode at 8V/7.5ms/0.23 mole/l and 9V/15ms/0.35 mole/l. It is evident from the Fig. 4a, that overcut is found to be lesser compared to the Fig. 4b.

Conclusions

The paper presented the optimization of the electrochemical machining of 304 stainless steel by the grey relational analysis. Based on the conducted experiments, the following conclusions are made:

1. The optimal tool tip shape and parametric combination for higher machining rate and lesser overcut were found to be conical with rounded tip, machining voltage at 9V, pulse on-time at 15ms and electrolyte concentration at 0.35mole/l.

2. The ANOVA of grey relational grade for multiple performance characteristics revealed that the electrolyte
concentration and tool tip shape are the most significant parameters.

3. It is clear from the above study that optimization of the complicated multiple performance characteristics can be greatly simplified through Taguchi and grey relational analysis approach. It is shown that the performance characteristics of the EMM process such as machining rate is improved by using the method proposed by this study. The effectiveness of this approach has been successfully established by confirmation test. Confirmation test result proves that there is a remarkable improvement in the GRA value from 0.3674 to 0.6087, when machining is done with the optimal parametric combination.

References