CHAPTER 4

EXPERIMENTS AND METHODS

In this chapter, the selection of input process parameters, performance measures of EDM process, process variables, measurement of EDM response parameters and surface characterization techniques of the machined surface are discussed. The procedure for multi response optimization of electrical process parameters of EDM process is also presented in this chapter.

4.1 DIE-SINKING EDM ARRANGEMENT

In the present study, the experiments have been conducted in the die-sinking EDM arrangement. Figure 4.1 shows the arrangement of die sinking EDM.

Figure 4.1 Die-sinking EDM arrangement
The workpiece has been inserted in the worktable which has been filled with dielectric medium. The position of work table has been adjusted using conventional hand wheel sliding mechanism. The tool electrode has been fitted in the tool holder which has been connected with the servo motor and encoder arrangement through the lead screw to obtain fine movement. The pulse generator has been connected across the tool and the workpiece to produce the DC pulses for controlling electrical energy flow. The flushing arrangement has been provided to produce proper deionization of insulating medium between tool and electrode. It has been also used to flush out the melted particles from the spark gap. The contaminated dielectric oil has been filtered using the filter arrangement and it has been circulated again for further machining process. The value of the flushing pressure can be controlled by adjusting the flushing knob.

4.2 SELECTION OF WORKPIECE AND TOOL ELECTRODES

Steel with sufficient chromium for avoiding corrosion is known as the stainless steel, which is being utilized in a variety of applications such as chemical, automobiles, power engineering, railway rolling stocks and home appliances. In the present study, AISI 202 stainless steel has been selected as the workpiece. In this type of austenitic steel, manganese and Nitrogen are added to lower nickel content for higher strength. The chemical composition of AISI 202 stainless steel is shown in Table 4.1.

The selection of tool electrode plays an important role in EDM process. In this study, three different tool electrodes such as Copper, Brass and Tungsten carbide have been selected with diameter of 4mm to analyze their influence on performance measures such as material removal rate, surface roughness and electrode wear rate in EDM process. The tool electrodes have diverse physical properties such as electrical conductivity and melting point. The properties of tool electrodes are shown in Table 4.2.
Table 4.1 Chemical composition of AISI 202 stainless steel

<table>
<thead>
<tr>
<th>Elements</th>
<th>Percentage Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon(C)</td>
<td>0.05</td>
</tr>
<tr>
<td>Silicon(Si)</td>
<td>0.35</td>
</tr>
<tr>
<td>Copper(Cu)</td>
<td>1.93</td>
</tr>
<tr>
<td>Manganese(Mn)</td>
<td>8.76</td>
</tr>
<tr>
<td>Phosphorus(P)</td>
<td>0.03</td>
</tr>
<tr>
<td>Sulphur(S)</td>
<td>0.011</td>
</tr>
<tr>
<td>Molybdenum(Mo)</td>
<td>0.22</td>
</tr>
<tr>
<td>Chromium(Cr)</td>
<td>16.04</td>
</tr>
<tr>
<td>Tin(Sn)</td>
<td>0.09</td>
</tr>
<tr>
<td>Nickel(Ni)</td>
<td>1.56</td>
</tr>
<tr>
<td>Tungsten(W)</td>
<td>0.17</td>
</tr>
<tr>
<td>Aluminium(Al)</td>
<td>0.07</td>
</tr>
<tr>
<td>Titanium(Ti)</td>
<td>0.011</td>
</tr>
<tr>
<td>Iron(Fe)</td>
<td>Remaining</td>
</tr>
</tbody>
</table>

Table 4.2 Physical properties of tool electrodes

<table>
<thead>
<tr>
<th>Tool Electrode</th>
<th>Electrical conductivity (S/m)</th>
<th>Melting point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>$5.96 \times 10^7$</td>
<td>1085</td>
</tr>
<tr>
<td>Brass</td>
<td>$1.67 \times 10^7$</td>
<td>930</td>
</tr>
<tr>
<td>Tungsten carbide</td>
<td>$6.37 \times 10^6$</td>
<td>2870</td>
</tr>
</tbody>
</table>

Figure 4.2 shows the different tool electrodes such as Copper, Brass and Tungsten carbide used for machining the workpiece in the EDM process [38].
4.3 SELECTION OF INPUT PROCESS PARAMETERS

The performance measures in the EDM process are influenced by the applied electrical energy which is a function of applied voltage, peak current and pulse duration (Mohan et al., 2004). Owing to the importance of the electrical process parameters in the EDM process, open circuit voltage($V_o$), peak current ($I_p$) and duty factor (DF) have been selected as the input process parameters for the present study.

Open circuit voltage is defined as the potential difference across the workpiece and the tool electrode in the machining process and it is measured in volts (V). Peak current is defined as the maximum current value attained in a pulse cycle and it is measured as ampere (A). Duty factor is the ratio of pulse on time to the total pulse duration as per the following Equation 4.1.

$$\text{Duty factor} = \frac{\text{Pulse on time}}{\text{Pulse on time} + \text{Pulse off time}}$$  \hspace{1cm} (4.1)
4.4 SELECTION OF PERFORMANCE MEASURES

The selection and measuring techniques of performance measures in EDM process are explained in this section. Since the performance measures such as material removal rate (MRR), surface roughness (R_a) and electrode wear rate (EWR) influence the process efficiency, these parameters have been taken as the performance measures in the present study.

4.4.1 Material Removal Rate (MRR)

It is the rate at which the material gets removed from the workpiece. It is normally represented in mm^3/min and which is measured by the volume difference of the workpiece before and after the machining process in EDM. The weight of workpiece has been measured using Uni-Blog high precision 0.1mg resolution digital weighing machine which is shown in Figure 4.3.

\[
\text{MRR} = \frac{(W_b - W_a) \times 1000}{\rho_w T}
\]  

(4.2)

\(W_b\) is the weight of the workpiece before the machining process (gram); \(W_a\) is the weight of the workpiece after the machining process (gram); \(\rho_w\) is the density of workpiece (g/cm^3) and \(T\) is the machining time (min).

Figure 4.3 High precision digital weighing machine
4.4.2 Electrode Wear Rate (EWR)

It is the rate at which the material gets removed from the tool electrode. It is normally represented in mm³/min and which is measured by the volume difference of tool electrode before and after the machining process in EDM.

\[
\text{EWR} = \frac{(T_b - T_a) \times 1000}{\rho_T T}
\]  

(4.3)

\(T_b\) is the weight of the tool electrode before the machining process (gram); \(T_a\) is the weight of the tool electrode after the machining process (gram); \(\rho_T\) is the density of tool electrode (g/cm³) and \(T\) is the machining time (min). The densities of the workpiece and the tool electrodes are shown in Table 4.3.

Table 4.3 Density of workpiece and tool electrodes

<table>
<thead>
<tr>
<th>Property</th>
<th>Workpiece</th>
<th>Tool electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AISI 202 stainless steel</td>
<td>Copper</td>
</tr>
<tr>
<td>Density(g/cm³)</td>
<td>7.8</td>
<td>8.94</td>
</tr>
</tbody>
</table>

4.4.3 Surface Roughness (\(R_a\))

The surface quality of the EDM product can well be evaluated by the average surface roughness (\(R_a\)) and it is normally expressed in μm (Kumar and Batra, 2012). On any machined surface, the imperfections are found in the form of a succession of hills and valleys which vary both in height and in spacing. The characteristics of the machining process can be accessed through these imperfections. Surface roughness is described by
The arithmetic mean value and which is based on the average length between peaks and valleys, and the deviation from mean line on the entire surface within the sampling length as per the centre line average roughness method. The surface roughness can be computed based on this method as per following Equation 4.4.

\[ R_a = \frac{1}{n} \int_0^l |y| \, dx \]  

(4.4)

where \( l \) is the cutoff length, \( n \) is the number of deviations in the cutoff length and \( y \) is the height of peak or valley (Jain, 2008)

![Surface profile of the workpiece](image)

Figure 4.4 Surface profile of the workpiece

The schematic surface profile of machined workpiece is shown in Figure 4.4. In the present study, the average surface roughness (\( R_a \)) has been computed using SE1200 Kasaka lab surfcoder surface roughness tester which is shown in Figure 4.5. The cutoff length has been taken as 0.8mm whereas the evaluation length has been chosen as 2.4mm.
4.5 SELECTION OF PROCESS VARIABLES

Open circuit voltage ($V_o$), peak current ($I_p$) and duty factor (DF) have been selected as the input variables, due to the significance of electrical process parameters. The blind hole drilling has been carried out for a depth of 5mm on workpiece AISI 202 stainless steel using EDM process. The experiments have been conducted with RC pulse generator, developed transistor pulse generator and modified iso energy pulse generator to analyze the effect of pulses on performance measures such as MRR, $R_a$ and EWR in the EDM process. Copper, Brass and Tungsten carbide have been chosen as the tool electrode to evaluate the influence of tool electrode properties on performance measures in EDM process. EDM oil has been used as dielectric medium whereas the flushing pressure has been fixed at 2 bar. Since the experiments have to be conducted in smaller, medium and larger level rating of electrical energy, open circuit voltage has been selected as 40V, 60V and 80V with duty factor of 0.4, 0.6 and 0.8. The peak current has been chosen as 9A, 12A and 15A. The consolidated selection of process variables for this study is shown in Table 4.4.
4.6 DESIGN OF EXPERIMENTS

The selection of orthogonal array (OA) is the important factor while designing the experiments using Taguchi method which has been used to conduct experiments in the present study. The orthogonal array should be greater than the degree of freedom (DOF) of the experiments. It can be computed based on following Equation 4.5 (Krishnaiah and shahabudeen, 2012).

\[
\text{DOF} = F(P - 1) + Q(P - 1)^2 + 1 \text{ for the average} \quad (4.5)
\]

where P is the number of levels; F is the number of input factors and Q is the number of interactions. Normally L_9, L_{18} and L_{27} orthogonal array are used for three levels factors. As the present study involves the three input factors with three interactions between them, L_{27} orthogonal array has been selected for conducting experiments in EDM process. Since all the three input process parameters are related to the electrical energy, three interactions between
them have been assumed. Table 4.5 shows the $L_{27}$ orthogonal array design of experiments in the present study.

### Table 4.5 $L_{27}$ orthogonal array based design of experiments

<table>
<thead>
<tr>
<th>Trial number</th>
<th>Open circuit voltage (V)</th>
<th>Peak current (A)</th>
<th>Duty factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>9</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>9</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>12</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>12</td>
<td>0.8</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>9</td>
<td>0.6</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>9</td>
<td>0.8</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
<td>12</td>
<td>0.4</td>
</tr>
<tr>
<td>14</td>
<td>60</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
<td>12</td>
<td>0.8</td>
</tr>
<tr>
<td>16</td>
<td>60</td>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>17</td>
<td>60</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>19</td>
<td>80</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>9</td>
<td>0.6</td>
</tr>
<tr>
<td>21</td>
<td>80</td>
<td>9</td>
<td>0.8</td>
</tr>
<tr>
<td>22</td>
<td>80</td>
<td>12</td>
<td>0.4</td>
</tr>
<tr>
<td>23</td>
<td>80</td>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>24</td>
<td>80</td>
<td>12</td>
<td>0.8</td>
</tr>
<tr>
<td>25</td>
<td>80</td>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>26</td>
<td>80</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>27</td>
<td>80</td>
<td>15</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Figure 4.6 explains the design of experiments for machining the workpiece using the EDM process with different pulse generators and tool electrodes. It is clear that the experiments have to be conducted with 9 various combinations of pulse generators and tool electrodes under L27 OA approach.

Totally 243 experiments had to be done using die sinking EDM process to analyze the influence of discharge current pulse and tool properties on performance measures in such process.

![Figure 4.6 Design of experiments](image)

### 4.7 SURFACE TOPOGRAPHY ANALYSIS

The surface topography of machined surface using EDM process has helped to analyze the influence of different pulse generators on surface roughness and arcing effect in the present study. The three dimensional views of machined surface by EDM process with conventional and modified pulse generators have been acquired using keyence VHX 2000 microscope which is shown in Figure 4.7. The two dimensional views of the machined surface have been obtained using Scanning Electron Microscope (SEM S-3400N) and
vision measurement system (SIPCON SVI107) which are shown in Figure 4.8 and Figure 4.9 respectively.

Figure 4.7 keyence VHX 2000 microscope

Figure 4.8 Scanning Electron Microscope (SEM S-3400N)
4.8 MULTI RESPONSE OPTIMIZATION OF PROCESS PARAMETERS

The need for multi response optimization, the procedure and the execution involved in Taguchi method with Grey relational analysis are explained in this section.

4.8.1 Need for Multi Response Optimization

Taguchi method deals with only single response optimization problems. Since many responses are involved in electrical discharge machining, Taguchi method alone does not help to obtain optimal process parameters in such process. In the current work, an endeavor has been made
to derive optimal combination of electrical process parameters in thermal erosion process using Grey relational analysis with Taguchi method. The Grey relational analysis is used to convert the multi responses of any process into the single response and then obtain the optimal levels of such process (Noorul Haq et al., 2008). Figure 4.10 shows the procedure of the Taguchi – Grey relational analysis based multi response optimization method. Tool electrode has also been taken as an input parameter in addition to the input process parameters such as open circuit voltage, peak current and duty factor to analyze the influence of tool electrode electrical conductivity on the performance measures such as material removal rate, surface roughness and electrode wear rate.

![Figure 4.10 Procedure of Taguchi- Grey relational analysis](image-url)
4.8.2 Taguchi Method

The calculation of signal to noise (S/N) ratio based on the quality characteristics is the important one in the Taguchi method. Since the MRR has to be maximized, it has been chosen as the ‘larger the better’ type of quality characteristics. Hence the S/N ratio for this response has been computed from the following Equation 4.6.

\[
\frac{S}{N} \text{ ratio} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{ij}} \right)
\]  

(4.6)

Surface roughness and EWR have been taken as the ‘smaller the better’ type and their S/N ratios have been computed from the following equation.

\[
\frac{S}{N} \text{ ratio} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_{ij}^{2} \right)
\]  

(4.7)

where \( n \) is number of experimental replication and \( y_{ij} \) is response of \( i^{th} \) trial of \( j^{th} \) dependent level. The response data has to be transformed into the S/N ratio and analyzed using ANOVA and optimal levels for the factors can be determined.

4.8.3 Steps Involved in Grey Relational Analysis

Grey relational technique is used for solving interrelationships among the multiple responses and to convert into the single Grey scale response. This analysis consists of the following steps (Krishnaiah and shahabudeen, 2012).
Step 1: Transform the original response data into S/N ratio ($Y_{ij}$) using the appropriate formulae depending on the type of quality characteristics.

Step 2: Normalize the S/N ratio to distribute the data evenly and scale it into acceptable range for further analysis by following equations.

For larger the better case,

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij}, i = 1, 2, ..., n)}{\max(Y_{ij}, i = 1, 2, ..., n) - \min(Y_{ij}, i = 1, 2, ..., n)}$$  \hspace{1cm} (4.8)

For smaller the better case,

$$Z_{ij} = \frac{\max(Y_{ij}, i = 1, 2, ..., n) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, ..., n) - \min(Y_{ij}, i = 1, 2, ..., n)}$$  \hspace{1cm} (4.9)

where $Z_{ij}$ is the normalized value for $i$th experimental for $j$th dependant variable/response and $n$ is the number of experimental replication.

Step 3: Compute the Grey relational coefficient (GC) for the normalized S/N ratio values

$$GC_{ij} = \frac{\Delta_{min} + \lambda \Delta_{max}}{\Delta_{ij} + \lambda \Delta_{max}}$$  \hspace{1cm} (4.10)

where,

$GC_{ij}$ = Grey relational coefficient for the $i$th experiment and $j$th response;
\Delta = \text{Absolute difference between } Y_{oj} \text{ and } Y_{ij} \text{ which is a deviation from target value and can be treated as quality loss;}

Y_{oj} = \text{ideal normalized value of } j\text{th response;}

Y_{ij} = \text{the } i\text{th normalized value of the } j\text{th response;}

\Delta_{\text{min}} = \text{minimum value of } \Delta;

\Delta_{\text{max}} = \text{maximum value of } \Delta;

\lambda = \text{distinguishing coefficient which is in the range between 0 and 1. The value may be adjusted based on the system needs. Since the present study involves larger the better and smaller the better types of quality characteristics, the value of distinguishing coefficient has been selected as 0.5 in the present study (Siddhi jailani et al., 2010).}

Step 4: Compute the Grey relational grade \(G_i\).

\[
G_i = \frac{1}{m} \sum G_{C_{ij}} \tag{4.11}
\]

where \(m\) is the number of process responses taken into account.

Step 5: Use the response graph method or ANOVA method to select the optimal levels for the factors based on maximum average \(G_i\) value. The most significant process parameter in any process can be identified using the highest difference between maximum and minimum average Grey relational grade of all process parameter levels.
4.8.4 Procedure for ANOVA Technique

Analysis of variance (ANOVA) technique is derived from the partitioning of total variability into its component parts. It is used to compute the contribution of each input factor on response parameter (Krishnaiah and shahabudeen, 2012).

Step 1: Compute the correction factor (CF)

\[
CF = \frac{\text{Grand total of all observations}}{\text{Total number of observations}}
\]  

(4.12)

Step 2: The total corrected Sum of Squares (SS) is used as a measure of overall variability in the data. It is partitioned into two components.

\[
SS_{\text{Total}} = SS_T + SS_e
\]  

(4.13)

where \(SS_{\text{Total}}\) is the total variation; \(SS_T\) is the variation between treatments and \(SS_e\) is the variation due to error

\[
SS_{\text{Total}} = \sum_{i=1}^{a} \sum_{j=1}^{n} Y_{ij}^2 - CF
\]  

(4.14)

\[
SS_T = \sum_{i=1}^{a} \frac{T_i^2}{n} - CF
\]  

(4.15)

where \(Y_{ij}\) is the j-th observation of the i-th treatment/ level; \(n\) is the number of replication and \(a\) is the number of factors \(T_i\) is the i-th treatment total.

\[
SS_e = SS_{\text{Total}} - SS_T
\]  

(4.16)
Step 3: Computation of variance and $F_o$. Table 4.6 shows the calculation procedure for each factor.

**Table 4.6 ANOVA: Single factor experiment**

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>$F_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between treatments</td>
<td>$SS_T$</td>
<td>$a-1$</td>
<td>$MS_T = \frac{SS_T}{a-1}$</td>
<td>$\frac{MS_I}{MS_e}$</td>
</tr>
<tr>
<td>Within treatments</td>
<td>$SS_e$</td>
<td>$N-a$</td>
<td>$MS_e = \frac{SS_e}{N-a}$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$SS_{Total}$</td>
<td>$N-1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean square is also called variance. The level of significance value has been taken as 5% (Siddhi jailani et al. 2009). The higher value of $F_o$ of the input factor denotes more contribution on response parameters.

**4.9 MACHINING OF WORKPIECE UNDER VARIOUS PROCESS PARAMETERS**

The experiments have been performed on the workpiece AISI 202 stainless steel with various pulse generators such as RC pulse generator, Transistor pulse generator and modified iso energy pulse generator using EDM process under various process variables levels. Copper, Brass and Tungsten carbide have been utilized as the tool electrodes for machining the workpiece to analyze the influence of tool electrode properties on performance measures.
Figure 4.11 shows the machined specimens using EDM process under various machining conditions.

Figure 4.11  Machined specimens using EDM process under various machining conditions