CHAPTER 3

EXPERIMENTATION

3.1 INTRODUCTION

An experimental study was undertaken to investigate the performance of various electrodes in die-sinking micro-EDM of EN24 die steel. The experimental set-up and experimental procedures used for machining of EN24 die steel in this study are presented. An overview of the set-up includes a brief description of machine tool, preparation of workpiece, various electrodes and dielectric material. Various measurement methods and equipments are also highlighted. The methodology followed for the present study is highlighted in the final section.

The experimental investigation was carried out in three stages. The first stage involved the performance analysis of different electrodes in terms of various influencing parameters such as MRR, TWR, overcut, circularity error and SR. The experiments were conducted based on Taguchi’s $L_{16}$ orthogonal array for each electrode.

The second stage involved the optimization of multiple performance characteristics using Taguchi-based GRA. A confirmation test was performed to predict and verify the quality characteristics using optimal parametric combination.
In the third stage, a mathematical modeling was developed with multi regression analysis using SPSS software to identify the most influencing factors.

3.2 EXPERIMENTAL SET-UP

This section includes a brief description of machine tool, workpiece material, various electrodes and dielectric fluid used.

3.2.1 Multi-Purpose Miniature Machine Tool

Increasing demands in the field of high precision machine technology require a higher quality standard of machining systems. Limitations in conventional machining are a result of inaccuracies such as axial and radial run out of the machining spindle, resolution of the measurement and control system, fluctuations in temperature, air pressure and humidity in the quality of the machining systems.

To overcome all these problems, a multi-purpose miniature machine tool was developed for high-precision micro-machining at the National University of Singapore (Lim et al. 2003), and it has been going through a process of continuous development. DT-110 is a 3-axis automatic multi-process integrated machining process with high accuracy. This machine was used for conducting the micro-EDM experiments. This machine is energized by a pulse generator which can be switched to both transistor-type and RC-type. This machine is capable of micro-EDM, micro-turning, micro-milling, micro-grinding and micro-electrochemical machining (micro-ECM). The maximum travel range of the machine is 210 mm (X) × 110 mm (Y) × 110 mm (Z) with the resolution of 0.1 μm in X, Y and Z directions and full closed-feedback control ensures sub-micron accuracy. Figure 3.1 shows
the schematic diagram of the set-up. The photograph of the set-up is presented in Figure 3.2.

Figure 3.1 Schematic diagram of the experimental set-up

Figure 3.2 Photograph of the experimental set-up
3.2.2 Workpiece Material

The workpiece material used in this study was EN24 die steel. It is a high quality alloy steel and is widely used as the workpiece material in tool and die making industry. It is renowned for its high strength and wear resistant properties. Each workpiece was hardened to a hardness of 650VHN (55HRc). The chemical composition and properties of EN24 die steel are given in Tables 3.1 and 3.2, respectively.

Table 3.1 Chemical composition of EN24 die steel

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38%</td>
<td>0.20%</td>
<td>0.69%</td>
<td>0.010%</td>
<td>0.017%</td>
<td>1.58%</td>
<td>0.95%</td>
<td>0.26%</td>
</tr>
</tbody>
</table>

Table 3.2 Properties of the workpiece material

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Hardness (VHN)</th>
<th>Thermal conductivity (W/m-K)</th>
<th>Electrical resistivity (ohm-mm²/m)</th>
<th>Specific heat capacity (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN24</td>
<td>7.85</td>
<td>650</td>
<td>42</td>
<td>0.19</td>
<td>460</td>
</tr>
</tbody>
</table>

3.2.3 Tool Material

The selection of electrodes plays a vital role as it influences the machining performance of die-sinking micro-EDM. In this study, four electrodes made of tungsten, copper, copper tungsten and silver tungsten with a diameter of 300μm each, respectively, were used. The major properties of the electrode materials are given in Table 3.3.
Table 3.3 Properties of various electrode materials

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Composition</th>
<th>Density (g/cm³)</th>
<th>Hardness (HRB)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Melting point (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Pure W (99.9%)</td>
<td>19.25</td>
<td>115</td>
<td>173</td>
<td>3695</td>
</tr>
<tr>
<td>Cu</td>
<td>Pure Cu (99.9%)</td>
<td>8.92</td>
<td>82</td>
<td>401</td>
<td>1357</td>
</tr>
<tr>
<td>CuW</td>
<td>60% W- 40% Cu</td>
<td>12.75</td>
<td>77</td>
<td>140-215</td>
<td>3683</td>
</tr>
<tr>
<td>AgW</td>
<td>80% W – 20% Ag</td>
<td>15.5</td>
<td>97</td>
<td>195</td>
<td>1200</td>
</tr>
</tbody>
</table>

The electrode material’s specific thermal conductivity and thermal stability (melting point) influence the machining performance significantly.

3.2.4 Dielectric

EDM oil 3 was used as dielectric fluid for this study owing to its relatively high flash point, low pour point, high auto-ignition temperature and high dielectric strength. The properties of EDM oil 3 are shown in Table 3.4.

Table 3.4 Properties of the dielectric fluid

<table>
<thead>
<tr>
<th>Material</th>
<th>EDM oil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric mass at 15 °C (Kg/m³)</td>
<td>813</td>
</tr>
<tr>
<td>Viscosity at 20 °C (mm²/s)</td>
<td>7.0</td>
</tr>
<tr>
<td>Flash point (°C/°C)</td>
<td>134/126</td>
</tr>
<tr>
<td>Auto-ignition temperature (°C)</td>
<td>243.3°C</td>
</tr>
<tr>
<td>Aromatics content (Wt %)</td>
<td>0.01</td>
</tr>
<tr>
<td>Distillation range, IBP/FBP (°C)</td>
<td>277/322</td>
</tr>
</tbody>
</table>
3.3 EXPERIMENTAL PROCEDURES

As electrodes play a vital role in die-sinking process, careful tool preparation and optimal conditions are essential to produce good quality micro-holes. This section describes the electrode dressing and workpiece preparation.

3.3.1 Die-Sinking Micro-EDM Process / Micro-Hole Machining

The study focuses on die-sinking micro-EDM of EN24 die steel, using different electrodes such as tungsten, copper, copper tungsten and silver tungsten. The selection of electrode polarity is important before setting various parameters. Hence, the suitable electrode polarity was selected based on MRR, TWR and surface quality obtained during micro-EDM of EN24 die steel. It was identified that the negative electrode polarity provided higher MRR, lower TWR and good surface finish (Put et al. 2001, Wang et al. 2011). Therefore, the experiments were carried out with electrode as negative polarity and workpiece as positive.

![Figure 3.3 Step-by-step procedures for tool electrode dressing](image)

Figure 3.3 Step-by-step procedures for tool electrode dressing

In die-sinking micro-EDM, after machining each hole the electrode was dressed using a sacrificial block of electrodes. The dressing was
necessary as the electrode became taper after machining of each micro-hole. Thus, the worn out height of the electrode was dressed after machining each hole. Figure 3.3 shows the steps of the tool electrode dressing during the micro-hole machining of EN24 using die-sinking micro-EDM.

3.3.2 Workpiece Preparation

Initially workpieces were reduced to 1mm thick and 20mm X 20mm size by surface grinding machining process. In order to maintain the uniformity in the hardness of the workpiece to 650VHN, heat treatment process was employed throughout the study.

The hardened EN24 die steel were metallographically prepared and etched for micro-structural observation. The methods involved in the preparation of the workpiece are listed below.

- Rough grinding with emery belt grinder.
- Fine grinding using a series of emery papers like 1/0, 2/0, 3/0 and 4/0.
- Wet polishing by rotating disk using alumina (Al₂O₃) 600 mesh powder and water as lubricant.
- Final fine dry polishing using 1/4 micron diamond paste and Hifin fluid as lubricant.
- After washing, drying, etched with potassium dichromate (1g K₂Cr₂O₇ +4ml H₂SO₄ +50ml H₂O + 2drops of HCl just before using).
- Microstructures were captured at various magnifications like 200X, 500X, 1000X and 2000X.
3.4 PARAMETERS CONSIDERED

In the die-sinking micro-EDM, the influencing machining parameters are listed below:

3.4.1 Input Parameters

- Gap voltage
- Capacitance
- Feed rate
- Threshold

3.4.2 Output Parameters

- Material removal rate (MRR)
- Tool wear ratio (TWR)
- Overcut
- Circularity error
- Surface roughness (SR)
- Heat affected zone (HAZ)

Gap voltage, capacitance, feed rate and threshold at four levels were considered as the machining parameters to optimize the process as given in Table 3.5.

3.5 DESIGN OF EXPERIMENTS (DOE)

DOE technique is an experimental strategy used to reduce the number of experiments without affecting the quality of the performance.
Orthogonal arrays are important means of DOE and the experiments were conducted based on the following calculations highlighted in the section.

**Table 3.5 Machining parameters and their levels**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gap Voltage</td>
<td>V</td>
<td>80</td>
<td>100</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>2</td>
<td>Capacitance</td>
<td>nF</td>
<td>0.1</td>
<td>1</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>Feed rate</td>
<td>µm/s</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Threshold</td>
<td>%</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
</tbody>
</table>

3.5.1 **Orthogonal Array (OA)**

The number of experiments conducted must be greater than the degree of freedom of the experiment conducted, which is calculated based on the number of parameters and their corresponding levels.

The two conditions which must be satisfied for the selection of OA are

- Degree of freedom (DOF) of an OA ≥ DOF of experiment
- Level of OA = Level of experiment

3.5.2 **Degree of Freedom**

The number of independent aspects associated with an experimental design or a factor is called its degree of freedom, which can be calculated as

\[
\text{DOF} = F + I + 1
\]

where,

\[
F = (\text{No. of levels} - 1) \text{ for each factor}
\]

\[
I = (\text{No. of levels} - 1) (\text{No. of levels} - 1) \text{ for each interaction}
\]
This experiment has four factors and four levels and there is no interaction among the factors.

\[
\text{DOF} = F + I + 1 \\
= (4-1) + (4-1) + (4-1) + (4-1) + 0 + 1 \\
= 13
\]

Hence, it has 13 degrees of freedom.

3.5.3 Orthogonal Array Selection

From the orthogonal array selector software, based on the parameters and their corresponding levels, L\textsuperscript{16} orthogonal array which has four columns was used.

**Table 3.6 L\textsuperscript{16} orthogonal array layout**

<table>
<thead>
<tr>
<th>Experiment Number (Exp. No)</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>3</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
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<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
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<td>1</td>
<td>2</td>
</tr>
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<td>12</td>
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</tr>
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<td>14</td>
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<td>1</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
Therefore, by using this orthogonal array, 256 experiments were reduced to 16 experiments which were greater than the degree of freedom of the experiments. Hence, the degree of freedom of the orthogonal array was greater than the degree of freedom of the experiment. The typical $L_{16}$ orthogonal array layout is given in Tables 3.6 and 3.7.

**Table 3.7 $L_{16}$ orthogonal array with factors**

<table>
<thead>
<tr>
<th>Exp. No</th>
<th>Gap voltage (V)</th>
<th>Capacitance (nF)</th>
<th>Feed rate ($\mu$m/s)</th>
<th>Threshold (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>0.1</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>1</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>10</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>100</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.1</td>
<td>4</td>
<td>60</td>
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<tr>
<td>6</td>
<td>100</td>
<td>1</td>
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<td>80</td>
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<td>20</td>
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<tr>
<td>8</td>
<td>100</td>
<td>100</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>120</td>
<td>0.1</td>
<td>6</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td>1</td>
<td>8</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>120</td>
<td>10</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>120</td>
<td>100</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>140</td>
<td>0.1</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>140</td>
<td>1</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>140</td>
<td>10</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>16</td>
<td>140</td>
<td>100</td>
<td>2</td>
<td>60</td>
</tr>
</tbody>
</table>

### 3.6 DETERMINATION OF MACHINING PERFORMANCE

The overview of various measurement methods involved to measure output parameters such as MRR, TWR, SR, overcut and circularity error are described in this section.
3.6.1 Material Removal Rate

MRR for micro-EDM process can be calculated by dividing the total volume of material removed and the total machining time. In the present study, MRR was calculated based on the effective depth of the hole with respective time. The effective depth of the hole was calculated based on the difference between the depth shown on the monitor of the machine and the difference between electrode length before and after the machining, which can be measured by using non-contact Video Measuring System (VMS) shown in Figure 3.4. Out of experiments conducted for three times, the average value was considered for the analysis.

![Figure 3.4 Non-contact VMS-2010F](image)

MRR was calculated by using the following formula:

\[
MRR = \frac{\text{Volume of the material removed from the workpiece}}{\text{Machined Time}}
\]
3.6.2 Tool Wear Ratio

Wear ratio is defined as the ratio of amount of electrode to the amount of workpiece removed. One of the most difficult output parameters is to calculate tool wear ratio in micro-EDM process. Four methods are used to measure the TWR by means of measuring weight, length, shape and total volume, respectively. In this study, the tool wear ratio was calculated based on the total volume.

\[
TWR = \frac{\text{Volume of the electrode wear}}{\text{Volume of the material removed from the workpiece}}
\]

3.6.3 Overcut

Overcut is the difference between the radius of the micro-hole and the radius of the electrode. This can be measured by using VMS. In this study, the overcut was represented in terms of percentage and was calculated as the ratio of the radial difference between the hole on the workpiece and the radius of the electrode divided by the radius of the electrode.

\[
\text{Overcut in \(\%\)} = \frac{R_h - R_e}{R_e} \times 100
\]

where, \(R_h\) – radius of the hole on the work piece

\(R_e\) – radius of the electrode

Figure 3.5 Measurement of overcut
3.6.4  Circularity Error

Circularity error is the radial distance between the two concentric geometrical circles. Circularity is the measure of concentricity, associated with form/geometric accuracy. It can be measured by various methods such as least square circle, minimum zone circle, maximum inscribed circle and minimum circumscribed circle. In the present study, the least square circle was used, as it was considered one of the effective methods to calculate circularity. The roundness parameters were measured using Talysurf CCI 3000A. The two main parameters such as roundness peak (RONp) and roundness valley (RONv) were measured and circularity of the holes was calculated. The parameters are illustrated in Figure. 3.6.

![Least square reference circle](image)

**Figure 3.6 Least square reference circle**

3.6.5  Surface Roughness

The average SR (R_a) and the distance between the highest peak and the lowest value (R_v/R_{max}) were measured using the non contact Talysurf CCI3000A and it is shown in Figure 3.7.
In this study, the micro-hole was divided into two parts by cutting along the axis. This was done using wire-EDM and then by grinding. The machined surfaces were examined with micrographs taken using Joel TSM-5300 model scanning electron microscope (SEM). An energy dispersive X-ray spectroscope (EDAX) machine associated with the SEM was also used to investigate the surface properties and the migration of material on the machined surface of the workpiece after the micro-EDM process. The recast layers and the HAZ were observed using SEM.

Micro-hardness measurements were carried out using an HVS-10/50 Digital Vickers Hardness Tester, which is shown in Figure 3.8. The load employed was 0.5kg and loading time was 15s. Micro hardness was measured from the values displayed on the monitor.
3.7 PROCEDURE OF OPTIMIZATION TECHNIQUE

The procedure of the Taguchi-based grey method is shown in Figure 3.9. In Figure 3.9, steps 1, 2 and 7 are general procedures of the Taguchi method and steps 3 to 6 are the procedure of GRA.

Step 1: Experiment design and execution

A large number of experiments have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with only a small number of experiments (Lin et al. 2002). Therefore, the first step of the proposed procedure of simulation optimization is to select an appropriate orthogonal array in which every row represents a simulation scenario. The simulation runs are then executed by following the experimental structure of the selected orthogonal array.
Step 2: Signal-to-noise ratio calculation

The Taguchi method aims to find an optimal combination of parameters that have the smallest variance in performance. The signal-to-noise ratio (S/N ratio, \( \eta \)) is an effective way to find significant parameters by evaluating minimum variance. A higher S/N ratio means better performance for combinatorial parameters. S/N ratio based on the larger-the-better criterion for overall grey relational grade is calculated by using equation

\[
S/N = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}
\]

S/N ratio based on the smaller-the-better criterion for overall grey relational grade is calculated by using equation

\[
S/N = -10 \log \frac{1}{n} \sum_{i=1}^{n} y_i^2
\]

Step 3: Grey Relational Pre-Processing

GRA involves pre-processing stages wherein the output parameters are normalized. Normalization is a very important step in GRA. The reason is that GRA is a multi-objective optimization technique and depends on more than one parameter for its result.

The output parameters being analyzed normally are of different units. Further, the range of these values may be different. For example, one parameter might be in the range of 80 to 140V. On the other hand, the other parameter might be in the range of 0.1 to 100nF. When GRA is applied to these values as such, then, they lead to erroneous results. These errors might be negligible in some cases; however, as a standard the values are normalized prior to GRA.
During normalization, all the output parameters are converted into dimensionless values. Further, the range of the parameters is restricted to 0 – 1, where “0” indicates the lowest value while “1” indicates the highest value. Comparing the various parameters based on this standard is very easy. Moreover, the chances of errors in these normalized values are very low.

Then normalization process of GRA involves three notions similar to Taguchi’s technique, i.e. nominal the better, smaller the better and higher the better.

![Figure 3.9 Flow chart of Taguchi-based GRA procedure](image)

The formulas for the normalization process are as follows

\[
Y(k) = 1 - \frac{|x^k - x^0|}{\max \{x^k - x^0\}}
\]

Nominal the better, \( Y(k) = 1 - \frac{|x^k - x^0|}{\max \{x^k - x^0\}} \)
Smaller the better, \( Y(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \)

Higher the better, \( Y(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \)

where, \( Y(k) = \) The normalized value for the \( k^{th} \) trial

\( x_i^o(k) = \) The value of the output parameter for the \( k^{th} \) trial

\( \min x_i^o(k) = \) The smallest value of the output parameter “\( x \)” for the \( k^{th} \) trial

\( \max x_i^o(k) = \) The largest value of the output parameter “\( x \)” for the \( k^{th} \) trial

**Step 4: Reference Sequence Definition**

Further, the designer must set a reference sequence for each of the output parameter. The reference sequence indicates the best that can be achieved. For in case of MRR of any process, the maximum MRR attainable can be taken as the best value. Usually, the reference sequence for any output parameter is taken as “1”. The aim of the optimization process should be to achieve the target value of “1” in the GRC.

Though it has been defined that “1” is the largest value which can be achieved, we can set a value lesser than “1” as the reference sequence if we wish to set limits to the values of the factors. The reference sequence thus indicates the targets which are required to be achieved, i.e., it indicates the ideal solution.

**Step 5: Grey Relational Coefficient (GRC) calculation**

The next step is the calculation of the GRC. The GRC for any output parameter can be calculated using the formula,
\[ \eta(j) = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{\text{oi}} + \zeta \Delta_{\text{max}}} \]  

(3.1)

where, \( \eta(j) \) = GRC for the \( j^{\text{th}} \) output parameter

\[ \Delta_{\text{oi}} = \left| x_{\text{oi}}^* (k) - x_i^0 (k) \right| = \text{Deviation Sequence} \]

\[ x_{\text{oi}}^* (k) = \text{Reference Sequence} \]

\[ \Delta_{\text{min}} = \min \left| x_{\text{oi}}^* (k) - x_i^0 (k) \right| \]

\[ \Delta_{\text{max}} = \max \left| x_{\text{oi}}^* (k) - x_i^0 (k) \right| \]

\[ \zeta = \text{weighting coefficient} \]

The weighting coefficient indicates the importance of the output parameter. The output parameters can be weighted by giving suitable values to the weighting coefficient. However, if all the output parameters are of equal importance the value of the weighting coefficient is taken as “0.5”.

Thus the GRC is calculated for each of the output parameters. The closer the value is to “1”, the better is its performance, i.e., it satisfies the conditions of higher/lower to greater extent.

**Step 6: Grey Relation Grade (GRG)**

Calculation of the GRG is the final step in GRA. Though, secondary analysis exists after this step, the actual GRA ends with this step. GRG is the step where the optimization technique converts from a single objective optimization to a multi-objective optimization. The GRG is calculated as an average of the GRCs of all the output parameters at a given level of the OA. The formula for GRG is
GRG = \frac{1}{n} \sum_{i=1}^{n} \eta(j) \tag{3.2}

Where \ n = \text{number of output parameters}

**Step 7: Determination of optimal factor levels**

According to the Taguchi method, if the effects of the control factors on performance are additive, it is possible to predict the performance for a combination of levels of the control factors by knowing only the main effects of the control factor. For a factor A that has two levels, 1 and 2, for example, the main effect of factor A at level 1 (mA1) is equal to the average GRG whose factor A in experimental scenarios is at level 1, and the main effect of factor A at level 2 (mA2) is equal to the average GRG whose factor A in experimental scenarios is at level 2. The higher the main effect is, the better the factor level is. Therefore, the optimal levels for factor A will be the one whose main effect is the highest among all levels.

**Step 8: Confirmation Tests**

Confirmation tests are carried out to predict and verify the enhancement of the quality characteristics using the optimal parametric combination. The estimated GRG using optimal level of machining parameters can be calculated as

\[ \hat{P} = \gamma_m + \sum_{i=1}^{P} (\overline{\eta_i} - \gamma_m) \tag{3.3} \]

where, \ \gamma_m = \text{Total mean grey relational grade}

\[ \overline{\eta_i} = \text{Mean grey relational grade at the optimal level} \]

\[ P = \text{Number of the main designed parameters that affect the quality characteristics} \]
In this thesis, GRA is used to solve the complicated multi-performance characteristics optimization effectively.

3.8 **ANALYSIS OF VARIANCE (ANOVA)**

Sir Ronald A. Fisher, the British biologist, has introduced the statistical foundations for design of experiments and the analysis of variance (ANOVA). ANOVA can be given by

Total sum of squares = Sum of squares due to factors + Sum of squares due to error

\[
SS_{\text{Total}} = SS_{\text{Factors}} + SS_{\text{Error}}
\]

\[
SS_{\text{Total}} = \sum Y_i^2 - \frac{(\sum Y_i)^2}{n}
\]

Where \( \sum Y_i \) is the grand total of observation, \( n \) is the total number of observations.
3.9 METHODOLOGY

The methodology adopted for the present study is illustrated in Figure 3.10.

![Figure 3.10 Block diagram for methodology](image-url)

- Analysis of machining characteristics of die-sinking micro-EDM
  - Workpiece material
    - Hardened EN-24 die steel with hardness of 650VHN
  - Tool electrode material with diameter of 300µm
    - Tungsten (W), Copper (Cu), Copper Tungsten (CuW), Silver Tungsten (AgW)
  - Machine tool used
    - DT-110 CNC Multi-process Micro Machine Tool
  - Machining parameters and variables
    - (Fixed Polarity, Die electric – EDM oil3)
      - Gap voltage (V)
        - 80, 100, 120 and 140
      - Capacitance (nF)
        - 0.1, 1.0, 10 and 100
      - Feed rate (µm/s)
        - 2, 4, 6 and 8
      - Threshold (%)
        - 20, 40, 60 and 80
  - Equipment used for monitoring
    - Video Measuring System, Talysurf CCI 3000A, Vickers Hardness Tester, SEM and EDAX facility
  - Performance indicators
    - Material Removal Rate (MRR), Tool Wear Ratio (TWR), Surface Roughness (SR), Geometrical Accuracy of Drilled Holes (Overcut, Circularity error) and Heat Affected Zone (HAZ) characteristics
  - Data acquired
  - Results and Discussion
    - Effect of process parameters on performance of MRR, TWR, SR, Geometrical Accuracy and HAZ. Optimization – Taguchi-based Grey Relational Analysis Modeling - Multi Regression Analysis (Non-Linear equation)
  - Conclusion
3.10 SUMMARY

The experiments were carried out as per the procedure outlined in this chapter. The experimental procedure started with the preparation of the work piece material EN24 die steel and then the selection of electrodes. Number of experiments to be carried out was finalized based on $L_{16}$ Orthogonal Array. The machining parameters and their levels were also highlighted. Various output parameters such as MRR, TWR, SR, overcut, circularity error, micro hardness and HAZ were measured with different measuring techniques. With the experimental data, optimization using Taguchi-based GRA and mathematical modeling using SPSS software with respect to MRR, TWR and SR were made. The analysis of machining performance and the results of both optimization and mathematical modeling will be given in the next chapter along with the discussion.