CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

This chapter presents a detailed discussion on the methodology adopted for conducting the experimental investigation, the description of the experimental set-up and the experimental procedure used for the successful completion of the experiments.

3.2 CRYOGENIC TREATMENT

3.2.1 Cryogenic treatment set-up

In this study, the influence of cryogenic treatment on copper 2 wt. % beryllium alloy was investigated. The photograph of the cryogenic treatment experimental set-up is shown in Figure 3.1. The cryogenic treatment set-up used in this experimental investigation consists of

- A well-insulated chamber
- Controller
- storage tank
- feedback system and
- solenoid valve

A well-insulated chamber is used to maintain a very low temperature. The dimension of the chamber is 30 cm in diameter and 45 cm high. A fan is provided inside the chamber to have proper distribution of cryogenic fluid. The samples have to be loaded inside the chamber. It should be stacked properly. The maximum thickness of the specimen should not be exceeding one inch or else the soaking time has to be increased, once the materials are loaded inside the chamber and the experiment has been started, the chamber should not be opened until the experiment finishes.
After loading the samples, the process parameters such as ramp-down rate, soaking period and ramp-up period can be set in the PLC controller; then the chamber has to be connected to the special purpose high-pressure storage tank which contains the cryogenic fluid. Based on the temperature requirement various cryogenic fluids, such as Liquid CO$_2$, liquid nitrogen, dry ice etc., [6, 11] can be used. Liquid nitrogen can be used to lower the temperature of the material till 77 K. Hence, in this study the Liquid nitrogen was used as the working fluid. The advantage of using Liquid nitrogen as cryogenic fluid is that it is available in abundance, non-toxic, can be left into the atmosphere. Also, it has a very low melting point and hence it can be used for a wide range of low temperatures (shallow cryogenic treatment and deep cryogenic treatment).

The strict control of the process parameter is very important because the sudden lowering of temperature may create thermal shock, so the ramp-down rate has to be minimum [82]. Similarly, exposure of the materials to the liquid nitrogen may also damage the specimen. Hence, the direct contact of the parts with the liquid nitrogen should be avoided. A feedback system with the help of thermocouple and the solenoid valve was used. The temperature inside the chamber at any point of time can be measured with the help of
thermocouple and the feedback system will compare it with the set value. If there is any deviation in the measured and set values, the automatic cut-off switch gets actuated and that will stop the supply of cryogenic fluid into the chamber. Once the set value is reached the supply will be resumed. This process will continue until the end of the experiment.

3.2.2 Cryogenic treatment cycle

In this study, the cryogenic treatment was conducted in three steps, namely ramp down, soaking, and ramp-up. The cryogenic treatment cycle used in this study is as shown in Figure 3.2.

![Figure 3.2 - Cryogenic treatment cycle used in this study](image)

**Figure 3.2 – Cryogenic treatment cycle used in this study**

From the Figure 3.2, it can be seen that for cold treating process or shallow cryogenic treatment (SCT), the ramp down rate was kept constant at the rate of 1.5 K/min [83]. The materials were cooled from ambient temperature until it reached the shallow cryogenic temperature. The soaking temperature for the shallow cryogenic temperature was considered as 193 K. Hence, the specimen was soaked at that temperature for 10 hours. The lowering of temperature was achieved by supplying the vapours of liquid nitrogen. During heating, the chamber’s temperature reached the ambient temperature spontaneously [4, 82].
For the deep cryogenically treated (DCT) sample, the ramp down was done at the rate of 1.5 K/min [83] because the faster cooling rate may create thermal shock in the samples. The chamber’s temperature was lowered until it reached 87 K which was very close to the boiling point (77K) of liquid nitrogen. The chamber’s temperature was maintained at 87 K for 10 hours. The selected soaking time was sufficient enough to create the effect until the core of the material. During the ramp-up period, the supplied nitrogen to the chamber was stopped and it was permitted to attain the ambient temperature naturally.

3.3 CHARACTERISATION

3.3.1 Microstructure analysis

In this research, the microstructural examination was carried out on the cryogenically treated copper 2 wt. % beryllium alloy as well as the untreated material. 5 mm thick and 10 mm dia. samples were used for microstructure analysis. The chemical composition of the hardened untreated copper 2 wt. % beryllium alloy is presented in table 3.1. The photograph of the sample and the experimental set-up for the optical microscope is shown in Figures 3.3 and 3.4 respectively. The samples were made flat and then they were polished in different emery sheet from 200 grit to 1000 grit. The wet polishing was done using alumina powder on an automatic polishing machine. Finally, diamond polishing was used for the better polishing surface. The polished specimen was thoroughly washed and dried before applying etchant. As per ASTM E3, standard hydrogen peroxide was used as an etchant [84]. When the etchant was applied, a controlled, self-induced and selective corrosion was occurring at various places, such as grain boundaries, microstructural phases etc..

<table>
<thead>
<tr>
<th>Chemical Composition (wt. %)</th>
<th>Be</th>
<th>Co + Ni</th>
<th>Si</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition</td>
<td>2%</td>
<td>0.2%</td>
<td>0.18%</td>
<td>Rest</td>
</tr>
</tbody>
</table>

Table 3.1 – Chemical composition of copper 2 wt. % beryllium alloy.
The microstructure of the etched sample was evaluated. This process was repeated until a clear microstructure of the specimen was obtained.

The optical microscope and scanning electron microscope were used to carry out microstructure analysis. The microstructures of untreated and cryogenically treated samples were examined using an optical microscope (Leitz). Linear interpretation method was used to determine the grain size. The ASTM grain size number was measured for both untreated and cryogenically treated samples.
The untreated and cryogenically treated samples were examined using Field Emission Scanning Electron Microscope (FESEM) (Supra 55-CarlZeiss) for further investigation of microstructural study. A typical FESEM set-up is shown in Figure 3.5. Energy Dispersive X-Ray Spectroscopy (EDS) examination was also performed using FESEM set-up. The purpose of EDS analysis was to find out the extent of beryllide particle dispersion in untreated as well as the cryogenically treated sample and also used to map the elements present on the surface of the specimen.

Figure 3.5 – Photograph of Field Emission Scanning Electron Microscope (FESEM)

At higher temperature, the beryllium forms a solid solution. The maximum solid solubility of the beryllium in the copper is 2.7 around 800 °C [18-23]. This phase of the alloy is called an alpha copper phase. The microstructure of copper 2 wt. % beryllium alloy at room temperature consists of, the alpha copper phase forms as a copper matrix, the gamma phase which is usually present at the grain boundaries and the beryllide particles. As the temperature of the specimen decreased, the solid solubility of beryllium in alpha copper phase decreased [85]. The beryllide particles expel and combine with Nickel and/or cobalt to form the precipitates of nickel beryllide and cobalt
beryllide. In the periodic table, the nickel and cobalt are well above the sodium. Hence nickel and cobalt from the nickel beryllide and cobalt beryllide can be mapped using EDS analysis [22].

3.3.2 X-Ray Diffractometry (XRD) study

In this study, the X-Ray Diffractometry (XRD) analysis was carried out using PW3040/60 PANalytical instrument. Copper ka radiation was used to generate the X-Rays. XRD examination aids to recognise the probable phases in untreated, shallow cryogenically treated and deep cryogenically treated samples. In this study, 2 mm thick and 16 mm dia disc samples were utilized. The crystallite size of untreated and cryogenically treated samples was also determined. Sherrer equation was used to determine the crystallite size of the sample [86]. The crystallite size of the samples was calculated from the XRD graph using Derby Sherrer’s formula.

\[
\text{Avg. Crystalline Size, } t = 0.9 \frac{\lambda}{\beta \cdot \cos \theta}
\]  

(3.1)

where,

\(\lambda\) – Wavelength of the X-Ray beam, in mm

\(\beta\) – Peak’s width at half of its maximum intensity (FWHM), in radians

\(\theta\) – Peak position, in radians.

3.3.3 Hardness survey

The hardness of the untreated and cryogenically treated samples was determined using a Vicker’s Hardness testing machine. Wilson Wolpert, 402 MVD hardness tester was used in this study. The metallographically polished specimen with a dimension of 10 mm diameter and 5 mm thick was used for performing the hardness test. The hardness test was conducted as per ASTM E384 standard. The load applied was 1 kg and the dwell period was kept as 10 seconds for all the samples. The average value of the three readings was taken for hardness number.
3.3.4 Differential scanning calorimeter (DSC)

Differential scanning calorimeter (DSC) is one of the thermal analysis techniques which is used to determine the peculiar thermal and physical properties of the metals and polymers [87]. In this technique, the heat flow rate of the sample is compared with the standard or reference sample by maintaining the same temperature in both the samples. It is used to determine the various phase transformations that occur in the metals and alloys [21, 28, 88-90].

The experimental set-up of the DSC is shown in Figure 3.6. It consists of an insulated chamber. In this chamber, the powder of the reference sample and the measurement sample has to be placed in an alumina crucible. The same quantities of the reference sample and the measurement sample were kept inside the alumina crucible. Copper was used as a reference sample and untreated & cryogenically treated copper-beryllium alloy samples were used as the measurement sample. The chamber was filled with Argon gas to avoid any oxidation at higher temperatures. The temperature was increased gradually at a constant rate and the rate of heating was maintained at 10 K/min. The temperature sensor and the heat flow sensor were used in the chamber to gauge the temperature and the heat flow. Both the samples were maintained at the same temperatures throughout the experiment. The heat input required for the measurement sample was compared with the reference sample. If the phase change occurs, the heat flow will be varied, because the phase change is accomplished by a change in heat flow at a constant temperature. With the help of the heat flow sensor, the rate of change of heat flow to the sample specimen with respect to the reference sample was measured and recorded. As per ASTM D3418 and E793 standard, the DSC analysis was performed.
A graph of heat flow vs. temperature was plotted and the peaks were analysed. Each peak represented a phase change process for the metals and alloys [87]. The width of the peak gave the duration of the phase transformation. The temperature of both the samples was increased until the required temperature was reached. In this study, the samples were heated until 873 K. Then the samples were cooled at the same rate and the heat flow during the cooling process was also noted.

3.3.5  **Tensile strength and yield strength**

The tensile strength is the most important and the basic mechanical property of any material. The tensile strength of the sample was measured using the universal tensile testing machine. The experimental set-up for the measurement of tensile strength is shown in Figure 3.7.
In this study, INSTRON 3367 tensile testing machine was used to measure the tensile strength of the specimen. The capacity of the machine was 40 kN. The machine consisted of a fixed jaw and a movable jaw. The test samples were fixed using the two jaws. The load was gradually applied to the specimen by lowering the movable jaw until the material ruptured and the presence of the LVDT sensor helped to measure the change in length of the specimen.
specimen. The test set-up was coupled with a computer to fetch the data and store it for further analysis.

The photograph of the tensile samples used in this study is shown in Figure 3.8. The test materials were prepared as per the ASTM E8 standard [91]. The dimensions of the tensile sample used in this experimental study are as follows:

- The diameter of reduced section = 9 mm
- Gauge length = 45 mm
- Length of the reduced section = 54 mm

### 3.3.6 Electrical resistivity

Copper and its alloys are utilised in industries for their excellent electrical and thermal properties [92]. Hence, the electrical resistivity of the untreated, SCT, and DCT samples were measured using the two-probe method. The electrical resistivity test was carried out as per ASTM D257 standard. The experimental set-up of the two probe method is shown in Figure 3.9.

![Figure 3.9 – Experimental Set-up for Two-Probe Method](image-url)
The set-up consisted of a sample holder, a voltage source and measuring device, a precision current source, the controller and a computer. The sample to be measured was placed between the two probes. The dimension of the sample used was 2 mm thick and 10 mm in diameter. When the power was supplied between the probes, the current passed through the probes via the sample. The voltage across the probe and the current were measured. By gradually increasing the current, the increase in voltage was recorded in the computer. The graph between the supplied current and the measured voltage was plotted. The slope of the curve was measured from the graph and it represented the resistance offered by the material.

The resistivity of the material could be determined by using the formula.

\[
\rho = \frac{R \times A}{L} \tag{3.2}
\]

where,

A – cross-sectional area of the specimen in m\(^2\).

L – Length of the specimen in m.

R – Resistance offered by the material for a particular current input, in ohms.

From the electrical resistivity, the electrical conductivity could be calculated thus:

\[
(\sigma) = \frac{1}{\text{Electrical Resistivity}} \tag{3.3}
\]

From the resistivity, the thermal conductivity could be determined using the Weidman–Franz–Lorenz Law [15, 92].

\[
L = \frac{K}{\sigma T} = \left(\frac{\pi^2}{3}\right) \left(\frac{k}{e}\right)^2 \tag{3.4}
\]
where,

\[ K_t \] – Thermal Conductivity, in W/mK.

\[ \sigma \] – Electrical Conductivity in mho.m\(^{-1}\)

\[ k \] – Boltzmann Constant, W/m\(^2\)K\(^4\)

\[ e \] – Charge of an Electron, in Coulomb

\[ T \] – Absolute Temperature, in K

\[ L \] – Lorenz Number = 2.45 x 10\(^{-8}\) WΩ/K\(^2\)

3.4 TRIBOLOGICAL STUDY

The Tribological study was conducted using the pin-on-disc tribo tester (DUCOM). The experimental set-up of the tribo-tester is shown in Figure 3.10. It consists of a rotating spindle connected to a motor with variable speed adjustment. The disc is connected with the spindle for its rotation. The pin is connected to the pin holder. It is attached to a beam. The LVDT sensor and the force measuring sensor were attached to the beam. The spindle speed is controlled by a controller (data acquisition system). In the controller, the various parameters can be fed, such as spindle speed, time of run etc. All the experimental data were recorded on the computer.

Figure 3.10 – Experimental set-up for the pin-on-disc wear test
In this study, the dry sliding wear analysis was carried out under the laboratory condition of around 25 °C. ASTM G99-05 standard was used to perform the wear study. Untreated, SCT and DCT Cu-Be2 alloy materials were considered as pin specimen. The photograph of the wear test specimen is shown in Figure 3.11. AISI 4140 steel of 115 mm dia and 10 mm height with a hardness of 513 HV (heat-treated) being considered for disc specimen. The roughness of the disc was determined with the help of a stylus probe roughness evaluating machine and it was observed to be less than 0.8 microns as recommended in ASTM G99 standard [93].

![Figure 3.11 – Photograph of the wear test specimen](image)

![Figure 3.12 – High precision Electronic weighing machine](image)
In this study, the experiment was conducted for the velocities of 1m/sec, 2m/sec & 3m/sec along with various loads of 10N, 30N & 50N and the constant sliding distance of 2000 m [83]. In the Ducom tribo tester, with the help of the automated data acquiring attachment the frictional force value was noted automatically. A high precision electronic weight measuring device was utilized to weigh the pin. The photograph of the weighing machine (Shimadzu) is shown in Figure 3.12. It is a high precision machine since the weight loss for the sample is very minute. The least count of the weighing machine is 0.0001 grams. The capacity of the machine is 220 grams.

The wear rate was measured as the weight difference of the pin before and after the experiment. Generally, weight loss is given in terms of volume [3, 47, 58, 64, 94]. Hence the wear rate in grams is transformed into volume loss.

3.5 PERFORMANCE STUDY OF COPPER BERYLLIUM ALLOY ELECTRODE IN ELECTRO-DISCHARGE MACHINING (EDM)

The effect of cryogenic treatment on the machining performance of electro-discharge machine was investigated. The experimental test rig of the electro-discharge machine is given in Figure 3.13. The photograph of the tool and the work-piece used in this study is shown in Figure 3.14.

![Figure 3.13 – Experimental set-up for Electro-Discharge Machining (EDM)](image-url)
3.5.1 Electro- Discharge Machine (EDM)

Electro-discharge machining is a thermo-electric process in which a specified high current at a specified voltage is passed between the tool and the workpiece, provided the gap between the tool and the workpiece is sufficiently small to generate an arc of very high intensity. This arc will create a localised high temperature significant enough to vaporise the exposed portion of the tool and the workpiece [74, 95-98]. The experimental set-up consists of:

- A die electric storage tank
- A controller
- High voltage beam
- Stabilizer
- Adjustable Workbench
- Flusher
- Die electric medium.

In the experimental set-up, a controller is used to control and set the process parameters. In the controller, all the input parameters, such as the applied current, the gap voltage required, how much gap to be maintained, pulse on time, pulse off time, the retraction distance etc, can be fed. Voltmeter and ammeter are also provided in the controller to measure the supplied...
current and the gap voltage. A high voltage beam is available in the EDM machine which helps to supply the required voltage at the regular interval to generate the arc. It also holds the tool material. The dielectric fluid is circulated using a flushing jet. The high-pressure jet of fluid is projected at the gap between the tool and the workpiece. The workpiece is placed in a movable workbench; the workbench is designed to hold a sufficient quantity of dielectric fluid because the EDM process is taking place in a pool of dielectric medium at the submerged condition. Also, it should accommodate the splashed dielectric fluid in the workbench itself.

The dielectric fluid plays a major role in the electro-discharge machining. The purpose of using dielectric fluid is that it acts as an insulator until the minimum gap required to produce dielectric breakdown is attained [97, 99, 100]. After attaining the required minimum gap, it will act as a conductor to facilitate the electrons to jump from tool to workpiece to generate an arc. Due to this, the surface of workpiece material which is having the lowest gap will get evaporated at various locations. These vaporised materials when come in to contact with the dielectric fluid, get solidified and carried away by the flush of dielectric fluid [101, 102].

![Diagram showing the process of dielectric breakdown and machining in EDM](image)

**Figure 3.15 – The process of dielectric breakdown and machining in EDM [97]**
The typical electro-discharge machining process can be seen in Figure 3.15. As soon as the generation of the arc is cut off, the dielectric fluid will combine and acts as an insulator. This process is continued until the replica of the tool is obtained in the workpiece. As mentioned earlier, in the EDM process a spontaneous high voltage is supplied to vaporise the material [96, 97, 103].

**3.5.2 Performance study of cryogenically treated Cu-Be2 electrode**

The performance study of the cryogenically treated copper-beryllium alloy tool electrode was conducted using the Electro-discharge machine (EDM). The performance characteristics, such as material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra) were considered. In this study, the input current, duty factor and the tool electrode were considered as the input parameters. The input current was varied as 3 Amps, 6 Amps and 9 Amps. The duty factor was varied as 40%, 60% and 80%, untreated, SCT and DCT specimen were used as tool electrode (10 mm diameter and 100 mm length) and all other parameters were kept as constant.

The MRR is the most important feature of any machining study. The ultimate aim of any machining process is to remove material for obtaining the required shape and size of the component. Therefore, in this study, the MRR was considered one of the performance characteristics. The MRR of the electro-discharge machining process is determined by using the following equation [15, 104].

\[
\text{MRR (mm}^3/\text{min}) = \frac{\text{WP}_f - \text{WP}_i}{\rho \times t}
\]  

(3.5)

where,

- \(\text{WP}_f\) – Weight of the workpiece after the experiment, in kg
- \(\text{WP}_i\) – Weight of the work-piece before the experiment, in kg
- \(\rho\) – Density of the work-piece, in kg/mm\(^3\)
- \(t\) – Machining time, in mins
The Tool Wear Rate (TWR) is another important feature for evaluating the performance of the electro-discharge machining processes. Hence, in this study, the TWR was calculated by using the following equation.

\[
\text{TWR (mm}^3\text{/min)} = \frac{\text{WL}}{\rho \cdot t}
\] (3.6)

where,

- \(\text{WL}\) – Weight loss of tool material, in kg.
- \(\rho\) – Density of the tool material, in kg/mm\(^3\)
- \(t\) – Machining time, in min.

The third principal feature is surface roughness. The roughness of the work-piece was evaluated using a stylus probe roughness tester (Taylor-Hobson) [83]. The work-piece was placed in a flat surface made of Granite. The probe was made to slightly touch the work-piece. The movement of the probe was converted into the electrical signals using a piezo-electric transducer. Further, the electrical signal can be utilised to create the profile or topology of the surface.

3.6 OPTIMISATION OF MULTI-PERFORMANCE CHARACTERISTICS

In this study, the multi-performance of Electric-Discharge Machining (EDM) process was optimised using Taguchi method and Grey relational analysis.

Taguchi method is a powerful statistical tool for evaluating the optimised characteristics of various processes. Taguchi uses an orthogonal array to obtain the optimum parameter with a minimum number of experiments. The efficacy of the Taguchi approach is often verified. It is being extensively used in industries as well as by researchers. In this approach, the performance characteristics are determined using signal-to-noise ratio usually called S/N ratio. High S/N ratio is the indicator of better characteristics. In general, the S/N ratio can be computed for three different situations, viz-a-viz, higher-the-better (HB), lower-the-better (LB) and nominal-the-best (NB) [72, 99, 105]. In any machining study, the output response can be of different categories, such
as, in a machining study, the MRR has to be higher, whereas the tool wear rate and the surface roughness should have to be less for the better performance. Hence, Taguchi presented a different S/N ratio for different categories.

In Taguchi method, the responses are converted in terms of the signal-to-noise ratio. The signal means the performance characteristics and the noise is undesirable or unavoidable errors while conducting the experiment. If the signal-to-noise ratio is high, it indicates the quality of the output response of that experiment is high. In a general scenario, different output responses have to be considered for obtaining the optimum value. Therefore, various output responses have to be considered for the attainment of overall optimised value. To achieve this, Julong introduced a new approach called Grey-Relational-Analysis (GRA).

In Grey-relational-analysis the optimisation of several objectives can be achieved simultaneously. GRA is one of the widely accepted approaches which works based on Grey system theory. In this theory, the word GREY is utilized, which indicates that it can be anywhere between black and white. Here, Black means nothing is known about the system, whereas white implies that all the relevant information is available. Therefore, Grey means partial information is available. In a real-world scenario, complete information about any system is not feasible. Therefore, Grey-relational-analysis can be applied to various real-world problems.

### 3.6.1 Experimental design

In this experimental design, three factors such as current, duty factor & electrode and their three levels were considered. Based on the selected input parameters the suitable orthogonal array has to be selected. The orthogonal array is the special design of experiment technique, which requires a minimum number of experiments for obtaining the desired output. The minimum number of experiments required can be obtained by using the following equation [106, 107].

$$N = 1 + V \{L-1\}$$  \hspace{1cm} (3.7)
where,

\[ N \] – Minimum number of experiments required

\[ V \] – Number of input parameters.

\[ L \] – Number of levels.

From the above equation, the minimum number of experiments was estimated to be 7. Hence, in this optimisation study, L9 Taguchi Orthogonal array was considered

### 3.6.2 Grey Relational Analysis

In this technique, the optimisation of multiple response features can be transformed into the optimisation of the single feature [27, 99, 108, 109]. In this study, the steps utilised for conducting grey-relational analysis are given below [70, 71, 76, 79-81].

1. Taguchi’s experimental design process was utilised to conduct the EDM experiment and the output responses were measured.

2. After conducting the experiment for the desired orthogonal array, the next step is to condition the raw experimental data into the pre-processed data, this step is called a Grey-relational generation, and this can be done by normalising the experimental data. The normalisation of the experimental data is given values between one and zero.

The data thus normalized for **Lower the Better** can be computed by the following formulation [110, 111].

\[
x_{i}(k) = \frac{y_{i}(k) - \min y_{i}(k)}{\max y_{i}(k) - \min y_{i}(k)}
\]  

(3.8)

The normalized value for **Higher the Better** can be computed by using the following equation.

\[
x_{i}(k) = \frac{\max y_{i}(k) - y_{i}(k)}{\max y_{i}(k) - \min y_{i}(k)}
\]  

(3.9)
where,

\[ x_i(k) \] – Normalised value after the grey-relational generation,

\[ \text{max } y_i(k) \] – Measured largest data for the given \( k \)th response,

\[ \text{min } y_i(k) \] – Measured smallest data for the given \( k \)th response

3. From the pre-processed data the Grey-Relational-Coefficient (GRC) can be evaluated. The GRC can be calculated using the following equation.

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

(3.10)

where,

\[ \Delta_{0i} = \|x_0(k) - x_i(k)\| \] = Difference of the absolute value \( x_0(k) \) and \( x_i(k) \)

\[ \Delta_{\min} \] = Smallest value of \( \Delta_{0i} \)

\[ \Delta_{\max} \] = Largest value of \( \Delta_{0i} \)

\[ \Phi \] = distinct value for the computation of grey relational coefficient; it should have to be between 0 & 1. In this study, the objective is a mixture of minimizing and maximizing the response, therefore, the value of \( \Phi \) may be considered as 0.5.

4. The grey relational grade can be generated by taking the average of the grey relational coefficients and it can be determined using the following equation.

\[
 \zeta_i = \frac{1}{n} \sum_{k=1}^{n} z_i(k) 
\]  

(3.11)

where,

\[ n \] = Number of performance characteristics.

5. From the Grey-relational data thus obtained, is ranked and found to be close to the ideal sequence.
6. The response table has to be constructed from the Grey-relational Grade.

7. From the given table, a plot between the average Grey-relational Grade and the levels of control factor can be drawn, which is called the response graph.

8. The optimum sequence can be obtained from the response graph.

9. For the optimum sequence, a confirmation test is to be performed to verify the validity of the optimum sequence.