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# Experimental Investigation of Surface Roughness Characteristics $R_a$, $R_q$ and $R_z$

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***Abstract***

*The challenge of modern machining industries is mainly to achieve high quality, in terms of dimensional accuracy, surface finish and high production rate. In the present work, an attempt has been made to explore the effect of EDM process parameters on various Surface Roughness characteristics $R_a$, $R_q$ and $R_z$. The experiments have been done on medium carbon steel EN8 which has high applications in tool, oil and gas industries. For the experimentation, Pulse on time ($P_{ON}$), Pulse off time ($P_{OFF}$), Wire tension (WT) and Wire feed rate (WF) were considered as EDM inputs. Similarly, Surface roughness parameters $R_a$, $R_q$ and $R_z$ were taken as output characteristics. Taguchi's standard L27 (3 level * 3 parameters) Orthogonal Array was used for conducting the experiments and optimization of multi responses was done by Grey analysis. From the Grey analysis, optimal combination of machining parameters for Surface Roughness characteristics was found at Pulse-on time ($P_{ON}$):131 $\mu s$ (level 3), Pulse-off time ($P_{OFF}$):58 $\mu s$ (level 2), Wire tension (WT):2 Kg-f (level 1) and Wire feed rate (WF):4 m/min (level 1). Analysis of variance was used to find the influence of process parameters on responses. From ANOVA of Grey Relational Grade, it is found that wire feed has high influence (F= 59.18) and pulse off time has very low influence (F= 2.50) in effecting the Surface Roughness parameters taken simultaneously. Regression models for the responses were prepared by using MINITAB-16 software. From the residual analysis, it is clear that the models prepared for the responses were more accurate, adequate and they can be used for prediction of surface roughness characteristics. Finally, the experimental and predicted values were compared and they found very close to each other.*

***Keywords**: Taguchi, ANOVA, Regression Analysis, Grey Analysis and Surface Roughness parameters $R_a$, $R_q$ and $R_z$..*

## 1. Introduction

Electro Discharge Machining (EDM) is an unconventional machining process which has the ability to machine hard, difficult-to-machine materials and the parts with complex internal shapes by using precisely controlled sparks. In EDM while machining the sparks will occur between an electrode and a workpiece in the presence of a dielectric fluid. The dielectric material will be used to maintain the constant sparking gap between the electrode and workpiece, to cool the heated material to form the EDM chip and for removing EDM chips from the sparking area. EDM also referred to as spark machining, spark eroding, burning, die sinking or wire erosion. [1-4] Surface roughness is most commonly refers to the variation in the height of the surface relative to a reference plane.

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It is usually characterised by the American National Standards Institute (ANSI) and the International Standardization Organization (ISO). Most commonly used Surface roughness parameters are $R_a$- Arithmetic average roughness or central line average (CLA), $R_q$- Geometric average roughness or Root mean square value (RMS) and $R_z$- Ten point height. Arithmetic average is defined as the average values of ordinates from the mean line. Root mean square value is defined as the square root of the arithmetic mean of the values of the squares of the ordinates of the surface measured from a mean line. Ten point height is defined as the average difference between the five highest peaks and five lower valleys of the surface texture within the sampling length, measured from a line parallel to the mean line. $R_a$, $R_q$ and $R_z$ values will be measured by using the formulae's. $R_a = \frac{1}{n}\sum_{i=1}^{n}|Y_i|$ where, Yi is the deviation value, n is the total number of deviations. $R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Y_i^2}$ where, Yi is the deviation value and n is the total number of deviations. $R_z = \frac{1}{5}\sum_{i=1}^{5} R_{Pi} - R_{Vi}$ where, $R_{Pi}$ and $R_{Vi}$ are the $I^{th}$ highest peak and lowest valleys respectively. [5-7]

It is difficult to consider all the machine parameters as inputs, as the number of input parameters increases the number of experiments to be done will also increase. To reduce the number of experiments, cost and time Denichi Taguchi has given a design called an orthogonal array. OA covers the entire parametric space with the least number of experiments and used to find the optimum conditions for achieving better output. [8-11] For multi response optimization problems, Taguchi based Grey Relational Grade method has been proposed. Grey method deals with the systems in which part of information is known and part of information is unknown. This method converts the multi objective problem into a single objective problem in terms of Grey relational grade. [12-14] In the present work, an attempt has been made to explore the effect of EDM machining parameters on various Surface Roughness parameters ($R_a$, $R_q$ and $R_z$). Medium carbon steel EN8 have taken as a workpiece. EN8 steel has high industrial applications in tool, oil and gas industries and commonly used where high tensile strength property is required. They also used for axial shafts, propeller shafts, crank shafts, high tensile bolts and studs, connecting rods, riffle barrels and gears manufacturing, *etc.* [15-18] For experimentation, parameters of EDM Pulse-on time ($P_{ON}$), Pulse-off time ($P_{OFF}$), Wire tension (WT) and Wire feed rate (WF) were considered as variables and Peak current, Spark gap voltage and Flushing pressure of dielectric fluid were considered as fixed parameters. Similarly, Surface roughness parameters $R_a$, $R_q$ and $R_z$ were taken as output responses. The experiment was done on ULTRACUT with Pulse generator ELPULS 50f EDM machine as per Taguchi's L27 orthogonal array. For the optimization of multi responses, Taguchi based Grey method has been used. The influence of machining parameters was studied by using ANOVA. The Regression models for the Surface Roughness parameters have been prepared by using the MINITAB-16 software and the model is checked for their accuracy and adequacy. Finally, the experimental and Regression results were compared. [19-20]

## 2. Experimental Details

For the experiment, the workpiece of EN8 has been taken. The experiment has been performed on CNC EDM (ULTRACUT with Pulse generator ELPULS 50f) machine with brass wire (0.25mm diameter) and water as tool electrode and dielectric fluid respectively. The chemical composition, Mechanical and physical properties of EN8 steel were given in the Tables 1 and 2. The process parameters with their levels and Taguchi L27 orthogonal array were given in the Tables 3 and 4 respectively. After machining, Surface Roughness parameters $R_a$ (Arithmetic surface roughness average), $R_q$ (Root mean square value) and $R_z$ (Maximum peak-to-valley height) of machined workpieces were measured by using SJ-301 (Mutituyo) gauge.

 

**Table 1. Chemical Composition of EN8 Steel**

| Element | C | Mn | Si | S | P | Cr | Ni | Mo |
|---|---|---|---|---|---|---|---|---|
| % Weight | 0.36-0.44 | 0.6-1.0 | 0.10-0.40 | 0.05 max | 0.05 max | - | - | - |

**Table 2. Mechanical Properties of EN8 Steel**

| Property | Maximum Stress ($N/mm^2$) | Yield Stress ($N/mm^2$) | Elongation (%) | Impact (J) | Hardness (BHN) |
|---|---|---|---|---|---|
| Value | 700-850 | 465 | 16 | 28 | 201-255 |

**Table 3. Experiment Input Parameters and Their Levels**

| S.No. | Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| 1 | Pulse on time($T_{ON}$), µs | 115 | 123 | 131 |
| 2 | Pulse off time, ($T_{OFF}$), µs | 53 | 58 | 63 |
| 3 | Wire tension (WT), Kg-f | 02 | 03 | 04 |
| 4 | Wire feed rate (WF), m/min | 04 | 05 | 06 |

**Table 4. L27 Orthogonal Array**

| Run No. | Pulse on time ($T_{ON}$) µs | Pulse off time ($T_{OFF}$) µs | Wire tension (WT) Kg-f | Wire feed rate (WF) m/min |
|---|---|---|---|---|
| 1 | 115 | 53 | 2 | 4 |
| 2 | 115 | 53 | 3 | 5 |
| 3 | 115 | 53 | 4 | 6 |
| 4 | 115 | 58 | 2 | 5 |
| 5 | 115 | 58 | 3 | 6 |
| 6 | 115 | 58 | 4 | 4 |
| 7 | 115 | 63 | 2 | 6 |
| 8 | 115 | 63 | 3 | 4 |
| 9 | 115 | 63 | 4 | 5 |
| 10 | 123 | 53 | 2 | 5 |
| 11 | 123 | 53 | 3 | 6 |
| 12 | 123 | 53 | 4 | 4 |
| 13 | 123 | 58 | 2 | 6 |
| 14 | 123 | 58 | 3 | 4 |
| 15 | 123 | 58 | 4 | 5 |
| 16 | 123 | 63 | 2 | 4 |
| 17 | 123 | 63 | 3 | 5 |
| 18 | 123 | 63 | 4 | 6 |
| 19 | 131 | 53 | 2 | 6 |
| 20 | 131 | 53 | 3 | 4 |
| 21 | 131 | 53 | 4 | 5 |
| 22 | 131 | 58 | 2 | 4 |
| 23 | 131 | 58 | 3 | 5 |
| 24 | 131 | 58 | 4 | 6 |
| 25 | 131 | 63 | 2 | 5 |
| 26 | 131 | 63 | 3 | 6 |
| 27 | 131 | 63 | 4 | 4 |

 

## 3. Multi-Response Parametric Optimization

The optimization of process parameters is usually done as per the traditional Taguchi approach using signal to noise ratio (S/N). Higher signal to noise ratio means closer to optimal of process parameters. Taguchi method can optimize the single response only and unable to optimize simultaneously if the number of responses is more than one. Hence the Grey relational analysis combined with the taguchi approach has been applied to solve multi-response optimization problems. The steps involved in Grey analysis are

1. Identification of responses ($R_a$, $R_q$ and $R_z$) and input parameters ($T_{ON}$, $T_{OFF}$, WF and WT).
2. Determine the different levels (3) for the input process parameters.
3. Selection of appropriate orthogonal array (L27) and assign the process parameters.
4. Carry out the experiment as per L27 orthogonal array.
5. Normalization of responses.
6. Finding out the grey relational generation and grey relational coefficient.
7. Calculation of the grey relational grade.
8. Analyze the grey relational grade.
9. Selection of optimal combination of process parameters.

A series of experiments were conducted on an EDM machine as per Taguchi's L27 array. The components after machining were tested for Surface Roughness and measured by using SJ-301. The experimental results of Surface Roughness parameters $R_a$, $R_q$ and $R_z$ of each sample are given in the Table 5.

**Table 5. Experimental Results**

| S.NO. | Process parameters | | | | Experimental results | | |
|---|---|---|---|---|---|---|---|
| | $T_{ON}$ | $T_{OFF}$ | WT | WF | $R_a$ (µm) | $R_q$ (µm) | $R_z$ (µm) |
| 1 | 115 | 53 | 2 | 4 | 2.5 | 2.7 | 9.9 |
| 2 | 115 | 53 | 3 | 5 | 5.1 | 4.4 | 21.5 |
| 3 | 115 | 53 | 4 | 6 | 7.2 | 6.8 | 26.3 |
| 4 | 115 | 58 | 2 | 5 | 4.3 | 4.8 | 18.0 |
| 5 | 115 | 58 | 3 | 6 | 6.1 | 5.8 | 23.9 |
| 6 | 115 | 58 | 4 | 4 | 3.0 | 3.7 | 13.1 |
| 7 | 115 | 63 | 2 | 6 | 7.1 | 6.0 | 27.8 |
| 8 | 115 | 63 | 3 | 4 | 4.2 | 4.1 | 15.9 |
| 9 | 115 | 63 | 4 | 5 | 5.2 | 5.8 | 22.1 |
| 10 | 123 | 53 | 2 | 5 | 3.7 | 2.7 | 15.1 |
| 11 | 123 | 53 | 3 | 6 | 7.5 | 7.0 | 28.9 |
| 12 | 123 | 53 | 4 | 4 | 3.2 | 3.6 | 13.0 |
| 13 | 123 | 58 | 2 | 6 | 4.3 | 4.1 | 16.4 |
| 14 | 123 | 58 | 3 | 4 | 3.2 | 2.5 | 11.9 |
| 15 | 123 | 58 | 4 | 5 | 5.7 | 5.3 | 21.1 |
| 16 | 123 | 63 | 2 | 4 | 2.8 | 2.5 | 10.7 |
| 17 | 123 | 63 | 3 | 5 | 4.2 | 5.1 | 17.1 |
| 18 | 123 | 63 | 4 | 6 | 6.9 | 5.7 | 28.3 |
| 19 | 131 | 53 | 2 | 6 | 5.5 | 5.3 | 19.3 |
| 20 | 131 | 53 | 3 | 4 | 3.5 | 3.1 | 13.7 |
| 21 | 131 | 53 | 4 | 5 | 4.9 | 5.1 | 19.2 |

 

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | 131 | 58 | 2 | 4 | 2.3 | 2.0 | 9.4 |
| 23 | 131 | 58 | 3 | 5 | 3.8 | 3.3 | 15.8 |
| 24 | 131 | 58 | 4 | 6 | 6.3 | 6.0 | 23.4 |
| 25 | 131 | 63 | 2 | 5 | 4.2 | 4.7 | 16.5 |
| 26 | 131 | 63 | 3 | 6 | 5.1 | 4.3 | 21.7 |
| 27 | 131 | 63 | 4 | 4 | 3.7 | 3.6 | 13.6 |

Signal-to-Noise (S/N) Ratios

Signal to Noise (S/N) ratios of $R_a$, $R_q$ and $R_z$ were calculated by using Lower-the-better characteristic and values were given in the Table 6.

Lower-the-better: it is used where the smaller value of response is desired.

S/N ratio = $-10 \log_{10} [Y_i^2]$

Where, $Y_i$ is observed response.

S/N ratio is Signal to Noise ratio

**Table 6. Signal to Noise Ratios of Responses**

| S.NO. | Signal to Noise (S/N) ratios | | |
|---|---|---|---|
| | $R_a$ | $R_q$ | $R_z$ |
| 1 | -8.03 | -8.63 | -19.89 |
| 2 | -14.15 | -12.81 | -26.65 |
| 3 | -17.18 | -16.70 | -28.41 |
| 4 | -12.71 | -13.59 | -25.11 |
| 5 | -15.74 | -15.28 | -27.58 |
| 6 | -9.60 | -11.25 | -22.37 |
| 7 | -17.07 | -15.53 | -28.88 |
| 8 | -12.49 | -12.26 | -24.01 |
| 9 | -14.39 | -15.24 | -26.90 |
| 10 | -11.43 | -8.66 | -23.59 |
| 11 | -17.52 | -16.91 | -29.22 |
| 12 | -10.21 | -11.03 | -22.28 |
| 13 | -12.59 | -12.34 | -24.30 |
| 14 | -10.10 | -7.89 | -21.51 |
| 15 | -15.13 | -14.55 | -26.49 |
| 16 | -8.82 | -8.06 | -20.59 |
| 17 | -12.40 | -14.15 | -24.66 |
| 18 | -16.79 | -15.04 | -29.04 |
| 19 | -14.74 | -14.50 | -25.71 |
| 20 | -10.93 | -9.86 | -22.73 |
| 21 | -13.84 | -14.15 | -25.67 |
| 22 | -7.23 | -5.85 | -19.46 |
| 23 | -11.69 | -10.32 | -23.97 |
| 24 | -15.92 | -15.53 | -27.38 |
| 25 | -12.49 | -13.42 | -24.35 |
| 26 | -14.15 | -12.69 | -26.73 |
| 27 | -11.41 | -11.03 | -22.67 |

Grey relational generation

Normalisation of responses from zero to one is made by using lower the better characteristic given below and the values were given in the Table 7.

$$Z_{ij} = \frac{\max\left(Y_{ij},\ i = 1,2,\ldots\ldots n\right) - Y_{ij}}{\max\left(Y_{ij},\ i = 1,2\ldots\ldots\ldots n\right) - \min\left(Y_{ij},\ i = 1,2,\ldots\ldots n\right)}$$

Where $Y_{ij}$ is response value.

**Table 7. Grey Relational Generation**

| S.NO. | Smaller the better | | |
|---|---|---|---|
| | $R_a$ | $R_q$ | $R_z$ |
| 1 | 0.96 | 0.86 | 0.98 |
| 2 | 0.46 | 0.53 | 0.38 |
| 3 | 0.05 | 0.03 | 0.13 |
| 4 | 0.61 | 0.44 | 0.56 |
| 5 | 0.27 | 0.24 | 0.26 |
| 6 | 0.86 | 0.67 | 0.81 |
| 7 | 0.07 | 0.20 | 0.06 |
| 8 | 0.63 | 0.58 | 0.67 |
| 9 | 0.43 | 0.24 | 0.35 |
| 10 | 0.73 | 0.86 | 0.71 |
| 11 | 0.00 | 0.00 | 0.00 |
| 12 | 0.82 | 0.69 | 0.82 |
| 13 | 0.62 | 0.57 | 0.64 |
| 14 | 0.83 | 0.90 | 0.87 |
| 15 | 0.34 | 0.33 | 0.40 |
| 16 | 0.91 | 0.89 | 0.93 |
| 17 | 0.64 | 0.38 | 0.61 |
| 18 | 0.11 | 0.27 | 0.03 |
| 19 | 0.39 | 0.34 | 0.49 |
| 20 | 0.77 | 0.78 | 0.78 |
| 21 | 0.50 | 0.38 | 0.50 |
| 22 | 1.00 | 1.00 | 1.00 |
| 23 | 0.70 | 0.74 | 0.67 |
| 24 | 0.24 | 0.20 | 0.28 |
| 25 | 0.63 | 0.46 | 0.64 |
| 26 | 0.46 | 0.54 | 0.37 |
| 27 | 0.73 | 0.69 | 0.78 |

Loss function

Loss function can be calculated by using formulae and the values were given in the table 8.

Delta (Δ) = (Quality loss) = $\left|Y_o - Y_{ij}\right|$

 

**Table 8. Loss Function Values**

| S.NO. | $R_a$ | $R_q$ | $R_z$ |
|---|---|---|---|
| 1 | 0.04 | 0.14 | 0.02 |
| 2 | 0.54 | 0.47 | 0.62 |
| 3 | 0.95 | 0.97 | 0.87 |
| 4 | 0.39 | 0.56 | 0.44 |
| 5 | 0.73 | 0.76 | 0.74 |
| 6 | 0.14 | 0.33 | 0.19 |
| 7 | 0.93 | 0.80 | 0.94 |
| 8 | 0.37 | 0.42 | 0.33 |
| 9 | 0.57 | 0.76 | 0.65 |
| 10 | 0.28 | 0.14 | 0.29 |
| 11 | 1.00 | 1.00 | 1.00 |
| 12 | 0.18 | 0.31 | 0.18 |
| 13 | 0.38 | 0.43 | 0.36 |
| 14 | 0.17 | 0.10 | 0.13 |
| 15 | 0.66 | 0.67 | 0.60 |
| 16 | 0.09 | 0.11 | 0.07 |
| 17 | 0.36 | 0.62 | 0.39 |
| 18 | 0.89 | 0.73 | 0.97 |
| 19 | 0.61 | 0.66 | 0.51 |
| 20 | 0.23 | 0.22 | 0.22 |
| 21 | 0.50 | 0.62 | 0.50 |
| 22 | 0.00 | 0.00 | 0.00 |
| 23 | 0.30 | 0.26 | 0.33 |
| 24 | 0.76 | 0.80 | 0.72 |
| 25 | 0.37 | 0.54 | 0.36 |
| 26 | 0.54 | 0.46 | 0.63 |
| 27 | 0.27 | 0.31 | 0.22 |

Grey coefficient (with $\Psi = 0.5$)

Grey relational coefficient represents the correlation between the desired and actual experimental data. The grey relational coefficient of responses can be calculated by using the below formulae and corresponding values were given in the Table 9.

$$GC = \frac{\Delta_{min} + \delta \Delta_{max}}{\Delta_{0i} + \delta \Delta_{max}}$$

Where,

$\Delta_{0i}$ = quality loss

$\Delta min$ = minimum value of $\Delta_{0i}$

$\Delta max$ = maximum value of $\Delta_{0i}$

$\delta$ = distinguishing coefficient ($0 \leq \delta \leq 1$)

**Table 9. Grey Coefficient Values of Responses**

| S.NO. | $R_a$ | $R_q$ | $R_z$ |
|---|---|---|---|
| 1 | 0.92 | 0.78 | 0.95 |
| 2 | 0.48 | 0.51 | 0.45 |
| 3 | 0.35 | 0.34 | 0.37 |
| 4 | 0.56 | 0.47 | 0.53 |
| 5 | 0.40 | 0.40 | 0.40 |
| 6 | 0.78 | 0.60 | 0.72 |
| 7 | 0.35 | 0.39 | 0.35 |
| 8 | 0.58 | 0.54 | 0.60 |
| 9 | 0.47 | 0.40 | 0.43 |
| 10 | 0.65 | 0.78 | 0.63 |
| 11 | 0.33 | 0.33 | 0.33 |
| 12 | 0.73 | 0.62 | 0.73 |
| 13 | 0.57 | 0.54 | 0.58 |
| 14 | 0.74 | 0.84 | 0.80 |
| 15 | 0.43 | 0.43 | 0.45 |
| 16 | 0.85 | 0.83 | 0.88 |
| 17 | 0.58 | 0.45 | 0.56 |
| 18 | 0.36 | 0.41 | 0.34 |
| 19 | 0.45 | 0.43 | 0.50 |
| 20 | 0.68 | 0.69 | 0.69 |
| 21 | 0.50 | 0.45 | 0.50 |
| 22 | 1.00 | 1.00 | 1.00 |
| 23 | 0.63 | 0.66 | 0.60 |
| 24 | 0.40 | 0.39 | 0.41 |
| 25 | 0.58 | 0.48 | 0.58 |
| 26 | 0.48 | 0.52 | 0.44 |
| 27 | 0.65 | 0.62 | 0.70 |

Grey relational grade and its order (GRG)

The Grey relational grade can be calculated by using the below formulae. The experiment with high grey relational grade value represents the optimal parametric combination for the multi responses. From the table10 and Figure 1, 22nd experiment gives the best multi performance characteristics among the twenty seven experiments.

$$GRG = \frac{1}{m}\sum GC$$

Where, GRG is grey relational grade
m is the number of responses.

 

**Table 10. Grey Relational Grade and Order**

| S.NO. | GRG | SN of GRG | Rank |
|---|---|---|---|
| 1 | 0.886 | -1.054 | 2 |
| 2 | 0.480 | -6.370 | 18 |
| 3 | 0.350 | -9.108 | 26 |
| 4 | 0.522 | -5.639 | 15 |
| 5 | 0.401 | -7.938 | 22 |
| 6 | 0.703 | -3.062 | 5 |
| 7 | 0.361 | -8.862 | 25 |
| 8 | 0.574 | -4.826 | 11 |
| 9 | 0.434 | -7.255 | 21 |
| 10 | 0.685 | -3.289 | 8 |
| 11 | 0.333 | -9.554 | 27 |
| 12 | 0.694 | -3.179 | 6 |
| 13 | 0.564 | -4.979 | 12 |
| 14 | 0.793 | -2.019 | 4 |
| 15 | 0.438 | -7.162 | 20 |
| 16 | 0.852 | -1.387 | 3 |
| 17 | 0.529 | -5.532 | 14 |
| 18 | 0.369 | -8.656 | 24 |
| 19 | 0.459 | -6.758 | 19 |
| 20 | 0.689 | -3.235 | 7 |
| 21 | 0.481 | -6.356 | 16 |
| 22 | 1.000 | 0.000 | 1 |
| 23 | 0.631 | -3.999 | 10 |
| 24 | 0.398 | -8.008 | 23 |
| 25 | 0.546 | -5.262 | 13 |
| 26 | 0.481 | -6.355 | 17 |
| 27 | 0.654 | -3.691 | 9 |

 

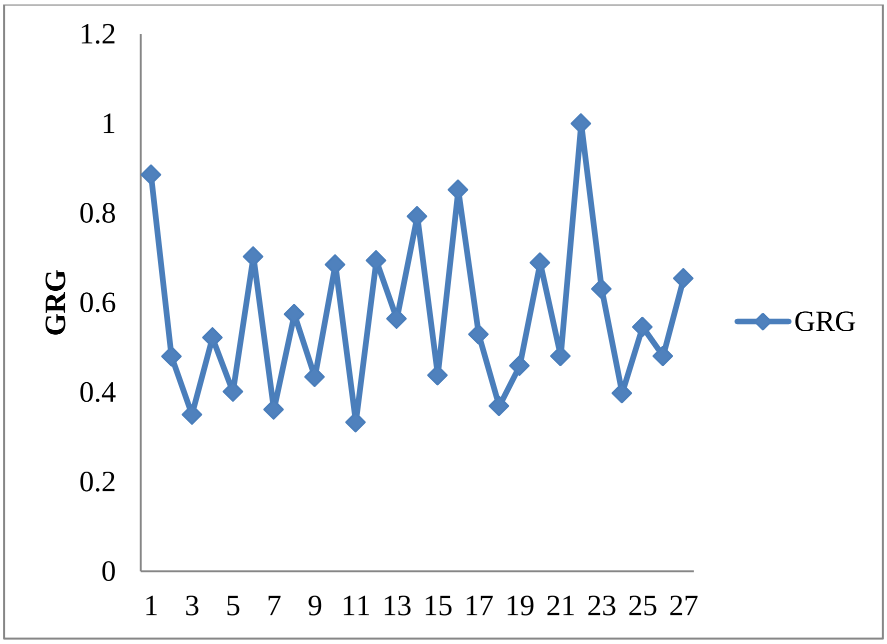


**Figure 1. Experiment Number Vs GRG**

The mean S/N ratios were calculated for the Grey relational grade and given in the Table 11. From, the mean S/N ratio values main effect plot for the grey relational grade was drawn and shown in Figure 2. From the Table 11, it is clear that the wire feed rate is the most significant factor affecting the multiple performance characteristics followed by wire tension, Pulse on time and Pulse off time. The optimal combination of process parameters with their levels and values was given in the Table 12.

**Table 11. Response Table for Signal to Noise Ratios of GRG**

| Level | $T_{ON}$ | $T_{OFF}$ | WT | WF |
|---|---|---|---|---|
| 1 | -6.013 | -5.434 | -4.137 | -2.495 |
| 2 | -5.084 | -4.756 | -5.536 | -5.652 |
| 3 | -4.852 | -5.758 | -6.275 | -7.802 |
| Delta | 1.161 | 1.002 | 2.138 | 5.307 |
| Rank | 3 | 4 | 2 | 1 |

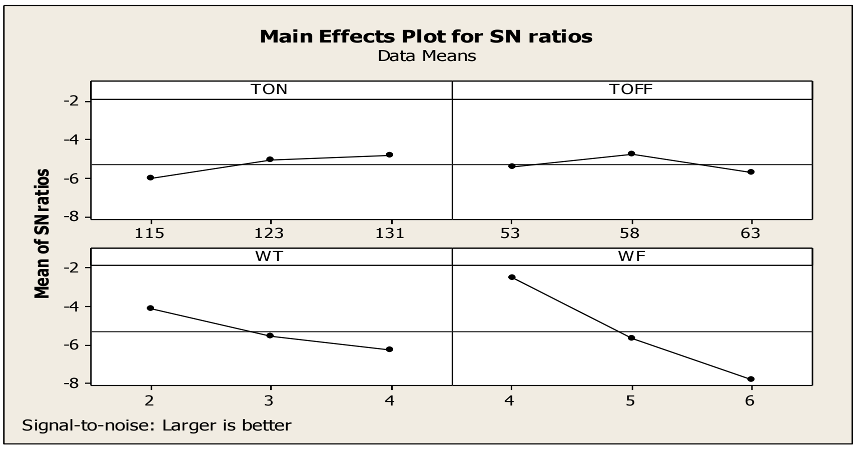


**Figure 2. Main Effect Plot for S/N Ratios of GRG**

 

**Table 12. Optimal Combination of Parameters**

| Process parameter | Best level | Value |
|---|---|---|
| $T_{ON}$, µs | 3 | 131 |
| $T_{OFF}$, µs | 2 | 58 |
| WT, Kg-f | 1 | 2 |
| WF, m/min | 1 | 4 |

**Table 13. Analysis of Variance for GRG**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Significance |
|---|---|---|---|---|---|---|---|
| TON | 2 | 0.025878 | 0.025878 | 0.012939 | 2.71 | 0.093 | - |
| TOFF | 2 | 0.023868 | 0.023868 | 0.011934 | 2.50 | 0.110 | - |
| WT | 2 | 0.107878 | 0.107878 | 0.053939 | 11.31 | 0.001 | Significant |
| WF | 2 | 0.564612 | 0.564612 | 0.282306 | 59.18 | 0.000 | significant |
| Error | 18 | 0.085859 | 0.085859 | 0.004770 | | | |
| Total | 26 | 0.808095 | | | | | |

S = 0.0690646   R-Sq = 89.38%   R-Sq(adj) = 84.65%

From the ANOVA of GRG given in the Table 13, it is observed that WF has high significance (F = 59.18, P = 0.000), WT (F = 11.31, P = 0.001) and TON (F = 2.71, P = 0.093) have moderate significance and TOFF (F = 2.50, P = 0.110) has very least significance in getting low surface roughness characteristics.

### 3.1. Regression Analysis

The surface roughness prediction models for $R_a$, $R_q$ and $R_z$ have been developed using the MINITAB-16 software. The coefficient of determination ($R^2$) has been computed for checking the accuracy of models. The relationship between input parameters and output characteristics were given by

$R_a = 0.05 - 0.0388\ T_{ON} + 0.0024\ T_{OFF} + 0.530\ WT + 1.53\ WF$

S = 0.661467   R-Sq = 83.5%   R-Sq (adj) = 80.5%

$R_q = 1.26 - 0.0466\ T_{ON} + 0.0110\ T_{OFF} + 0.592\ WT + 1.30\ WF$

S = 0.700627   R-Sq = 78.4%   R-Sq (adj) = 74.5%

$R_z = 0.8 - 0.180\ T_{ON} + 0.075\ T_{OFF} + 2.06\ WT + 5.83\ WF$

S = 2.34622   R-Sq = 85.7%   R-Sq (adj) = 83.1%

The residual plots for $R_a$, $R_q$ and $R_z$ were drawn and shown in Figures 3, 4 and 5. From the figures it is clear that the errors are distributed normally and good agreement that the models are significant. The analysis confirms that the models prepared can be used for accurate prediction of surface roughness characteristics.

 

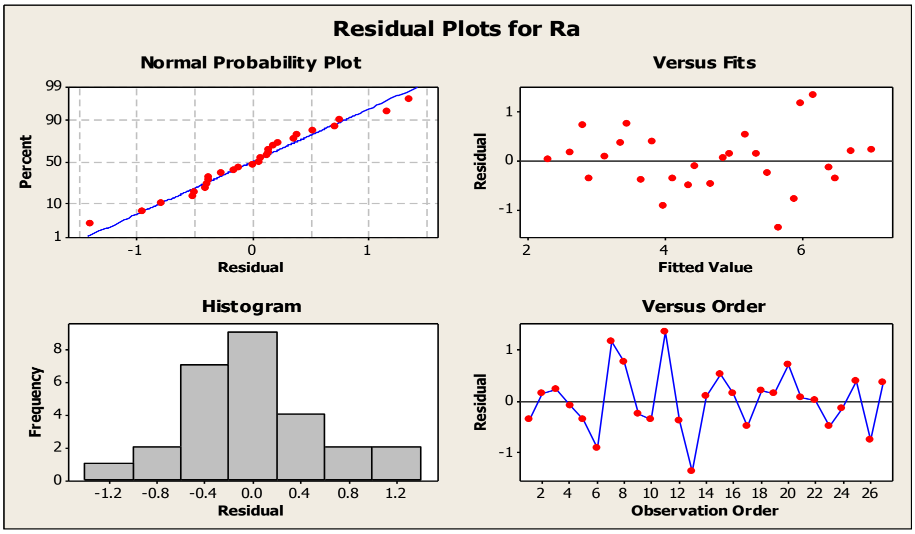


Figure 3. Residual Plots for $R_a$

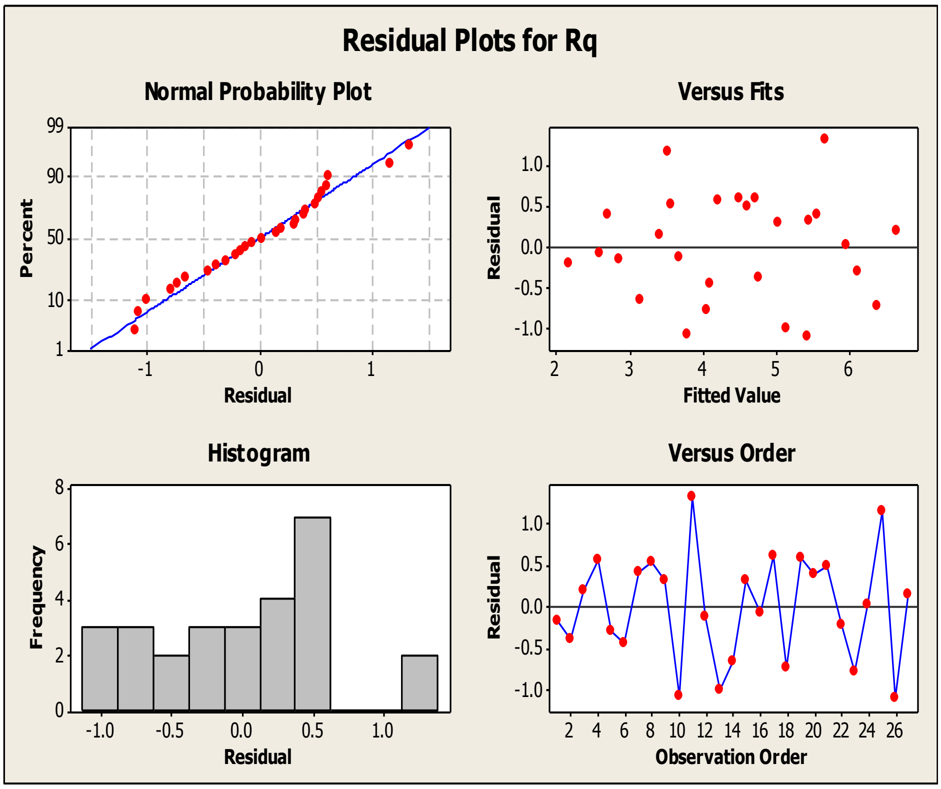


Figure 4. Residual Plots for $R_q$

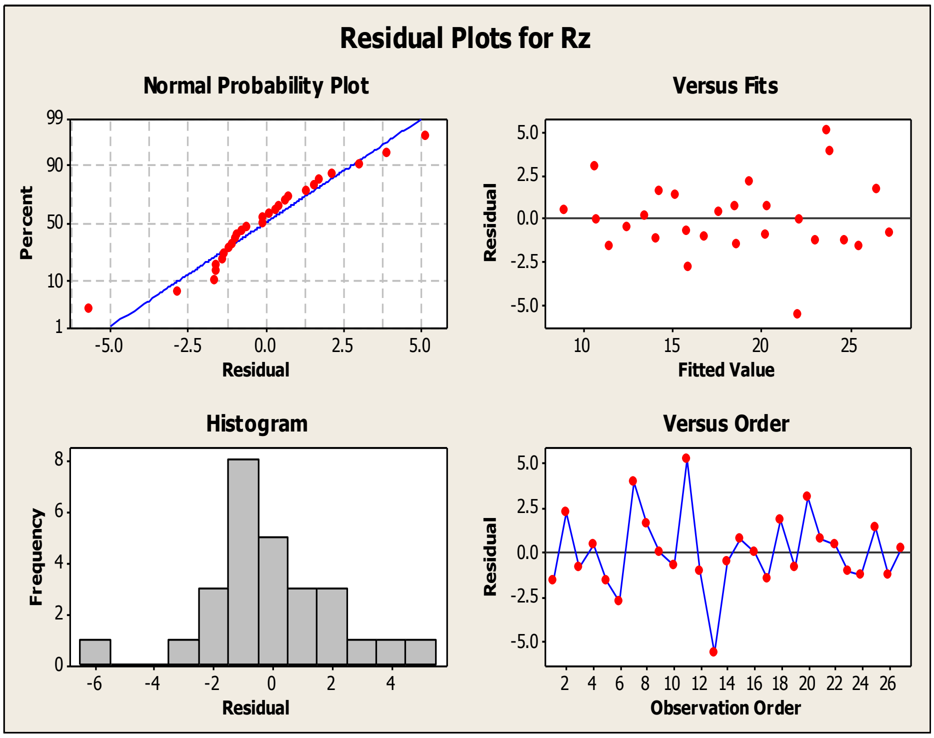


**Figure 5. Residual Plots for $R_z$**

Finally from the regression models, predicted values of $R_a$, $R_q$ and $R_z$ were calculated and given in the Table 14. The predicted values were compared with the experimental values and comparison graphs were drawn by taking experiment number on X-axis and output Responses on Y-axis and shown in Figures 6, 7 and 8. From the Figures it is clear that both experimental and regression values are close to each other.

**Table 14. Comparison of Experimental and Regression Values**

| S.NO. | $R_a$ | | $R_q$ | | $R_z$ | |
|---|---|---|---|---|---|---|
| | Experimental | Regression | Experimental | Regression | Experimental | Regression |
| 1 | 2.5 | 2.9 | 2.7 | 2.9 | 9.9 | 11.5 |
| 2 | 5.1 | 5.0 | 4.4 | 4.8 | 21.5 | 19.4 |
| 3 | 7.2 | 7.0 | 6.8 | 6.7 | 26.3 | 27.3 |
| 4 | 4.3 | 4.4 | 4.8 | 4.2 | 18.0 | 17.7 |
| 5 | 6.1 | 6.5 | 5.8 | 6.1 | 23.9 | 25.6 |
| 6 | 3.0 | 4.0 | 3.7 | 4.1 | 13.1 | 16.0 |
| 7 | 7.1 | 6.0 | 6.0 | 5.6 | 27.8 | 23.9 |
| 8 | 4.2 | 3.4 | 4.1 | 3.6 | 15.9 | 14.3 |
| 9 | 5.2 | 5.5 | 5.8 | 5.5 | 22.1 | 22.2 |
| 10 | 3.7 | 4.1 | 2.7 | 3.8 | 15.1 | 15.9 |
| 11 | 7.5 | 6.2 | 7.0 | 5.7 | 28.9 | 23.8 |
| 12 | 3.2 | 3.6 | 3.6 | 3.7 | 13.0 | 14.2 |
| 13 | 4.3 | 5.7 | 4.1 | 5.2 | 16.4 | 22.1 |
| 14 | 3.2 | 3.1 | 2.5 | 3.1 | 11.9 | 12.5 |
| 15 | 5.7 | 5.2 | 5.3 | 5.0 | 21.1 | 20.4 |
| 16 | 2.8 | 2.6 | 2.5 | 2.6 | 10.7 | 10.8 |
| 17 | 4.2 | 4.7 | 5.1 | 4.5 | 17.1 | 18.7 |
| 18 | 6.9 | 6.7 | 5.7 | 6.4 | 28.3 | 26.6 |

 

| | | | | | | |
|---|---|---|---|---|---|---|
| 19 | 5.5 | 5.3 | 5.3 | 4.7 | 19.3 | 20.3 |
| 20 | 3.5 | 2.8 | 3.1 | 2.7 | 13.7 | 10.7 |
| 21 | 4.9 | 4.9 | 5.1 | 4.6 | 19.2 | 18.6 |
| 22 | 2.3 | 2.3 | 2.0 | 2.2 | 9.4 | 9.0 |
| 23 | 3.8 | 4.3 | 3.3 | 4.1 | 15.8 | 16.9 |
| 24 | 6.3 | 6.4 | 6.0 | 6.0 | 23.4 | 24.8 |
| 25 | 4.2 | 3.8 | 4.7 | 3.5 | 16.5 | 15.2 |
| 26 | 5.1 | 5.9 | 4.3 | 5.4 | 21.7 | 23.1 |
| 27 | 3.7 | 3.4 | 3.6 | 3.4 | 13.6 | 13.5 |

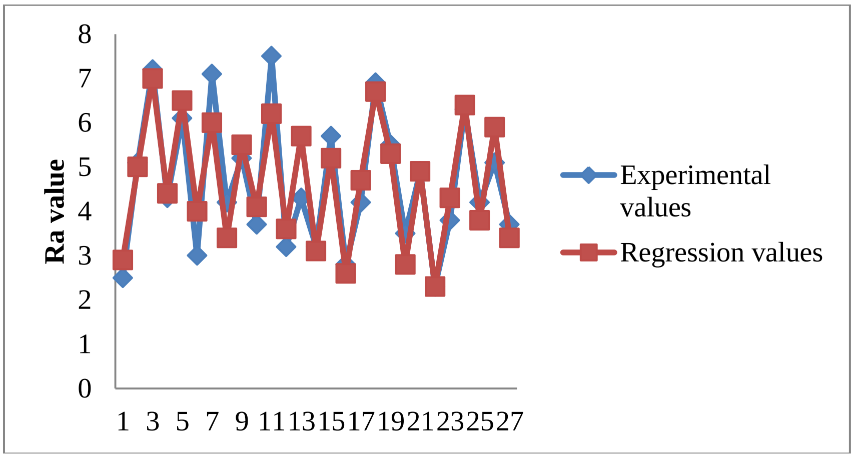


**Figure 6. Experiment No. Vs Ra**

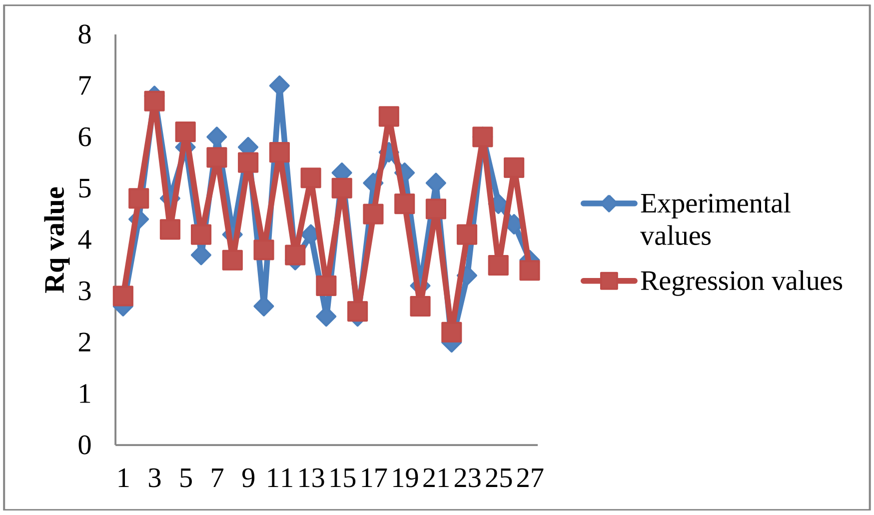


**Figure 7. Experiment No. Vs Rq**

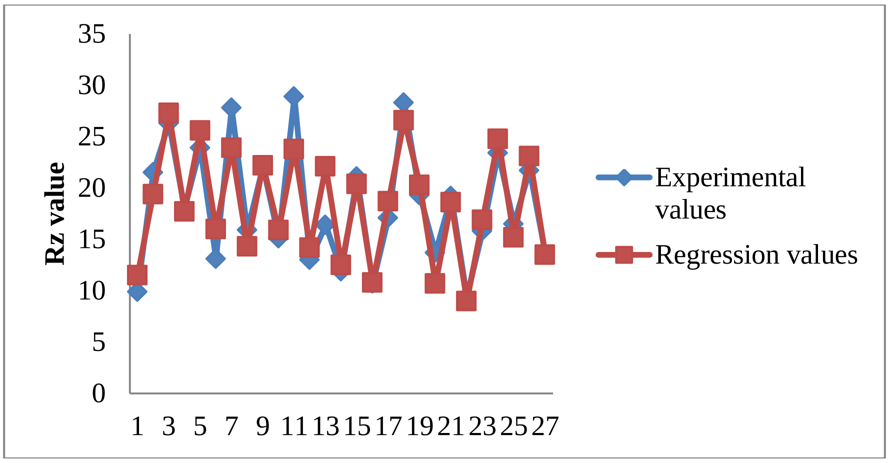


**Figure 8. Experiment No. Vs Rz**

## 4. Conclusions

Based on the experimental and Regression results obtained by Grey analysis and ANOVA, the following conclusions can be drawn:

- From Grey analysis, the Optimal combination of process parameters is obtained at
  Pulse on time ($T_{ON}$): level 3, 131 µs
  Pulse-off time ($T_{OFF}$): level 2, 58 µs
  Wire Tension (WT): level 1, 2 Kg-f
  Wire Feed rate (WF): level 1, 1 m/min.
- From ANOVA results, it is clear that the wire feed rate is the most dominant parameter that has high influence on Grey relational grade followed by wire tension, Pulse on time ($T_{ON}$) and Pulse off time ($T_{OFF}$) has very low influence.
- Regression models prepared were accurate and adequate and they can be used for the prediction of Surface Roughness parameters $R_a$, $R_q$ and $R_z$.

## 5. Scope of Future Work

- The present work can be extended further for different conditions of EDM process parameters at different levels for different materials.
- The present work can be analyzed with other optimization methods available.
- The present work can be done by changing the dielectric fluid and the wire electrode for the same material and EDM process parameters.

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