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# A Comparative Experimental Investigation on Process Parameters Using Molybdenum, Brass and Zinc-Coated Wires in Wire cut EDM

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**Abstract**— In this paper, a comparative experimental investigation on process parameters is carried out in reusable type wire electrical discharge machining on high nickel chromium based Inconel 600 material, using three different wires namely, molybdenum, plain brass and zinc coated brass wires. This investigation is carried out to find best optimal level for higher material removal rate at lower surface roughness for Inconel 600 material and to check best suitable wire among the three wires. The experiments were conducted under varying pulse on time, pulse off time and peak current. A full factorial design of experiment with $L_{27}$ array used for determining the setting of machining parameters. Based on array total 81 experiment has been conducted for three wires. The level of importance and percentage contribution of each parameter for material removal rate and surface roughness are determined by using analysis of variance (ANOVA). The optimum machining parameter combination is obtained by using grey relational analysis. The variation of the material removal rate and surface roughness is mathematically modeled by using regression analysis method. The optimal search for machining parameters for objective of maximum material removal rate with lower surface roughness is performed by comparing the optimal level obtained by grey relational analysis with the established mathematical model.

**Index Terms**— ANOVA, full factorial, GRA, INCONEL 600, MRR, Surface Roughness, WEDM

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## 1 Introduction

Electrical discharge wire cutting, more commonly known as wire electrical discharge machining (WEDM), is a spark erosion process used to produce complex two- and three-dimensional shapes through electrically conductive work pieces by using wire electrode. The sparks will be generated between the work piece and a wire electrode flushed with or immersed in a dielectric fluid. The degree of accuracy of work piece dimensions obtainable and the fine surface finishes make WEDM particularly valuable for applications involving manufacture of stamping dies, extrusion dies and prototype parts. Without WEDM the fabrication of precision work pieces requires many hours of manual grinding and polishing.

The most important performance measures in WEDM are material removal rate (or cutting speed), and workpiece surface finish. Discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, average working voltage and dielectric flushing conditions are the machining parameters which affect the performance measures.

Optimum utilization of the capability of the WEDM process requires the selection of an appropriate set of machining parameters. The machinability database supplied by the manufacturer helps the users and the system make decision regarding the stages of machining operations, wire electrode materials, machine and power supply setting, electrode position etc. This available technological data, which is based on manufacturer's in house experimentation, is helpful but insufficient. Moreover, the manufacturer's guidelines for the selection of machining parameters are conservative in nature and do not leads to optimal and economically effective use of the machines for the particular work piece materials.

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## 2 Literature Review

Tosun Nihat et al. [1] have investigated the effect and optimization of machining parameters on the kerf (cutting width) and material removal rate (MRR) in WEDM operations on AISI 4140 steel with brass wire of 0.25mm. Chiang Ko-Ta et al. [2] present an effective approach for the optimization of the wire electrical discharge machining of $Al_2O_3$ particle reinforced material (6061 alloy) with multiple performance characteristics based on grey relational analysis. Shandilya Pragya et al. [3] have presented a study to optimize the process parameters during machining of SiCp/6061Al metal matrix composite (MMC) by wire electrical discharge machining (WEDM) using response surface methodology (RSM). Sarkar S. et al. [4] carried out an extensive research study with an aim to select the optimum cutting condition for y-titanium aluminide alloy with an appropriate wire offset setting in order to get the desired surface finish and dimensional accuracy. Ching Chen Hsien, et al. [5] have studied that, the cutting velocity and work piece surface finish depending on wire electrical discharge machining (WEDM) process parameters during manufacture of pure tungsten profiles. For that they proposed an integrating method of back-propagation neural network (BPNN) and simulated annealing algorithm (SAA) to determine the optimal parameter setting for WEDM process. Cabanesa I. et al. [6] have proposed a methodology that used for early detection of instability of wire that can be used to avoid the detrimental effects associated to both unstable machining and wire breakage. Again, Cabanesa I. et al. [7] have studied that, the risk of wire breakage affects adversely the full potential of WEDM and reduced the overall process efficiency so they discusses on the results of the analyses of an exhaustive experimental database that reproduces unexpected disturbances that may appear during normal operation. The results of the analyses reveal new symptoms that allow one to predict wire breakage. Y.S. Liao et al. [8] have studied on the wire breaking process and its monitoring during wire electrical discharge machining. For that they developed a new computer-aided pulse discrimination system based on the characteristics of voltage waveform during machining to reduce the wire breakage. Saha S. et al. [9] have developed a simple finite element model and new approach to predict the thermal distribution in the wire. The model can be used to optimize the different parameters of the system to prevent the wire breakage. Puri A.B. et al. [10] have carried out an extensive study of the wire lag phenomenon in Wire-cut Electrical Discharge Machining (WEDM). In which they carried out trim and rough cutting operation and find out the main influencing factors for average cutting speed, surface finish characteristics and geometrical inaccuracy caused due to wire lag, and also find out the optimum parameter. Sanchez J.A et al. [11] have studied on Experimental and numerical study of angular error in wire-EDM taper-cutting. For that, they presented a new approach for the prediction of angular error in wire-EDM taper cutting. In which by systematic analysis of influence process parameters on angular error and FEM analysis they optimize the error. Ramakrishnana R. et al. [12] have developed an ANN using Back propagation neural network (BPNN) to predict the performance characteristics such as MRR, Surface roughness and to select the best cutting parameters of WEDM. For experiments they select Inconel 718 as a work piece material and 0.25 mm diameter Brass wire as a wire electrode. Hewidy M.S. et al. [13] have studied on modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. In which they use 0.25 mm brass wire as electrode. Liao Y.S. et al. [14] have studied specific discharge energy in WEDM and its application. In which they used a Al alloy 6061, Super alloy Inconel 718, Ti alloy Ti–6Al–4V, Stainless steel, US 304, Cold work tool steel, SKD11, Hot work tool steel, SKD61 as a work piece materials and Brass wire of 0.25mm in diameter as a wire electrode. Aspinwall D.K. et al. [15] have worked on Work piece surface roughness and integrity after WEDM of Ti–6Al–4V and Inconel 718 using minimum damage generator technology. In which they use Zinc-coated brass wire of 0.20 mm and Brass wire of 0.25 mm as a wire electrodes. Balasubramanian S. [16] has studied on optimization of process parameters in Wire Electro Discharge Machining for Inconel 718 material. They also used Brass wire of 0.25 mm in diameter as an electrode.

The survey of literature indicates that there are published works on wire wear, wire crater, accuracy of wire, wire rupture and WEDM monitoring and control, but still limited work has been published on effect of machining parameters and its optimization. Most of the work performed using Brass wire alone but very limited work published on molybdenum and zinc-coated wires. In this study, the effect of the machining parameters and their level of significance on the MRR and surface roughness are statistically evaluated by using analysis of variance (ANOVA). Also, an optimization study with multi-performance outputs is introduced for the case of high MRR and low Surface roughness. Experiments were conducted under different machining parameters, namely, pulse on time, pulse off time and peak current. The settings of machining parameters were determined by using full factorial experimental design method.

## 3 Experiments

### 3.1 Materials, Test Condition and Measurement

The experiment studies were performed on CNC-Wire cut EDM. Different setting of pulse on time, pulse off time and peak current were used in the experiments (Table 1). Wire speed (11.2 m/s), and wire tension (1.2 kg.) were kept constant throughout the experiments.

The three different wire electrode namely Molybdenum wire of 0.18mm, Plain Brass wire of 0.25mm and Zinc coated brass wire of 0.25mm were used in the experiments. As work piece material, Nickel- chromium based INCONEL 600 with two plate of 150mm × 300mm × 10 mm size was used. During the experiments 10mm×10mm×10mm block size was made on the work piece.

The surface roughness was measured using the Mitutoyo Surface roughness tester Model: SJ 201P. The surface roughness values given in the study are the mathematical average of four measurements made from the work piece on four sides. Similarly the kerf width measured on profile projector. The values in the study are mathematical average of three measurements made from the work piece.

Material Removal rate (MRR) is calculated by using the following formulae:

$$MRR = k \times t \times l \quad (1)$$

Here, k is the kerf width, t is the work piece thickness (10 mm) and l is the cutting length (40mm) per unit machining time in minute.

Table 1
Machining setting used in the experiments

| Symbol | Machining Parameters | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Peak Current | Amp | 3 | 5 | 7 |
| B | Pulse_on Time | μs | 16 | 32 | 48 |
| C | Pulse_off Time | μs | 4 | 8 | 12 |

### 3.2 Design of Experiment Based on Full Factorial Method

To evaluate the effects of machining parameters on performance characteristics, (MRR and Surface roughness) and to identify the performance characteristics under the optimal machining parameters, a specially designed experimental procedure is required. In this study, a full factorial method was used, because, which gives all the possible pair of selected

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levels for experiments. The Table 2 shows the $L_{27}$ full factorial array and result obtained after performing experiments based on it.

## 4 Analysis and Discussion of Experimental Results

The analysis of variance was used to establish statistically significant machining parameters and the percentage contribution of these parameters on the MRR and surface roughness. The analysis of variance (ANOVA) was done using minitab-16 software.

### 4.1 Analysis of Variance (ANOVA) for Molybdenum Wire Response

#### 4.1.1 ANOVA for Material Removal Rate (MRR)

The Table 3, shows the analysis of variance for material removal rate, in which the coefficient of determination $R^2$ as 96.42%.The higher the value of the $R^2$ indicates the better fitting the model with the data. The value of P (probability) for peak current, pulse on time and pulse off time is less than 0.05, shows all parameters are significant for MRR. The rank order as per significance level is pulse on time (Ton), peak current (Ip) and pulse off time (Toff). The percentage contribution of residual error is 3.58%, it is strengthen the analysis because it is on minimum side.

Table 3

ANOVA for MRR – Moly Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 6.3608 | 6.3608 | 3.1804 | 80.21 | 0 | 28.69 |
| $T_{on}$ | 2 | 11.522 | 11.522 | 5.7615 | 145.3 | 0 | 51.97 |
| $T_{off}$ | 2 | 3.4943 | 3.4943 | 1.7471 | 44.06 | 0 | 15.76 |
| Error | 20 | 0.793 | 0.793 | 0.0397 | | | 3.58 |
| Total | 26 | 22.171 | | | | | 100 |

S = 0.199123 R-Sq = 96.42% R-Sq(adj) = 95.35%

Table 2

$L_{27}$ Full Factorial Array and Experimental Results

| Input Parameters | | | | Output Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Molybdenum Wire | | Plain Brass Wire | | Zinc-Coated Brass Wire | |
| Ex. No | Peak Current (Amp) | Pulse on Time (μs) | Pulse off Time (μs) | MRR ($mm^3$/sec) | Ra (μm) | MRR ($mm^3$/sec) | Ra (μm) | MRR ($mm^3$/sec) | Ra (μm) |
| 1 | 3 | 16 | 4 | 2.257 | 2.660 | 2.990 | 3.062 | 2.920 | 2.913 |
| 2 | 3 | 16 | 8 | 2.030 | 2.123 | 2.628 | 2.512 | 2.529 | 2.178 |
| 3 | 3 | 16 | 12 | 1.650 | 1.807 | 2.381 | 2.309 | 2.222 | 2.159 |
| 4 | 3 | 32 | 4 | 3.074 | 3.660 | 3.540 | 3.963 | 3.411 | 3.815 |
| 5 | 3 | 32 | 8 | 2.709 | 2.621 | 3.184 | 2.545 | 3.133 | 2.675 |
| 6 | 3 | 32 | 12 | 2.220 | 2.548 | 2.913 | 2.324 | 2.843 | 2.797 |
| 7 | 3 | 48 | 4 | 3.879 | 3.886 | 4.565 | 4.188 | 4.643 | 4.039 |
| 8 | 3 | 48 | 8 | 3.591 | 3.349 | 4.228 | 3.447 | 4.222 | 3.494 |
| 9 | 3 | 48 | 12 | 2.900 | 3.033 | 3.406 | 3.339 | 3.360 | 3.189 |
| 10 | 5 | 16 | 4 | 3.210 | 3.578 | 3.614 | 3.679 | 3.520 | 3.827 |
| 11 | 5 | 16 | 8 | 2.650 | 3.122 | 3.442 | 3.425 | 3.340 | 3.279 |
| 12 | 5 | 16 | 12 | 1.750 | 1.967 | 2.396 | 2.469 | 2.307 | 2.318 |
| 13 | 5 | 32 | 4 | 3.701 | 3.796 | 4.303 | 4.097 | 4.301 | 3.749 |
| 14 | 5 | 32 | 8 | 3.241 | 3.260 | 3.772 | 3.564 | 4.010 | 3.610 |
| 15 | 5 | 32 | 12 | 2.849 | 2.944 | 3.227 | 3.347 | 3.221 | 3.198 |
| 16 | 5 | 48 | 4 | 4.540 | 4.318 | 5.103 | 4.516 | 5.132 | 4.387 |
| 17 | 5 | 48 | 8 | 4.271 | 3.741 | 5.120 | 4.046 | 4.978 | 3.898 |
| 18 | 5 | 48 | 12 | 3.851 | 2.987 | 4.547 | 3.384 | 4.458 | 3.234 |
| 19 | 7 | 16 | 4 | 3.310 | 3.450 | 3.889 | 3.759 | 3.766 | 3.660 |
| 20 | 7 | 16 | 8 | 2.980 | 2.914 | 3.476 | 3.317 | 3.288 | 3.168 |
| 21 | 7 | 16 | 12 | 2.480 | 2.597 | 3.142 | 2.998 | 3.111 | 2.848 |
| 22 | 7 | 32 | 4 | 4.690 | 4.157 | 5.070 | 4.355 | 4.825 | 4.226 |
| 23 | 7 | 32 | 8 | 4.268 | 3.874 | 4.243 | 4.177 | 4.726 | 4.027 |
| 24 | 7 | 32 | 12 | 3.616 | 3.565 | 4.146 | 3.869 | 4.153 | 3.713 |
| 25 | 7 | 48 | 4 | 4.892 | 4.447 | 5.401 | 4.875 | 5.314 | 4.676 |
| 26 | 7 | 48 | 8 | 4.429 | 4.140 | 5.187 | 4.343 | 5.245 | 4.218 |
| 27 | 7 | 48 | 12 | 4.160 | 3.823 | 5.044 | 4.127 | 4.908 | 3.977 |

#### 4.1.2 ANOVA for Surface Roughness ($R_a$)

The Table 4, shows the analysis of variance for surface roughness, the coefficient of determination $R^2$ is 93.02%, because it is higher value, which fit the data correctly. The value of probability P for Pulse on time, Pulse off time and Peak Current is less than 0.05, so all the parameters are significant for surface roughness. The rank order as per significance level is pulse on time ($T_{on}$), pulse off time ($T_{off}$) and peak current ($I_p$). The percentage contribution of residual error is 6.98%, it is strengthen the analysis because it is on minimum side.

Table 4
ANOVA for $R_a$ – Moly. Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 2.9551 | 2.9551 | 1.4775 | 31.92 | 0 | 22.29 |
| $T_{on}$ | 2 | 5.1763 | 5.1763 | 2.5882 | 55.91 | 0 | 39.04 |
| $T_{off}$ | 2 | 4.2012 | 4.2012 | 2.1006 | 45.38 | 0 | 31.69 |
| Error | 20 | 0.9258 | 0.9258 | 0.0463 | | | 6.98 |
| Total | 26 | 13.258 | | | | | 100 |
| S = 0.215150 R-Sq = 93.02% R-Sq(adj) = 90.92% | | | | | | | |

### 4.2 Analysis of Variance (ANOVA) for Plain Brass Wire Response

#### 4.2.1 ANOVA for Material Removal Rate

Table 5
ANOVA for MRR – Plain Brass Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 5.3436 | 5.3436 | 2.671 | 56.15 | 0 | 25.18 |
| $T_{on}$ | 2 | 11.971 | 11.971 | 5.985 | 125.7 | 0 | 56.42 |
| $T_{off}$ | 2 | 2.9519 | 2.9519 | 1.476 | 31.02 | 0 | 13.91 |
| Error | 20 | 0.9517 | 0.9517 | 0.047 | | | 4.49 |
| Total | 26 | 21.218 | | | | | 100 |
| S = 0.218142 R-Sq = 95.51% R-Sq(adj) = 94.17% | | | | | | | |

The above table 5 shows the analysis of variance for material removal rate, which shows the coefficient of determination $R^2$ is 95.51%, as it is higher value, which fit the data correctly. The value of probability (P) for Pulse on time, Pulse off time and Peak Current is less than 0.05. The rank order as per significance level is pulse on time ($T_{on}$), peak current ($I_p$) and pulse off time ($T_{off}$). The percentage contribution of residual error is 4.49%, it is strengthen the analysis because it is on minimum it is on side.

#### 4.2.2 ANOVA for Surface Roughness

The Table 6, shows the analysis of variance for the surface roughness, which shows the value of coefficient of determination $R^2$ as 91.22 %, as it the higher value, which fit the data correctly. The value of probility (P) is less than 0.05 of pulse on time, pulse off time and peak current, so all the parameters are significant for surface roughness, the rank order as per significance level is pulse on time ($T_{on}$), pulse off time ($T_{off}$) and peak current ($I_p$). The percentage contribution of residual error is 4.49%, it is strengthen the analysis because it is on minimum it is on side.

Table 6
ANOVA for $R_a$ – Plain Brass Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 3.1674 | 3.1674 | 1.5837 | 30.42 | 0 | 26.72 |
| $T_{on}$ | 2 | 3.8683 | 3.8683 | 1.9342 | 37.15 | 0 | 32.63 |
| $T_{off}$ | 2 | 3.7799 | 3.7799 | 1.89 | 36.31 | 0 | 31.88 |
| Error | 20 | 1.0411 | 1.0411 | 0.0521 | | | 8.78 |
| Total | 26 | 11.856 | | | | | 100 |
| S = 0.237286 R-Sq = 91.22% R-Sq(adj) = 88.58% | | | | | | | |

### 4.3 Analysis of Variance (ANOVA) for Zinc Coated Brass Wire Response

#### 4.3.1 ANOVA for Material Removal Rate

Table 7
ANOVA for MRR – Zinc coated Brass Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 5.6834 | 5.6834 | 2.8417 | 64.31 | 0 | 25.22 |
| $T_{on}$ | 2 | 12.931 | 12.931 | 6.466 | 146.33 | 0 | 57.38 |
| $T_{off}$ | 2 | 3.0373 | 3.0373 | 1.5186 | 34.37 | 0 | 13.48 |
| Error | 20 | 0.8837 | 0.8837 | 0.0442 | | | 3.92 |
| Total | 26 | 22.536 | | | | | 100 |
| S = 0.210208 R-Sq = 96.08% R-Sq(adj) = 94.90% | | | | | | | |

The above table 7 shows the analysis of variance for material removal rate, which shows the coefficient of determination $R^2$ is 96.08%, as it is higher value, which fit the data correctly. The value of probability (P) for Pulse on time, Pulse off time and Peak Current is less than 0.05. The rank order as per significance level is pulse on time (Ton), peak current (Ip) and pulse off time (Toff). The percentage contribution of residual error is 3.92%, it is strengthen the analysis because it is on minimum it is on side.

#### 4.3.2 ANOVA for Surface Roughness

The Table 8, shows the analysis of variance for the surface roughness, which shows the value of coefficient of determination $R^2$ as 91.22 %, as it the higher value, which fit the data correctly. The value of probility (P) is less than 0.05 of pulse on time, pulse off time and peak current, so all the parameters are significant for surface roughness, the rank order as per significance level is pulse on time, pulse off time and pulse off time. The percentage contribution of residual error is 4.49%, it is strengthen the analysis because it is on minimum it is on side

Table 8

ANOVA for $R_a$ – Zinc coated Brass Wire

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|---|
| $I_p$ | 2 | 2.9513 | 2.9513 | 1.4756 | 29.99 | 0 | 25.08 |
| $T_{on}$ | 2 | 4.3514 | 4.3514 | 2.1757 | 44.22 | 0 | 36.98 |
| $T_{off}$ | 2 | 3.4806 | 3.4806 | 1.7403 | 35.37 | 0 | 29.58 |
| Error | 20 | 0.984 | 0.984 | 0.0492 | | | 8.36 |
| Total | 26 | 11.767 | | | | | 100 |

S = 0.229785 R-Sq = 91.64% R-Sq(adj) = 89.13%

### 4.4 Main Effect Plots for Material Removal Rate (MRR) and Surface Roughness ($R_a$)

In order to understand the effect of each parameter on the material removal rate and surface roughness obtained by the use of molybdenum, plain brass and zinc coated brass wire, main effective plots were plotted.

#### 4.4.1 Effects of Peak Current on MRR and Surface Rougness

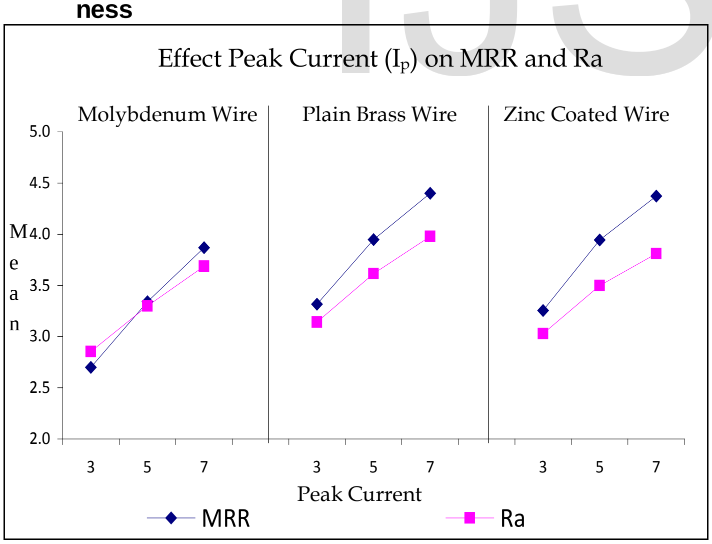


Fig. 1. Effects of Peak Current on MRR and $R_a$

Above figure 1, shows the main effect plots of peak current on material removal rate and surface roughness of molybdenum, plain brass and zinc coated brass wires. From the figure, material removal rate and surface roughness of the three wires are found to have increasing trend with the increase in peak current, because increasing in peak current generates a longer spark between wire and workpiece interface, which melts the more material of the work piece and leads to increase in material removal rate and surface roughness.

#### 4.4.2 Effects of Pulse on Time on MRR and Surface Rougness

Figure 2, shows the main effect plots of pulse on time on material removal rate and surface roughness of molybdenum wire, plain brass wire and zinc coated brass wires. From the figure, material removal rate and surface roughness of the three wires are found to have increasing trend with the increase in pulse on time, because increase in pulse on time allows generating more energy in wire and work piece interface, which makes longer spark and create more deeper crater, this leads to increase the melting and evaporation of the work piece material and increases the material removal rates and surface roughness.

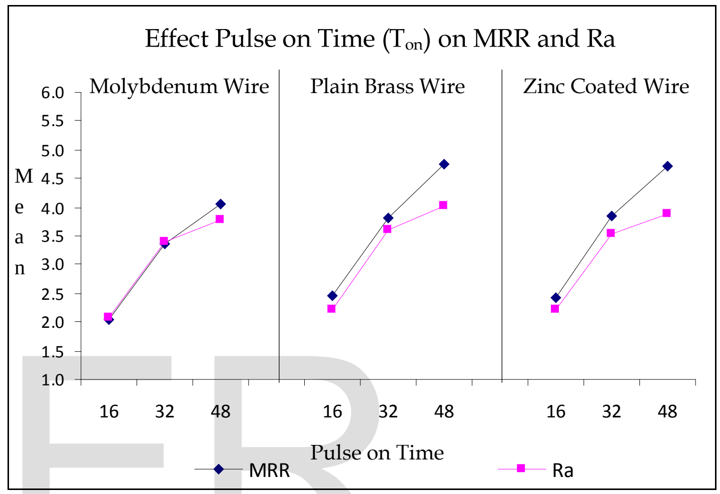


Fig. 2. Effects of Pulse on Time on MRR and $R_a$

#### 4.4.3 Effects of Pulse on Time on MRR and Surface Rougness

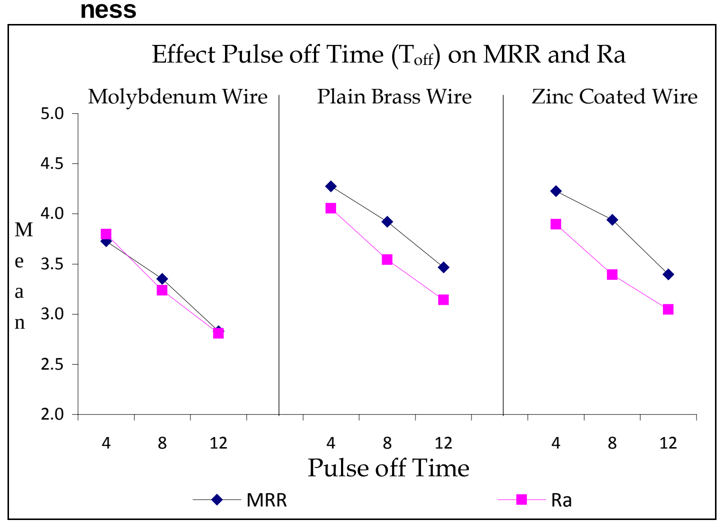


Fig. 3. Effects of Pulse off Time on MRR and $R_a$

Above figure 3, shows the main effect plots of pulse off time on material removal rate and surface roughness of molybdenum, plain brass and zinc coated wires. From the figure, material removal rate and surface roughness of the three wires are found to have decresing trend with the increase in pulse off time, because increase in pulse off time decrease the energy generating in wire and work piece interface, which leads to decrease the melting and evaporation of the work piece material and decreases the material removal rates and surface roughness.

## 5 Grey Relational Analysis (GRA) For Experimetnal Result

In real world problem the situation can never be perfectly black (with no information) or perfectly white (with complete information). Situation between these extremes are described as being gray, hazy, or fuzzy. Therefore a grey system means that a system in which a part of information is known and a part of information is unknown. In recent years, the gray relational analysis has become powerful tool to analyze the process with multiple performance characteristics. In grey relational analysis, the complex multi response optimization can be simplified in to an optimization problem can be simplified in to an optimization of single response gray relational grade. The procedure for determining the gray relational grade is discussed below:

**Step 1 Normalization of experimental result of each performance characteristics**

The data should normalize within range 0 to 1 for all responses using below equation. MRR corresponding to Larger the Better can be expressed as

$$Z_{ij} = \frac{Y_{ij} - Min.Y_{ij}}{Max.Y_{ij} - MinY_{ij}} \tag{2}$$

Surface Roughness corresponding to lower is the Better can be expressed as

$$Z_{ij} = \frac{Max.Y_{ij} - Y_{ij}}{Max.Y_{ij} - MinY_{ij}} \tag{3}$$

Where $i$ = 1, 2, 3…..n (number of experiment data)

**Step 2 Calculate Grey relational coefficient**

Grey relation coefficient calculated to express relationship between the ideal (best) and actual normalized result. The Grey relational co efficient can be expressed as

$$\gamma(y_o(\mathrm{k}), y_i(\mathrm{k})) = \frac{\Delta_{\min} + (\xi \times \Delta_{\max})}{\Delta_{oi}(k) + (\xi \times \Delta_{\max})} \tag{4}$$

Where, $\Delta_{oi}(k) = |X_o(k) - X_i(k)|$ is the absolute difference of two comparative sequence, $\Delta_{min}$= min min $|X_o(k) - X_i(k)|$ and $\Delta_{min}$= max max $|X_o(k) - X_i(k)|$ are the minimum and maximum value of $\Delta_{oi}(k) = |X_o(k) - X_i(k)|$, respectively, and ξ is the distinguish coefficient which its value is adjusted with the systematic actual need and defined in the range between 0 and 1. It will be 0.5 generally.

**Step 3 Calculate Grey relational Grade**

After averaging the gray relational coefficient the gray relational grade $\gamma_i$ can be computed as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(\mathrm{k}) \tag{5}$$

Here, $n$ is the number of process responses

The higher value of gray relational grade corresponds to intense relational degree between the reference sequence $X_0(k)$ and the given sequence $X_i(k)$. The reference sequence $X_0(k)$ represent the best process sequence, therefore higher gray relational grade means that the corresponding parameter combination is closer to the optimal.

For the present problem, higher material removal rate with lower surface roughness as the target values are desirable. After data pre-processing the normalized values for each Quality characteristic MRR and Ra, against different experimental runs have been calculated using Eq.(2,3) and, the grey relational coefficient for the two quality value for each quality characteristic MRR and Ra, against different experimental run have been calculated using Eq.(4). The grey relational coefficient for three qualities characteristic of each deviation sequence were calculated using Eq. (5) taking of distinguishing coefficient ξ = 0.5.

The grey relational analysis has been performed for responses of three wire, Molybdenum wire, plain brass wire and zinc coated brass wire.

### 5.1 Grey Relational Analysis (GRA) for Molybdenum Wire Response

The following table lists the grey relational analysis of the molybdenum wire responses based on the $L_{27}$ full factorial array.

Table 9
GRA of Molybdenum Wire Response

| Ex. No | Normalized data | | Grey Relational Coefficient | | GRG | Rank |
|---|---|---|---|---|---|---|
| | MRR | $R_a$ | MRR | Ra | | |
| 1 | 0.187 | 0.677 | 0.413 | 0.608 | 0.494 | 18 |
| 2 | 0.117 | 0.880 | 0.382 | 0.807 | 0.584 | 5 |
| 3 | 0.000 | 1.000 | 0.333 | 1.000 | 0.669 | 1 |
| 4 | 0.439 | 0.298 | 0.539 | 0.416 | 0.444 | 27 |
| 5 | 0.327 | 0.692 | 0.479 | 0.619 | 0.522 | 12 |
| 6 | 0.176 | 0.719 | 0.407 | 0.640 | 0.509 | 14 |
| 7 | 0.688 | 0.213 | 0.701 | 0.388 | 0.502 | 16 |
| 8 | 0.599 | 0.416 | 0.637 | 0.461 | 0.508 | 15 |
| 9 | 0.385 | 0.536 | 0.510 | 0.518 | 0.484 | 23 |
| 10 | 0.481 | 0.329 | 0.563 | 0.427 | 0.459 | 26 |
| 11 | 0.309 | 0.502 | 0.470 | 0.501 | 0.460 | 25 |
| 12 | 0.031 | 0.939 | 0.346 | 0.892 | 0.616 | 4 |
| 13 | 0.633 | 0.247 | 0.661 | 0.399 | 0.488 | 21 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14 | 0.491 | 0.450 | 0.569 | 0.476 | 0.486 | 22 |
| 15 | 0.370 | 0.569 | 0.501 | 0.537 | 0.490 | 20 |
| 16 | 0.891 | 0.049 | 0.880 | 0.345 | 0.583 | 6 |
| 17 | 0.808 | 0.267 | 0.800 | 0.406 | 0.564 | 10 |
| 18 | 0.679 | 0.553 | 0.694 | 0.528 | 0.568 | 9 |
| 19 | 0.512 | 0.378 | 0.582 | 0.446 | 0.476 | 24 |
| 20 | 0.410 | 0.581 | 0.523 | 0.544 | 0.501 | 17 |
| 21 | 0.256 | 0.701 | 0.444 | 0.626 | 0.514 | 13 |
| 22 | 0.938 | 0.110 | 0.928 | 0.360 | 0.624 | 3 |
| 23 | 0.808 | 0.217 | 0.800 | 0.390 | 0.556 | 11 |
| 24 | 0.607 | 0.334 | 0.643 | 0.429 | 0.494 | 19 |
| 25 | 1.000 | 0.000 | 1.000 | 0.333 | 0.667 | 2 |
| 26 | 0.857 | 0.116 | 0.846 | 0.361 | 0.570 | 7 |
| 27 | 0.827 | 0.236 | 0.818 | 0.396 | 0.570 | 8 |

The sequence with largest grey relational grade indicates the closest value to the desired value of the quality characteristics; it is clearly observed from table 9 and figure 4 that WEDM parameter setting of experiment no.3 has the best performance in two characteristics, It is consider as initial level.

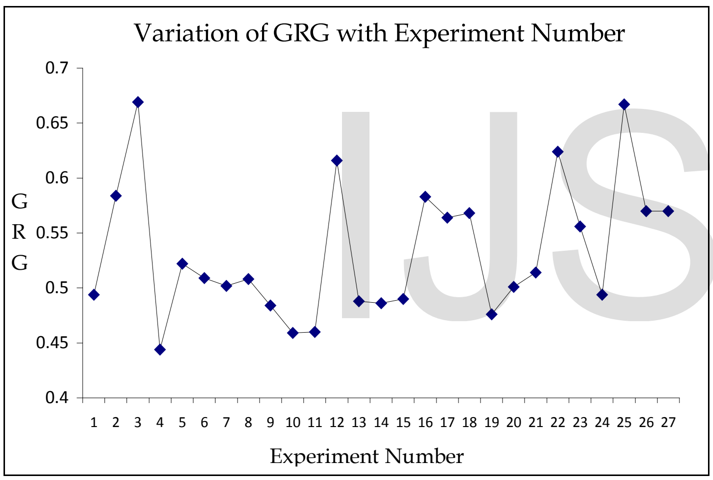


Fig. 4. Variation of GRG with Experiment Number

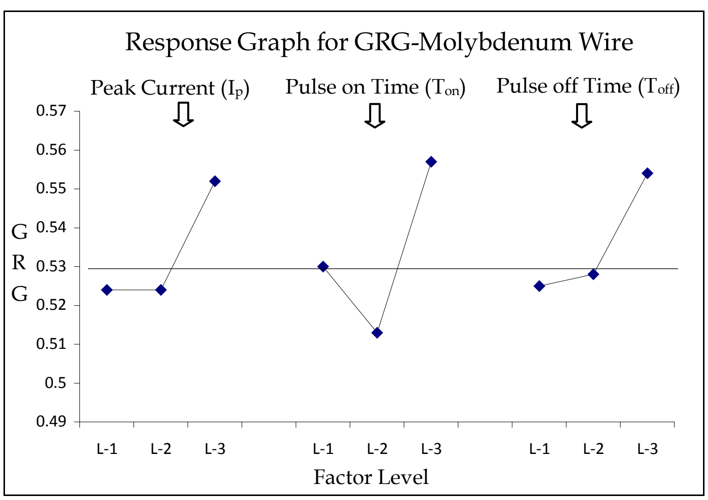


Fig. 5. Response Graph for GRG - Molybdenum Wire

Above Figure 5 shows the response graph for factor level. The optimum input parameter level corresponds to maximum average grey relational grade is $A_3$ $B_3$ and $C_3$, and below table 10 shows the result of confirmation test, in table optimal value of material removal rate is 4.160 mm³/min which is greater than the initial factor level obtained by maximum grey relational grade (as per table 9), and the optimal value of surface roughness (Ra) is 3.823µm which is not lower than initial level of Ra, but with MRR it is the optimal level.

Table 10
Result of Confirmation test

| Factor Level | Initial $A_1$ $B_1$ $C_3$ | Optimal $A_3$ $B_3$ $C_3$ |
|---|---|---|
| Material Removal Rate, mm³/min. | 1.650 | 4.160 |
| Surface Roughness, µm | 1.801 | 3.823 |

### 5.2 Grey Relational Analysis (GRA) for Plain Brass Wire Response

The following table lists the grey relational analysis of the plain brass wire responses based on the $L_{27}$ full factorial array.

Table 11
GRA of Plain Brass Wire Response

| Ex. No | Normalized data | | Grey Relational Coefficient | | GRG | Rank |
|---|---|---|---|---|---|---|
| | MRR | $R_a$ | MRR | $R_a$ | | |
| 1 | 0.2018 | 0.7065 | 0.3851 | 0.6302 | 0.508 | 16 |
| 2 | 0.0817 | 0.8040 | 0.3525 | 0.7184 | 0.535 | 13 |
| 3 | -0.000 | 0.9610 | 0.3333 | 0.9278 | 0.631 | 4 |
| 4 | 0.3838 | 0.3554 | 0.4478 | 0.4369 | 0.442 | 27 |
| 5 | 0.2657 | 0.8301 | 0.4050 | 0.7464 | 0.576 | 11 |
| 6 | 0.1763 | 0.9942 | 0.3777 | 0.9885 | 0.683 | 1 |
| 7 | 0.7232 | 0.2677 | 0.6435 | 0.4058 | 0.525 | 15 |
| 8 | 0.6117 | 0.5565 | 0.5628 | 0.5300 | 0.546 | 12 |
| 9 | 0.3395 | 0.5986 | 0.4308 | 0.5547 | 0.493 | 20 |
| 10 | 0.4082 | 0.4661 | 0.4579 | 0.4837 | 0.471 | 26 |
| 11 | 0.3512 | 0.5651 | 0.4352 | 0.5349 | 0.485 | 23 |
| 12 | 0.0050 | 0.9376 | 0.3344 | 0.8892 | 0.612 | 6 |
| 13 | 0.6363 | 0.3032 | 0.5788 | 0.4178 | 0.498 | 19 |
| 14 | 0.4607 | 0.5109 | 0.4810 | 0.5056 | 0.493 | 21 |
| 15 | 0.2801 | 0.5955 | 0.4098 | 0.5528 | 0.481 | 25 |
| 16 | 0.9012 | 0.1399 | 0.8348 | 0.3677 | 0.601 | 9 |
| 17 | 0.9069 | 0.3231 | 0.8428 | 0.4249 | 0.634 | 3 |
| 18 | 0.7171 | 0.5811 | 0.6385 | 0.5442 | 0.591 | 10 |
| 19 | 0.4992 | 0.4349 | 0.4995 | 0.4695 | 0.485 | 24 |
| 20 | 0.3627 | 0.6072 | 0.4396 | 0.5601 | 0.500 | 17 |
| 21 | 0.2520 | 0.7315 | 0.4006 | 0.6507 | 0.526 | 14 |
| 22 | 0.8904 | 0.2027 | 0.8200 | 0.3854 | 0.603 | 8 |
| 23 | 0.6166 | 0.2720 | 0.5659 | 0.4072 | 0.487 | 22 |
| 24 | 0.5845 | 0.3920 | 0.5460 | 0.4513 | 0.499 | 18 |
| 25 | 1.0000 | 0.0000 | 0.9998 | 0.3334 | 0.667 | 2 |
| 26 | 0.9293 | 0.2073 | 0.8759 | 0.3868 | 0.631 | 5 |
| 27 | 0.8819 | 0.2915 | 0.8088 | 0.4138 | 0.611 | 7 |

The sequence with largest grey relational grade indicates the closest value to the desired value of the quality characteristics; it is clearly observed from table 11 and figure 6 that WEDM parameter setting of experiment no.6 has the best performance in two characteristics, which is consider as initial level.

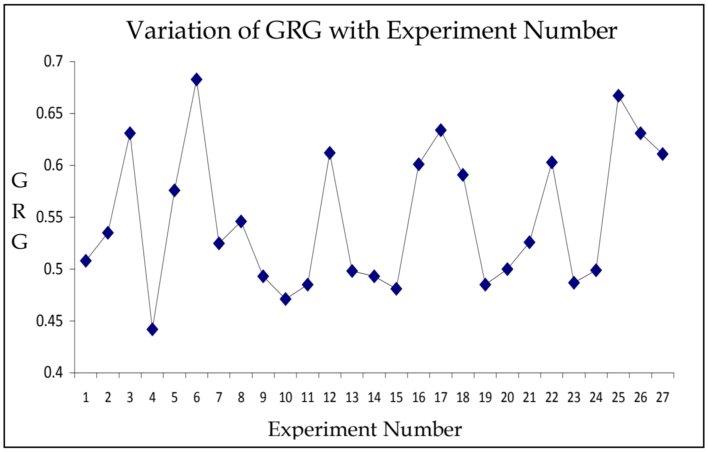


Fig. 6. Variation of GRG with Experiment Number

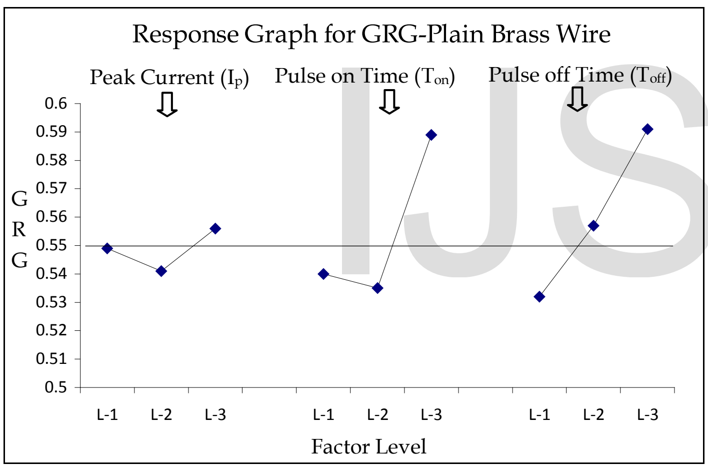


Fig. 7. Response Graph for GRG – Plain Brass Wire

Above Figure 7 show the response graph for factor level. The optimum input parameter level corresponds to maximum average grey relational grade is $A_3$ $B_3$ and $C_3$, and below table 12 shows the result of confirmation test, in table optimal value of material removal rate is 5.044 $mm^3$/min which is greater than the initial factor level obtained by maximum grey relational grade (as per table 11), and the optimal value of surface roughness ($R_a$) is 4.127µm which is not lower than initial level of Ra, but with MRR it is the optimal level.

Table 12
Result of Confirmation test

| Factor Level | Initial $A_1$ $B_2$ $C_3$ | Optimal $A_3$ $B_3$ $C_3$ |
|---|---|---|
| Material Removal Rate, $mm^3$/min. | 2.913 | 5.044 |
| Surface Roughness, µm | 2.324 | 4.127 |

## 5.3 Grey Relational Analysis (GRA) for Zinc Coated Brass Wire Response

The following table lists the grey relational analysis of the zinc coated brass wire responses based on the L'27 full factorial array.

Table 13
GRA of Zinc Coated Brass Wire Response

| Ex. No | Normalized data | | Grey Relational Coefficient | | GRG | Rank |
|---|---|---|---|---|---|---|
| | MRR | $R_a$ | MRR | $R_a$ | | |
| 1 | 0.2259 | 0.700 | 0.3925 | 0.6253 | 0.509 | 18 |
| 2 | 0.0993 | 0.992 | 0.3571 | 0.9851 | 0.671 | 2 |
| 3 | 0.0001 | 1.000 | 0.3334 | 1.0000 | 0.667 | 4 |
| 4 | 0.3845 | 0.342 | 0.4484 | 0.4318 | 0.440 | 27 |
| 5 | 0.2948 | 0.795 | 0.4150 | 0.7092 | 0.562 | 12 |
| 6 | 0.2007 | 0.746 | 0.3849 | 0.6636 | 0.524 | 16 |
| 7 | 0.7829 | 0.253 | 0.6974 | 0.4010 | 0.549 | 13 |
| 8 | 0.6468 | 0.469 | 0.5862 | 0.4852 | 0.536 | 14 |
| 9 | 0.3681 | 0.590 | 0.4418 | 0.5499 | 0.496 | 21 |
| 10 | 0.4198 | 0.337 | 0.4630 | 0.4300 | 0.446 | 26 |
| 11 | 0.3617 | 0.555 | 0.4394 | 0.5291 | 0.484 | 24 |
| 12 | 0.0274 | 0.936 | 0.3396 | 0.8878 | 0.614 | 7 |
| 13 | 0.6723 | 0.368 | 0.6043 | 0.4418 | 0.523 | 17 |
| 14 | 0.5783 | 0.423 | 0.5426 | 0.4645 | 0.504 | 20 |
| 15 | 0.3232 | 0.587 | 0.4250 | 0.5477 | 0.486 | 23 |
| 16 | 1.0128 | 0.114 | 1.0264 | 0.3609 | 0.694 | 1 |
| 17 | 0.8915 | 0.309 | 0.8218 | 0.4198 | 0.621 | 6 |
| 18 | 0.7232 | 0.572 | 0.6438 | 0.5393 | 0.592 | 9 |
| 19 | 0.4994 | 0.403 | 0.4998 | 0.4560 | 0.478 | 25 |
| 20 | 0.3448 | 0.599 | 0.4329 | 0.5550 | 0.494 | 22 |
| 21 | 0.2876 | 0.726 | 0.4125 | 0.6462 | 0.529 | 15 |
| 22 | 0.8419 | 0.178 | 0.7599 | 0.3784 | 0.569 | 10 |
| 23 | 0.8098 | 0.257 | 0.7246 | 0.4025 | 0.564 | 11 |
| 24 | 0.6245 | 0.382 | 0.5713 | 0.4474 | 0.509 | 19 |
| 25 | 1.0001 | 0.000 | 1.0005 | 0.3333 | 0.667 | 5 |
| 26 | 0.9776 | 0.182 | 0.9574 | 0.3793 | 0.668 | 3 |
| 27 | 0.8688 | 0.277 | 0.7923 | 0.4090 | 0.601 | 8 |

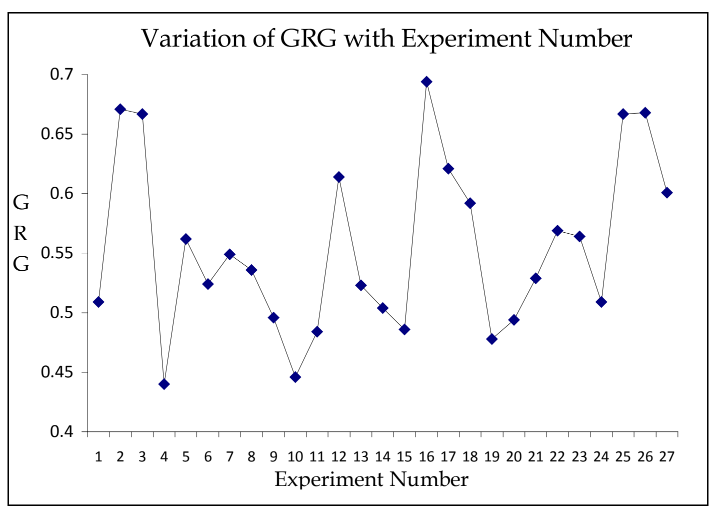


Fig. 8. Variation of GRG with Experiment Number

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The sequence with largest grey relational grade indicates the closest value to the desired value of the quality characteristics; it is clearly observed from table 13 and figure 9 that WEDM parameter setting of experiment no.16 has the best performance in two characteristics, which is consider as initial level.

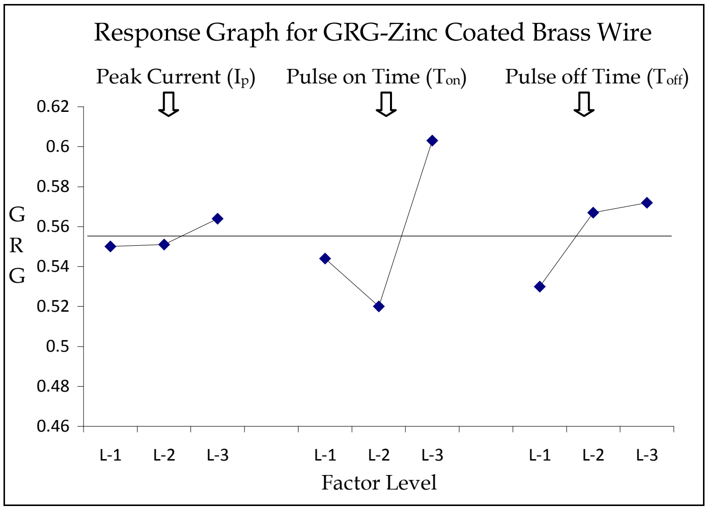


Fig. 9. Response Graph for GRG – Zinc Coated Brass Wire

Above Figure 9 show the response graph for factor level. The optimum input parameter level corresponds to maximum average grey relational grade is A3 B3 and C3, and below table 14 shows the result of confirmation test, in table optimal value of material removal rate is 4.908 $mm^3$/min which is greater than the initial factor level obtained by maximum grey relational grade (table 13), and the optimal value of surface roughness (Ra) is 3.977μm which is not lower than initial level of Ra, but with MRR it is the optimal level.

Table 14
Result of Confirmation test

| Factor Level | Initial $A_2$ $B_2$ $C_2$ | Optimal $A_3$ $B_3$ $C_3$ |
|---|---|---|
| Material Removal Rate, $mm^3$/min | 4.010 | 4.908 |
| Surface Roughness, μm | 3.610 | 3.977 |

## 6 Mathematical Modelling

The mathematical model is made by multiple regression analysis, because it is the powerful statistical techenique that identifies the association between two or more quantitative variables, multiple regression analysis provide an equation that predict the dependent variable.

Linear model for Molybdenum wire response:

MRR = 1.16 + 0.292 Peak Current + 0.0493 Pulse on Time - 0.112 Pulse off Time

$R_a$ = 2.15 + 0.209 Peak Current + 0.0338 Pulse on Time - 0.124 Pulse off Time

Linear model for Plain Brass wire:

MRR = 1.71 + 0.271 Peak Current + 0.0508 Pulse on Time - 0.101 Pulse off Time

$R_a$ = 2.52 + 0.209 Peak Current + 0.0289 Pulse on Time - 0.114 Pulse off Time

Linear model for Zinc Coated Brass wire:

MRR = 1.56 + 0.279 Peak Current + 0.0530 Pulse on Time - 0.101 Pulse off Time

$R_a$ = 2.37 + 0.195 Peak Current + 0.0296 Pulse on Time - 0.106 Pulse off Time

## 7 Validation of The Result

As the analysis were done for material removal rate and surface roughness given by three different wires, its result confirmation as given below

1. For molybdenum wire, the grey relational analysis optimizes the $A_3$ $B_3$ and $C_3$ level, i.e. material removal rate is 4.160$mm^3$/min. and surface roughness is 3.823μm. This is same as full factorial array experiment no.27 and mathematical model with MRR 1.57 % and $R_a$ 1.98 % of error.
2. For plain brass wires, the grey relational analysis optimizes the $A_3$ $B_3$ and $C_3$ level, i.e. material removal rate is 5.044$mm^3$/min and surface roughness is 4.127μm. This is same as full factorial array experiment no.27 and mathematical model with MRR 4.17% and $R_a$ 3.23 % of error.
3. For zinc coated brass wire, the grey relational analysis optimize the same level $A_3$ $B_3$ and $C_3$, i.e. material removal rate is 4.908$mm^3$/min and surface roughness is 3.977μm. This is same as full factorial array experiment no.27 and mathematical model with MRR 1.28 % and 2.34 % of error.

## 8 Conclusion

In present study parametric analysis was carried out for two responses, MRR and Surface roughness using three different wires namely, molybdenum, plain brass and zinc coated brass wire. The experiments were conducted under various parameters setting. $L_{27}$ Orthogonal Array designed. Minitab 16 software was used for analyze the experimental data. Following conclusions drawn after analysis.

1. A Plain Brass wire gives the 21.25 % higher material removal rate than molybdenum wire and 2.77 % more than zinc coated brass wire.
2. A Molybdenum wires gives the 7.95 % lower surface roughness than plain brass wire and 4.02 % lower than zinc coated brass wire.
3. Whereas, a Zinc Coated Brass wire gives the material removal rate 17.98% higher than molybdenum wire and 2.77% lower than the plain brass wire. The surface roughness gives 4.02% higher than the molybdenum wire and

3.77% lower than plain brass wire so, for INCONEL 600 material among the three wires, the zinc coated brass wire gives the optimum results.

4. The optimum parameters obtained by the GRA for higher material removal rate (4.908 $mm^3$/min) at optimum surface roughness (3.977µm) is 7amp Peak current; 48 µs Pulse on time and 12µs Pulse off time.

## ABBREVATION

| | |
|---|---|
| WEDM | Wire electrical discharge machine |
| $T_{on}$ | Pulse on time |
| $T_{off}$ | Pulse off time |
| $I_p$ | Peak Current |
| MRR | Material Removal Rate |
| DOE | Design of experiments |
| ANOVA | Analysis of Variance |
| GRA | Grey Relational Analysis |
| GRG | Gray Relational Grade |
| $R_a$ (µm) | Surface roughness after execution of region |

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