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COMPARATIVE STUDY OF WIRE ELECTRODES IN A WIRE EDM GEAR CUTTING PROCESS USING GREY MOORA METHOD

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Abstract: Wire Electric Discharge Machining (WEDM) is widely used for cutting different complex materials which are electrically conductive. Evolution of Wire EDM made a remarkable change in the manufacturing of small miniature gears that are difficult to be machined by other non-conventional operations. The present work is carried out by conducting the experiments and the analysis is made based upon the tool material that is the Wire EDM wires. Two types of wires that is Brass and Diffused coated wire of 0.25 mm diameter have been used in the experiment and the gear is cut with both the type of wires with the same work-piece material i.e. copper. The experiment is carried out using L9 array having three input parameters at three different levels. The response parameters that is Material removal rate (MRR) and Kerf width (KW) have been calculated and the responses are optimized by using Grey based MOORA method. Pulse on time (Ton), Pulse off time (Toff) and Wire Feed rate (WF) were taken as the input parameters and its effects were studied for both Brass and Diffused coated wire. The work-piece material copper of thickness 2 mm is being machined by both the wires and ANOVA table was obtained to determine the most significant factor affecting the Wire EDM parameters. Response table and main effect plots were plotted to know the rank and optimum settings for the Wire EDM parameters by both the wires respectively. A microscopic study using SEM is also carried out after the machining operation to analyse the structure and characteristics of the wire using the same process parameters. XRD analysis was made to know the compounds crystallinity for both the type of wires. The graph was analysed and the results obtained was further investigated to produce a large quality of gears.

Keywords: Gears; Grey; MOORA; Pulse on time; Pulse off time; Wire feed rate; Wire EDM.

I. INTRODUCTION

Wire EDM is one of the most traditional electric discharge machining processes which requires a repeatedly travelling wire electrode, the electrode being in the form of thin copper or brass or tungsten of diameter ranging from 0.05 mm-0.5 mm [1]. EDM was first realized by B and N Lazarenko in 1943 in the UDSSR. Later-on, the term EDM was coined by an English scientist named Joseph Priestly [2] in the year 1770. Since then the EDM technique was applied in many machine tools of electrically conductive materials. Different types of conductive materials like copper, Inconel, mild steel, aluminium, stainless steel etc. can be easily cut using Wire EDM. The machine setting parameters however vary for different types of materials. Different shapes can be obtained using Wire EDM. The response parameters are generally affected by a large number of process parameters. Generally, the rough cutting operation is one of the most challenging tasks as more than one improvement/performance measures such as MRR, surface finish and cutting width are likely to get accuracy work.

In Wire ED machining, the material is removed from the work-piece by a series of continuous sparks produced from the electrical discharges. The dielectric fluid i.e. the distilled water or de-ionized water [3] is allowed to flow from upper and lower guides in order to control the resistivity and moreover it acts as a coolant. During the machining process, many sparks can be seen at a time. The actual discharges occur more than one lakhs per second while the discharge sparks last in the range of 1/1*10^6 of a second or less. The temperature obtained from the electrical spark is estimated around 8000 to 11000 degree Celsius. During the machining process, the volume of the material is removed from the work-piece. Also, there is some wear in the wire material. The size and positional accuracy of the thermal expansion are affected without this cooling. However, the volume of the material removed depends mainly upon the Pulse on time and the desired cutting speed.

One of the major machining characteristics that plays an important role in determining the quality of the engineering components is the surface integrity. In WEDM, the machining quality with respect to its surface integrity and precision is not only related to the machining parameters of voltage, discharge duration, current, wire speed, wire tension, polarity but also depends on machining techniques (wet or dry). It is a well-known fact that good quality surface improves the corrosion, wear resistance and fatigue strength of the work-piece. So in order to view the surface integrity of any machined part, it is important to achieve better surface integrity during wire EDM process. As EDM is a thermal dominant process, a very high temperature has a significant impact on surface integrity including microstructure change, micro- cracks, porosity, micro-hardness and elements distribution.

Gears are the most important elements used in machinery and small industries. The output of the gear depends on the accuracy of the design and its manufacturing. So the correct manufacturing in a gear requires number of calculations and design considerations. Gear cutting by wire EDM is one of the most important phenomena in this operation. Many gears are of complex shapes and sizes that are difficult to machine by other nonconventional operations can be easily machined by wire EDM. Gears find its applications in many industries, truck brakes, gear boxes and differentials in the automotive industry, rotors, pumps, clock, aerospace etc. In WEDM these gears can be easily cut with required numbers of teeth.

Generally miniature gears are of two types. They can either be micro-gears (outside diameter <1 mm) or meso-gears (outside diameter in the range of 1–10 mm). Miniature gears are the basic key components in various miniaturized devices such as pumps, miniature motors, home appliances and electronics, business machines, timing devices, automotive parts, sophisticated toys, etc. Brass, bronze, copper, aluminium, stainless steel are the most commonly used materials for these gears.

Fig. 1 shows the setup of Wire EDM machine cutting a gear. The specifications of the Wire EDM machine are shown in Table 1.

Fig. 1. Wire EDM machine setup cutting a gear

Table 1. Specifications of Wire EDM machine

Make	Electronica, ELPULSE 15
Model	Ecocut
X*Y	250*350 mm
Maximum work-piece height	200 mm
Maximum Table size	370*600 mm
Maximum cutting speed	70 mm/min
Taper	+- 8° over 50 mm
Maximum bed speed movement	25 mm/min

II. LITERATURE REVIEW

Some of the worth mentioning works have been carried out by different researchers. Tang et al. [4] worked on neural network system to determine the settings of pulse interval, pulse duration, peak current, open circuit voltage, electric capacitance and surface finish. Hsue et al. [5] proposed a model that material removal rate (MRR) in geometrical machining was built considering the wire deflection. Tosun et al. [6] brought a statistical approach to determine the optimal machining parameters for minimum size of wire craters in WEDM. Tosun and Cogun [7] studied the effect of machining parameters on wire wear ratio based on the weight loss of wire in WEDM. Dongre et al. [8] used wires of diameter ranging from 25 µm to100µm in order to reduce the kerf loss and to get ultra-thin wafers. Mohri et al. [9] studied the electrode wear against the machining time. The results showed that the electrode wear rate (EWR) reached an equilibrium state. Several researchers tried their level best to optimize the machining parameters and material properties to analyze the surface integrity. However, Kapoor et al. [10] found that the response parameters closely depend on the machining parameters. So the machining parameters should be chosen properly in accordance with the work-piece properties in order to obtain good results. Rao et al. [11] optimized the effect of WEDM conditions on surface roughness using Taguchi method. Prasad et al. [12] investigated that appropriate selection of machining parameters and heat treatment affects the surface quality, surface properties and surface roughness. He also tried to optimize the machining parameters in WEDM using the Taguchi method. Mohapatra and Sahoo [13-15] studied the microstructural analysis and optimization in gear cutting process for AISI 304 stainless steel using wire EDM. They further investigated the wire EDM parameters for gear cutting process using Desirability with PCA. Moreover they optimized the parameters in wire EDM process for gear cutting parameters using Taguchi quality Loss function. The effect of process parameters on Material removal rate in WEDM was investigated by Singh and Garg

They concluded that the Material Removal Rate increases with the increase in Pulse on time and Peak current. Subhramanyam and Sarkar [17] studied the statistical analysis of WEDM on surface finish. Gupta et al. [18] studied the manufacturing of high quality meso-gears in Wire EDM. The analysis and optimization of micro geometry of miniature spur gears was carried out by Gupta and Jain [19], manufactured by wire electric discharge machining. They observed larger deviations in the profile and pitch error due to the interaction between voltage and Pulse off time and Pulse on time and Pulse off time. Gupta et al. [20] studied the spark erosion machining of miniature gears. They conclude that spark-erosion-based machining processes are able to manufacture high-quality miniature gears provided that the machining is conducted with adequately accurate machine tools and appropriate parameter settings.

From the past literature, it is found that very less work has been carried out in the manufacturing of gear cutting by wire EDM process. Moreover few studies have been carried out regarding the variation in the wire for the gear cutting process in wire EDM. So the present paper focuses on the comparative study of both the brass and DCW and its manufacturing for producing high quality gears. Further as gear cutting is important in wire EDM, better machining rate with proper accuracy must be attained so that the gears can be manufactured without fail. So a parametric combination must be attained so that the minimization of wire consumption (wire wear rate) can also be achieved.

As the machining of gears by copper have an application in various transportation oils such as diesel, petroleum, semiconductor industries, lubricant oils, clocks, radiators, aerospace, printing, papermaking, mining industries, electric motors, trucks and air brakes etc., the obtained optimized setting can be an advantage over other combinational settings to produce high quality miniature spur gears made of copper.

III. EXPERIMENTAL SETUP

3.1. Materials, specifications and setup

The experiment was performed in the ELECTRONICA Epulse 15 machine. The parameter selection is one of the major criteria in wire EDM process. From the past literature, it is viewed that Pulse on time and Pulse off time are the most significant factors affecting the responses. However in the present experiment wire feed rate is varied keeping peak current, wire tension and servo voltage as constant. Pulse on time, Pulse off time and Wire feed rate were taken as the input factors for the experiment. However the output parameters were considered to be Material Removal Rate and Kerf width. Wire EDM cut the materials that are difficult to machine. However in this experiment copper is used as the work-piece material. Copper gears find its applications in electric motors, trucks, air brakes, radiators, clocks, paper making etc. The thickness of the work- piece is taken as 2 mm. Fig. 2 shows the detailed measurements of work-piece material and the wire.

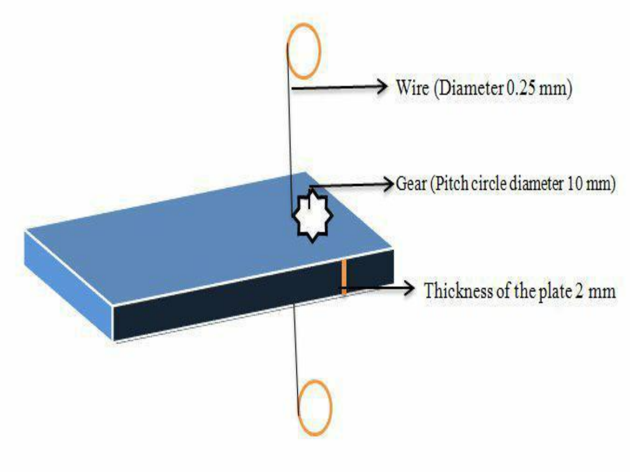


Fig. 2. Measurements of copper work-piece, gear and the wire

Two types of tool wires have been used in this experiment. One is the brass wire and the other is the Diffused coated wire (DCW). Diffused coated wires were developed to put zinc on the surface of the wire. The Zinc atoms diffuse into the Brass. This diffusion process transforms the Zinc coating into a high Zinc alloy Brass which is Zinc rich, has a relatively high melting point and is known as Zinc coated brass wire. Brass and DCW were mainly chosen for the experiment as they are resistant to corrosion, have a high precision cutting and offers high cutting speed due to the increased zinc concentration. Brass when added with copper or aluminum improves the heat resistance while cutting thick materials. These two wires can also be used for gear cutting as they give a better surface finish with accurate precision and accuracy. The diameter of the brass wire and diffused coated wire is taken as 0.25 mm. The whole analysis is made on the wire only. The dielectric fluid used is distilled water. The compositions of the brass and diffused coated wire are listed in Table 2. Initially the experiment was conducted and the gear was machined using the brass wire and later the experiment was performed on the gear using the diffused coated wire.

Table 2. Compositions of the wire electrodes

Electrodes	Brass	Diffused Coated wire
Cu	65%	63%
Zn	35%	37%
Tensile strength (kgf/mm^2)	45~60	49.8~65
Diameter	0.25 mm	0.25 mm

Table 3. Machine parameters used in the experiment

Parameters/Levels	Units	I	II	III
Pulse on time (T_{on})	µs	7	11	15
Pulse off time (T_{off})	µs	52	54	56
Wire feed rate (W_f)	m/min	4	5	6

Table 3 depicts the machine parameters and settings for the conduction of the experiment. The minimum and maximum range for the Pulse on time can be varied from 0 to 31 µs, Pulse off time from 40 µs to 63 µs and wire feed rate from 1 to 15. Taking the values too close to the minimum and maximum limits leads to a chance of wire breakage. So the values were taken within the range in such a way that there will be occurrence of sparks and minimization of wire breakage in order to produce gear without fail.

The experiment was carried out using three parameters at three different levels each. Pulse on time (µs), Pulse off time (µs) and Wire feed rate (m/min) were taken as the process parameters and were varied accordingly. The values are chosen based on the past literature review and within the machine constraints. Pulse on time is varied from 7 to 15 µs. Similarly Pulse off time is varied from 52 to 56 µs and Wire feed rate is varied from 4 to 6. Taguchi L_9 orthogonal array has been obtained using suitable software (Design Expert 8) and the number of teeths to be cut for the gear is chosen as 9. Each tooth has to be machined with each of the 9 parameter settings by both the type of wires. However the gear teeth may vary other than 9, but to obtain a pitch circle diameter of 10 mm, 9 sets of teeth were considered for the experiment as taking higher number of teeth’s (< 9) with smallest pitch circle diameter may lead to difficulties in assessment of the output responses. Some of the other input parameters in the machine such as Peak voltage (1, 1), peak current (1, 2), wire tension (7 kg-f), servo feed rate (2250 mm/min) and servo voltage (20 V) were kept as constant for the experiment.

1 (low voltage), 1 (low voltage) in the peak voltage refers to the selection of open gap voltage between the work-piece and the tool.

In EPulse 15 WEDM machine, Peak voltage (V_P) = XY where, 1=Low voltage, 2=High voltage

Similarly Peak current I_P= XY, where X is the selection of fine Pulse and Y is the selection of Power Pulse.

X=0: Fine pulse OFF, X=1: Fine pulse ON

Y=0: Power pulse OFF, Y=1: One power pulse section ON, Y=2: Both Power pulse section ON.

3.2. Gear cutting in Wire EDM

The gear figure is obtained from the suitable software (ELCAM) and the code obtained is transferred to wire EDM for machining the gear. Fig. 3(a) depicts the machining of the gear by wire EDM process. The pitch circle diameter of the gear is taken as 10 mm, the pressure angle is taken as 20 and the number of teeth to be cut was taken as 9. The machine parameters and the constant input parameters should be chosen carefully in order to minimize the wire breakage. Fig. 3(b) displays the two types of wire of 0.25 mm diameter to machine the gear. Fig 3(c) shows the top surface of the gear after being machined by the brass wire.

Fig. 3(d) shows the scaling at 10X optical zoom. The scaling measures 5 mm to be 118.129 micrometer.

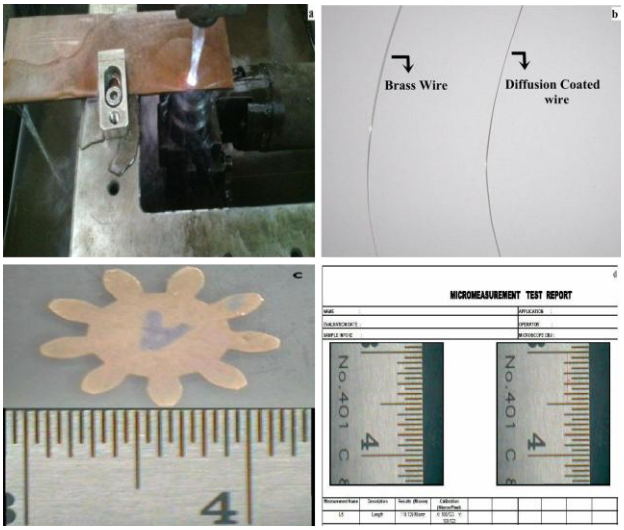


Fig. 3(a). Machining of copper gear by wire EDM, (b) different types of wires, (c) Top surface of the gear at 10X Zoom (d) Scaling at 10X zoom

3.3. Material removal rate and kerf width measurement

The material removal rate is the rate at which the material is removed from the work-piece during machining. On the other hand, there are also some losses in the wire. The wire once used for machining cannot be reused back. However if reused will not provide good surface finish. The material removal rate depends upon the cutting speed, thickness of the gap side and time. The material removal rate is calculated by the following formula:

$$MRR = V_C * h * k \text{ mm}^3/\text{min} \quad (1)$$

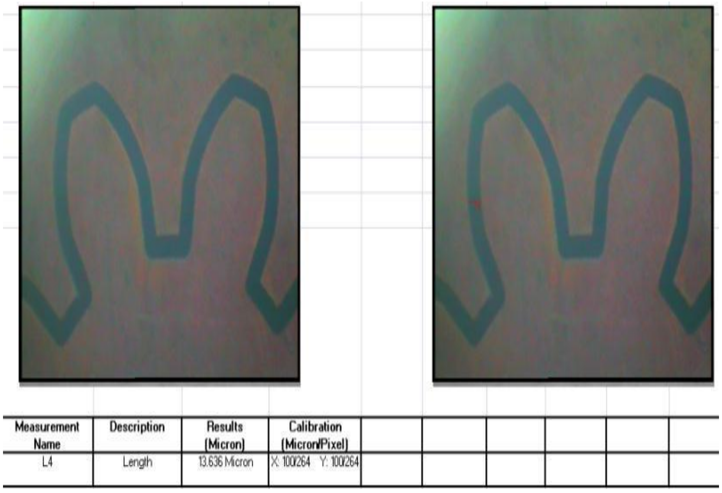
Where is the cutting speed in mm/min, h is the work-piece thickness (2 mm) and k is the wire diameter (0.25 mm).

Cutting speed mainly depends upon the cutting length and time. Cutting speed is calculated by the formula:

$$V_c = \frac{l}{t} \text{ mm/min} \quad (2)$$

Where *l* is the cutting length in mm and *t* is the machining time in minutes.

The kerf width is the width obtained after the cutting operation. The kerf width obtained is being viewed under the optical microscope and by using suitable software (Image J or Caliper Pro), the kerf width can be measured. Kerf width is measured in mm. Generally, the kerf obtained is greater than the wire diameter. Fig. 4 shows the measurement of kerf-width using suitable software (Caliper Pro) after the image has been viewed under the microscope at 20X optical zoom.



Measurement Name	Description	Results (Micron)	Calibration (Micron/Pixel)						
L4	Length	13.636 Micron	X: 100/264 Y: 100/264						

Fig. 4. Measurement of kerf width after the image has been viewed under the microscope

IV. ANALYSIS OF DATA WITH THE EXPERIMENTAL RESULTS

The experiment is carried out for 9 sets of combinations. The output response that is the MRR and kerf width has been calculated for both the brass wire and the diffused coated wire. In order to maximize the MRR and minimize the kerf width, the process parameter is varied and the experiment is conducted. The experimental design using L9 orthogonal array is depicted in Appendix A.1.

V. OPTIMIZATION USING GREY TAGUCHI BASED MOORA METHOD

Multi-objective optimization technique is implemented to determine the best possible outcomes for the given set of results. In the present work a hybrid technology that is Grey Taguchi based MOORA method is used to identify the best results and rank among the given set of combinations.

In the grey relational analysis the data's are first normalized in a range from zero to unity and this process is called as grey (1) relational generation. Generally, there are three categories of performance characteristics in the analysis of normalized values, that is lower the better, higher the better and nominal the better.

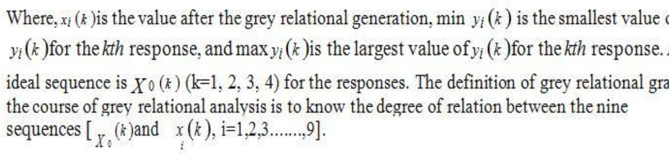
For lower the better (LB) criterion

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

For higher the better (HB) criterion

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

(3)(4)



Where, $x_i(k)$is the value after the grey relational generation, min $y_i(k)$ is the smallest value ‹
$y_i(k)$for the *kth* response, and max $y_i(k)$is the largest value of $y_i(k)$for the *kth* response.
ideal sequence is $\chi_0(k)$ (k=1, 2, 3, 4) for the responses. The definition of grey relational gra
the course of grey relational analysis is to know the degree of relation between the nine
sequences [$\chi_0(k)$and $x_i(k)$, i=1,2,3.......,9].

The grey relational coefficient $\zeta_i(k)$ can be calculated as

$$\zeta_i(k) = \frac{\Delta\min + \psi\Delta\max}{\Delta_{0i}(k) + \psi\Delta\max} \tag{5}$$

Where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence and ψ is the identification coefficient whose value lies between 0 and 1, usually taken as 0.5. Δ max and Δmin are the largest and smallest values of each sequence respectively. The ideal sequence is taken as 1. In order to find $\Delta_{0i}(k)$, 1 is subtracted from each values of

The next step is to find out the ranking by using Multi-Objective Optimization using Ratio Analysis (MOORA) method. *Brauers* [21] proposed the MOORA method to solve different types of complicated decision-making problems. The objectives (responses) must be computable and their output values should be measured for every individual alternative, in a decision-making problem. For multi-objective optimization, these normalized performances are added in case of maximization (for beneficial attributes) and subtracted in case of minimization (for non-beneficial attributes). Thus the optimization problem becomes

$$y_i = \sum_{j=1}^{g} x^*_{ij} - \sum_{j=g+1}^{n} x^*_{ij} \tag{6}$$

Where g is the number of attributes to be maximized, (n-g) is the number of attributes to be minimized, and y_i is the normalized assessment value of i^{th} alternative with respect to all the attributes. Here x_{ij}^* is a dimensionless number which belongs to the interval [0,1] which represents the normalized performance of i^{th} alternative on the j^{th} attribute. If weights are to be considered then Eq. 6 becomes

$$y_i = \sum_{j=1}^{g} w_j x^*_{ij} - \sum_{j=g+1}^{n} w_j x^*_{ij} \tag{7}$$

Where w_j is the weight of the *jth* attribute. The highest values of y_i determines the best alternative rank.

Depending on the totals of its maxima (beneficial attributes) and minima (non-beneficial attributes) in the decision matrix, the y_i value may be positive or negative. The final preference is obtained by an ordinal ranking of y_i . Hence the best alternative has the highest y_i value, while the worst alternative has the lowest y_i value. The Modified Coefficient Ratio (MCR) is given by the following formula:

$$y_i = \frac{\sum_{j=1}^{g} x^*_{ij}}{\sum_{j=g+1}^{n} x^*_{ij}} \tag{8}$$

The multi-objective optimization of brass wire and diffused coated wire is depicted in Appendix A.2 and Appendix A.3 respectively. From Appendix A.2 it is clear that the best alternative/rank occurs for 7th run (T_{on} 115, T_{off} 52, W_F 6) and the worst alternative occurs for 2nd run (T_{on} 107, T_{off} 54, W_F 5) in case of brass wire. Similarly, the best alternative occurs for 8th run (T_{on} 115, T_{off} 54, W_F 4) and the worst alternative occurs for 1st run (T_{on} 107, T_{off} 52, W_F 4) in case of diffused coated wire.

VI. MICROSTRUCTURAL ANALYSIS

6.1. *Microscopic study of the wire*

The experiment is carried out and the response parameter that is MRR and Kerf width was calculated machined with both brass wire and diffused coated wire. The wire is viewed under scanning electron microscope (SEM) at the optimized setting of the combination for the gear material machined (L7 for brass and L8 for DCW) and analysis is made by studying the structure of the wire. Fig. 5 describes the SEM image of Brass wire and Diffused coated wire before machining of the material.

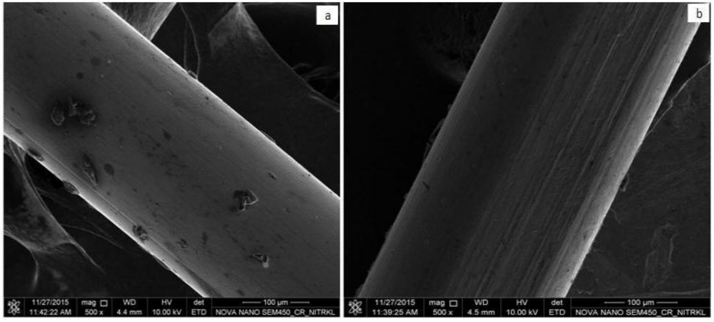


Fig. 5. Micrograph of the wire before cutting operation (a) Brass wire and (b) Diffused coated wire

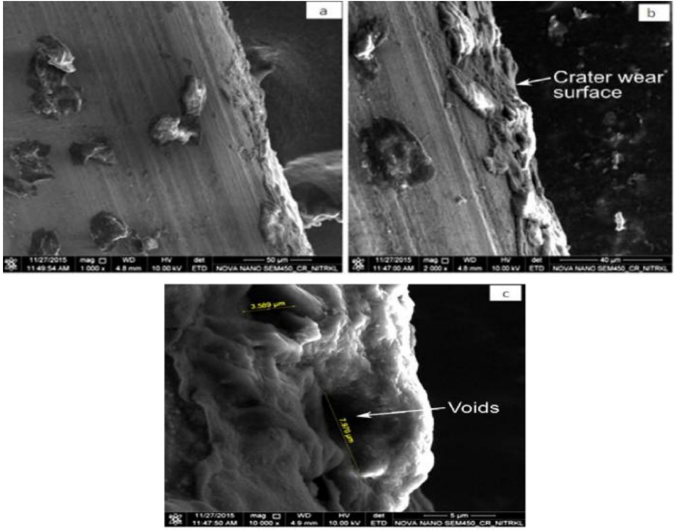


Fig. 6 Micrographs of the brass wire at (T_{on} 115, T_{off} 52, W_F 6) after machining operation (a) at 1000X, (b) at 2000X and

(c) voids in the wire

Fig. 6 displays the micrographs of Brass wire at 1000X, 2000X and 10000X zoom. Fig. 6(a) shows the SEM image of the wire after machining operation. From Fig. 6(b) it can be clearly observed that some crater wears are formed on the wire surface. As the wire suffers high voltage and current, the surface generates crater. The decrease in the pulse off time results in an increase in height of the craters. The crater size may vary depending on the energy discharges from the wire, wire speed and the pulse on time. Large size craters in the wire may lead to wire rupture and also results in poor surface finish and machining accuracy. Similarly from Fig. 6(c), voids can be visible on the cutting edge of the wire. The higher spark energy density is expected to be a cause of such voids or holes. The voids were also measured and the higher void is nearly equal to 8 µm.

Fig. 7 depicts the SEM image of Diffused coated wire after the machining operation. In Fig. 7(a) some cutting straight lines can be visible which indicates the cutting direction of the wire. From Fig. 7(b), the burrs can be clearly visible on the wire. Higher wire feed rate and high spark energy density causes the wire to create a burr during cutting operation. In Fig. 7(c) some voids can be visible at 4000X zoom. From Fig. 7(d), the length of the void was measured and is found to be nearly equal to 3.914 µm The increase in the pulse on time and wire feed rate results in an increase in the crater size.

From the SEM micrographs and above microstructural analysis it is clear that pulse on time is the determining factor in affecting and influencing the formation of various surface defects of the wire.

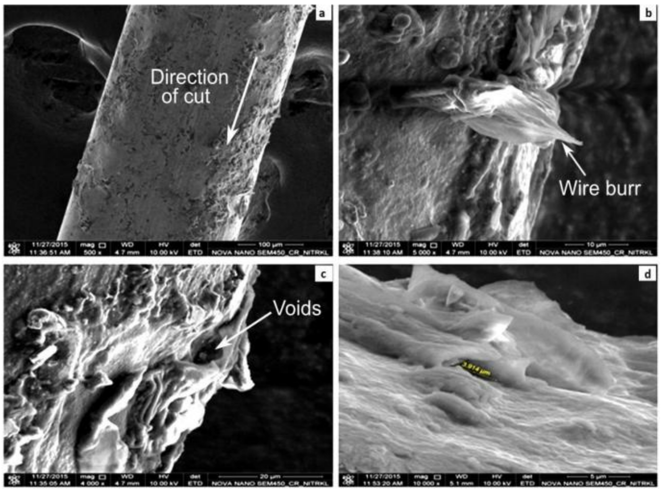


Fig. 7. Micrographs of the diffused coated wire at (T_{on} 115, T_{off} 54, W_F 4) after cutting operation (a) at 500X, (b) wire burr (c) voids in the wire and (d) length of the void

6.2. XRD analysis of the wire

X-ray Diffraction Spectrometer is the most sophisticated and important powerful analytical tools available for identifying unknown crystalline substances present in the material. When X-ray is directed to a crystal, the atom of each crystal gets interacted with the X-ray by exciting their electrons, causing them to vibrate with the frequencies of the incoming radiation. Bragg's law: $n\lambda = 2d \sin\theta$ explains the relationship between angle of the diffraction peaks ($2\theta(^0)$) and the inter-atomic spacing (d-spacing) of a crystalline lattice. In order to know the shape and size of the unit cell for any compound, mostly XRD is done. In the present paper, XRD analysis is done to know the chemical composition on the wire surface after it is being machined to copper material. Fig. 8 shows the XRD diffractograms of 2θ ranging from 10^0 to 90^0 for Diffused coated wire after cutting operation. From Fig. 8, it is seen that the highest peak intensity is located at 2θ 49.07^0, d spacing 1.85 Å, followed by 2θ 72.00^0 and 42.14^0. The intensities and location of these peaks indicate a vast majority of study materials composed of Copper Gallium Zinc Telluride, Copper Zinc, Copper manganese and Copper Zinc Telluride. Higher is the intensity, better is the crystalline structure of the material. Copper-Zinc and Copper Zinc Telluride are located at the highest peaks that are at 2θ 49.07^0. Small traces of Copper Manganese and Copper Zinc are found at lower peaks

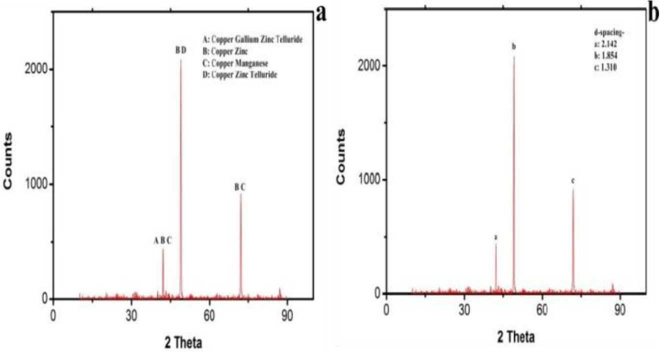


Fig. 8. XRD diffractograms from 2θ 10^0 to 90^0 for DCW after cutting operation (a) formation of chemical compounds and (b) corresponding d-spacing

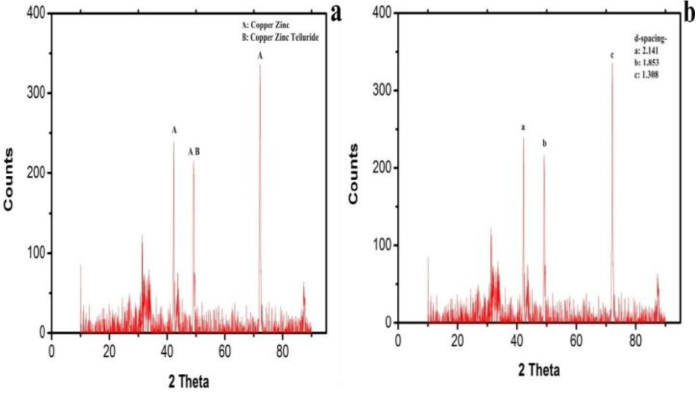


Fig. 9. XRD traces from 2θ 10^0 to 90^0 for Brass wire after cutting operation (a) formation of chemical compounds and (b) corresponding d-spacing

Similarly Fig. 9 shows the XRD diffractograms of 2θ ranging from 10^o to 90^o of Brass wire after cutting operation. The wire was in contact with the Copper material. The highest peak is located at 2θ 72.11^o, d spacing 1.308Å, followed by 2θ 42.20^o and 49.18^o. Copper Zinc is located at the highest peak where as Copper Zinc Telluride is located at lower peak of d-spacing 1.853 Å.

VII. RESULTS AND DISCUSSION

7.1. Effect of process parameters on Modified Coefficient ratio for Brass wire and DCW

Fig. 10 shows the main effect plot diagram of Modified Coefficient Ratio with the input parameters for both Brass and Diffused coated wire.

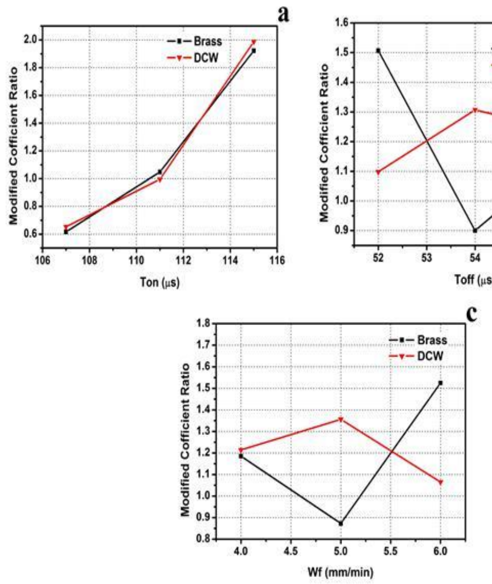


Fig. 10. Main effect plot diagram of Brass wire and DCW of Modified ratio for (a) Pulse on time, (b) Pulse off time and (c) Wire feed rate

From Fig. 10(a) it is clear that the Modified Coefficient Ratio increases with the increase in Pulse on time for both Brass wire and diffused coated wire. This is due to the fact that the discharge energy of the plasma channel increases which results in an increase in sparking efficiency resulting in higher values of Modified Coefficient Ratio. From the Fig. 10(b) and Fig. 10(c) the Modified Coefficient Ratio decreases and then increases with an increase in pulse off time and wire feed rate for the Brass wire as the spark concentration duration is reduced by the increase of wire feed rate resulting in low values of MCR. Similarly, high values of Ton and low values of Toff facilitate the dielectric ionization resulting in an increase in discharge energy leading to low values of MCR. For the Diffused coated wire, from the Fig. 10(a), the MCR increases with the increase in pulse on time. Higher values of pulse on time result in an increase in sparking efficiency which further results in high values of material removal. Similarly from the Fig. 10(b) and Fig. 10(c) it can be concluded that with the increase in the values of the input parameters, MCR first increases and then decrease. The cutting rate increases with the increase in the spark energy density resulting in an increase in MCR. Moreover high reaction forces and water pressure are the cause for the decrease in the Modified Coefficient Ratio.

7.2. Statistical models for MRR and Kerf width

Kanlayasiri and Boonmung [22] suggested some multiple linear regression models that are suitable in predicting various performance measures in Wire EDM process. The regression equations were obtained by using Design Expert software by selecting the input and output responses of the model.

The suggested equations of regression for MRR and KW obtained are as follows:

$$MRR_{Brass} = -9.02 + 0.122*T_{on} - 0.0554*T_{off} - 0.052*W_F \tag{9}$$

$$KW_{Brass} = -0.860 + 0.0119*T_{on} + 0.00400*T_{off} + 0.0060*W_F \tag{10}$$

$$MRR_{DCW} = -7.82 + 0.0919*T_{on} - 0.0229*T_{off} - 0.0100*W_F \tag{11}$$

$$KW_{DCW} = 0.213 + 0.00187*T_{on} + 0.00500*T_{off} + 0.0030*W_F \tag{12}$$

Fig. 11 depicts the comparison between statistical and experimental model for MRR and Kerf width values machined by brass wire electrode. Similarly Fig. 12 depicts the comparison between statistical and experimental model for MRR and Kerf width values machined by DCW electrode.

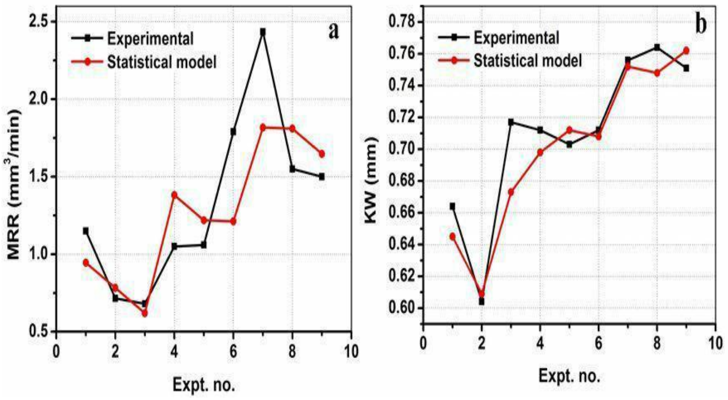


Fig. 11. Comparison between Statistical and Experimental model (a) MRR and (b) Kerf width values of brass wire

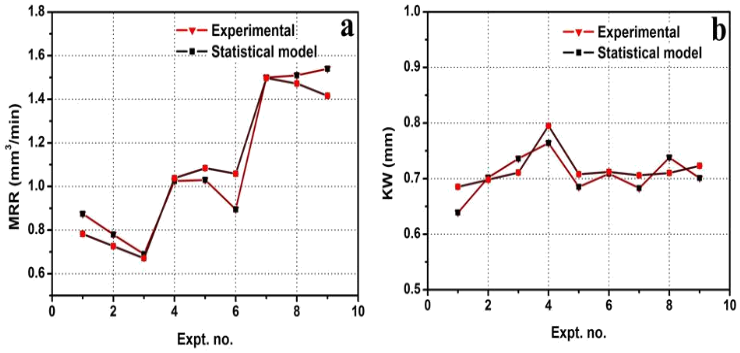


Fig. 12. Comparison between Statistical and Experimental model (a) MRR and (b) Kerf width values of DCW

Absolute error is one of the powerful tools to validate the performance of the proposed models. The percentage of the absolute error is given by the following formulae:

$$Error\% = \frac{\left|Experimenal\ value - predicted\ value\right|}{Experimental\ value} *100 \tag{13}$$

7.2.1. Analysis of the Statistical models for MRR and Kerf width of Brass wire

The predicted statistical model analysis for both MRR and KW for Brass wire is depicted in Appendix A.4 and A.5 respectively. It is observed from Fig. 11 that both the experimental and statistical model values coincide with each other showing a good result of agreements. Appendix A.4 and A.5 depicts the comparison of absolute error % between experimental and predicted values of MRR and KW respectively, machined by brass wire electrode. Further from

Appendix A.4 and A.5 it is observed that the average absolute error of MRR and KW is found to be 18.5 % and 1.96 % (< 20 %) which is acceptable in the engineering accuracy. Hence the model is correct and acceptable in calculating the WEDM performance measures.

7.2.2. Analysis of the Statistical models for MRR and Kerf width of DCW

The predicted statistical model analysis for both MRR and KW for Diffused Coated wire is depicted in Appendix A.6 and A.7 respectively. It is observed from Fig. 12 that both the experimental and statistical model values coincide with each other showing a good result of agreements. Appendix A.6 and A.7 depicts the comparison of absolute error % between experimental and predicted values of MRR and KW respectively, machined by Diffused Coated wire electrode. Further from Appendix A.6 and A.7 it is observed that the average absolute error of MRR and KW is found to be 6.19 % and 3.25 % (< 20 %) which is acceptable in the engineering accuracy. Hence the model is correct and acceptable in calculating the WEDM performance measures.

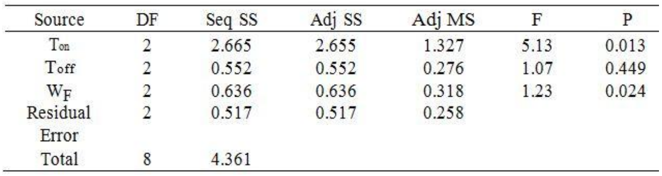
7.3. ANOVA for Modified Coefficient Ratio

ANOVA or Analysis of Variance is important as it determines the significant process parameters affecting the output responses. The Probability value (P) is said to be significant if it is less than 0.05.

7.3.1. ANOVA for Brass wire

Table 4 depicts the ANOVA test machined with brass wire. From the Table 4, it is clear that Pulse on time and Wire feed rate have the values less than 0.05. This clearly indicates that the significant parameters affecting the responses are Pulse on time and Wire feed rate for the Brass wire. However Pulse off time has also some effects in affecting the responses, but after combining and optimizing the three input parameters with Grey based MOORA, it is found that Pulse off time is the least significant parameter affecting the responses.

Table 4. ANOVA for means of Brass wire

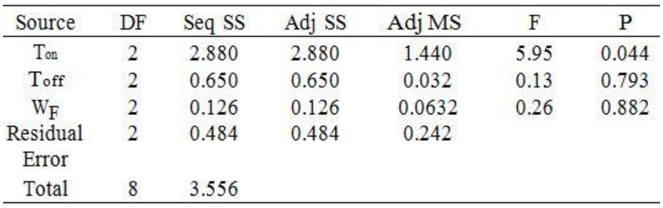


Source	DF	Seq SS	Adj SS	Adj MS	F	P
T_{on}	2	2.665	2.655	1.327	5.13	0.013
T_{off}	2	0.552	0.552	0.276	1.07	0.449
W_F	2	0.636	0.636	0.318	1.23	0.024
Residual Error	2	0.517	0.517	0.258		
Total	8	4.361				

7.3.2. ANOVA for Diffused Coated Wire

Similarly Table 5 depicts the ANOVA test machined with diffused coated wire. From Table 5, it is clear that only Pulse on time has the value less than 0.05 which indicates that the significant parameters affecting the responses for Diffused coated wire is Pulse on time only.

Table 5. ANOVA for means of DCW



Source	DF	Seq SS	Adj SS	Adj MS	F	P
T_{on}	2	2.880	2.880	1.440	5.95	0.044
T_{off}	2	0.650	0.650	0.032	0.13	0.793
W_F	2	0.126	0.126	0.0632	0.26	0.882
Residual Error	2	0.484	0.484	0.242		
Total	8	3.556				

7.4. Response table for Modified coefficient Ratio

The response table determines the rank of the process parameters. Table 6 depicts the response table of brass wire electrode. From the response Table 6 it is clear that pulse on time plays a significant role in optimizing the process parameters followed by wire feed rate and pulse off time for Brass wire. Table 7 depicts the response table of DCW. For Diffused coated wire, pulse on time is the significant parameter affecting the responses followed by pulse off time and wire feed rate.

Table 6. Response table for means of Brass wire

Level	T_{on}	T_{off}	W_F
1	0.617	1.507	1.186
2	1.045	0.901	0.874
3	1.922	1.774	1.525
Delta	1.305	0.606	0.650
Rank	1	3	2

Table 7. Response table for means of DCW

Level	T_{on}	T_{off}	W_F
1	0.653	1.101	1.215
2	0.995	1.307	1.356
3	1.987	1.228	1.065
Delta	1.334	0.290	0.206
Rank	1	2	3

7.5. Measurement of Surface roughness and Wire Wear Rate

Apart from Material removal and Kerf width, Wire Wear Rate (WWR), accuracy and machined surface quality like Surface finish, Surface roughness, plays a significant role in determining the output responses in wire EDM process. Wire EDM is capable of producing a good surface finish similar to the surface ground finish with a fine wheel. The volume of the material removed depends on the desired cutting speed and the surface finish achieved. Surface Roughness is measured by an instrument called Talysurf. Wire wear rate is also an important phenomenon to determine the loss in the wire after the machining operation. The loss in the wire leads to wire breakage. Wire Wear Rate is calculated by taking initial weight of the wire and final weight of the wire into consideration. The WWR is given by the following formulae:

$$WWR = \frac{I_W - F_W}{I_W} \qquad (14)$$

Where, I_W is the initial weight of the wire and F_W is the final weight of the wire.

The experiment was conducted out for the surface roughness and WWR at the optimized setting of both Brass and DCW. The optimized settings machined with brass electrode for copper material was found to be T_{on} 115μs, T_{off} 52μs, W_F 6 m/min and DCW was found to be T_{on} 115μs, T_{off} 54μs, W_F 4 m/min. Table 8 shows the values of surface roughness and

Wire Wear Rate conducted at the optimized settings of both the wires.

Table 8. Surface roughness and WWR at optimized settings

Wire electrodes	Optimized Setting	Surface Roughness (μm)	Wire Wear Rate
Brass	115-52-6	2.1	0.12
DCW	115-54-4	2.2	0.08

From Table 8 it can be observed that the Brass wire provides better surface finish than the Diffused coated wire. High electrical and thermal conductivity are the reasons for the Brass wire to achieve better surface finish than DCW.

Similarly the wire wear ratio is calculated for both the Brass and DCW wire. It is concluded that wire loss occurs more in Brass wire than DCW. So the chance of wire breakage is slightly more in Brass wire than DCW. This is due to the fact that the tensile strength of DCW is comparatively more than Brass wire. So there is less chance of wire breakage in DCW than the Brass wire.

VIII. CONCLUSIONS

The paper has presented a comparative study between the wires taking the same process parameters and response parameters and its effect in Wire EDM operations. Based on the current research, following conclusions can be drawn as follows:

- The experimental results confirmed the validity of the used Grey based MOORA method for establishing the machining performance and optimizing the machining parameters in WEDM operations.
- SEM image confirms that after the machining operation, the wire undergoes craters and voids due to high voltage and current at high pulse on time for Brass wire. Similarly for Diffused coated wire, burr, voids and cutting directions can be marked due to high wire feed rate and high spark energy density. The microstructural analysis confirms that pulse on time is the determining factor in affecting and influencing the formation of various surface defects of the wire.
- XRD analysis confirms some traces of migration of work-piece material (Copper) to the wire electrode.
- Based on ANOVA, pulse on time and wire feed rate are found to be the most significant parameters affecting the responses for Brass wire. Similarly for Diffused coated wire the significant factor affecting the response is Pulse on time.
- Variation effects are also investigated for the Brass wire and DCW with the changing process parameters. The Modified Coefficient Ratio increases with the increase in Pulse on time for both Brass wire and diffused coated wire. This is due to the fact that the discharge energy of the plasma channel increases which results in an increase in sparking efficiency resulting in higher values of Modified Coefficient Ratio.
- The predicted statistical model analysis for both MRR and KW for Brass wire and DCW confirms a good sign of agreement with higher R2 values between experimental and predicted data's.
- The analysis confirms that Brass wire provides a good surface finish than DCW but there is more chance of wire breakage in Brass wire than DCW wire.
- From the above analysis it is also clear that the Brass wire is more suitable and convenient than Diffused coated wire in machining of the gear.

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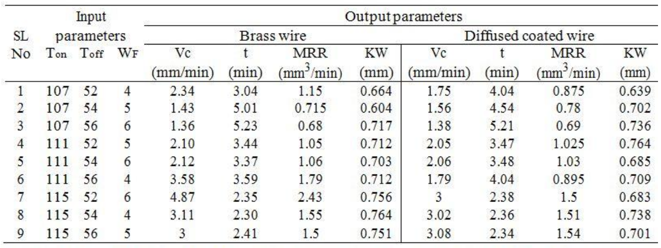
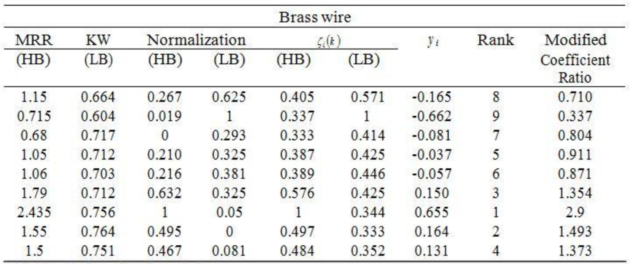
Appendix A.1. Design of experiments using L_9 orthogonal array



SL No	Input parameters			Output parameters							
				Brass wire				Diffused coated wire			
	T_{on}	T_{off}	W_F	Vc (mm/min)	t (min)	MRR (mm^3/min)	KW (mm)	Vc (mm/min)	t (min)	MRR (mm^3/min)	KW (mm)
1	107	52	4	2.34	3.04	1.15	0.664	1.75	4.04	0.875	0.639
2	107	54	5	1.43	5.01	0.715	0.604	1.56	4.54	0.78	0.702
3	107	56	6	1.36	5.23	0.68	0.717	1.38	5.21	0.69	0.736
4	111	52	5	2.10	3.44	1.05	0.712	2.05	3.47	1.025	0.764
5	111	54	6	2.12	3.37	1.06	0.703	2.06	3.48	1.03	0.685
6	111	56	4	3.58	3.59	1.79	0.712	1.79	4.04	0.895	0.709
7	115	52	6	4.87	2.35	2.43	0.756	3	2.38	1.5	0.683
8	115	54	4	3.11	2.30	1.55	0.764	3.02	2.36	1.51	0.738
9	115	56	5	3	2.41	1.5	0.751	3.08	2.34	1.54	0.701

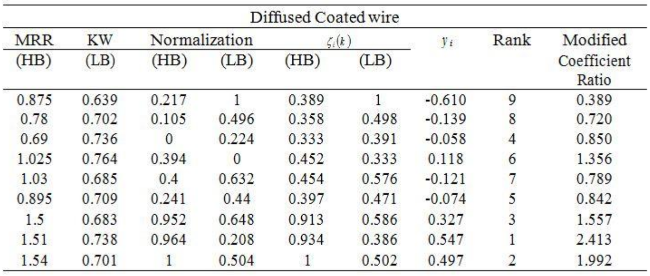
Appendix A.2. Multi-Objective Optimization using Grey Taguchi based MOORA of Brass wire



Brass wire								
MRR	KW	Normalization		$\zeta_i(k)$		y_i	Rank	Modified Coefficient Ratio
(HB)	(LB)	(HB)	(LB)	(HB)	(LB)			
1.15	0.664	0.267	0.625	0.405	0.571	-0.165	8	0.710
0.715	0.604	0.019	1	0.337	1	-0.662	9	0.337
0.68	0.717	0	0.293	0.333	0.414	-0.081	7	0.804
1.05	0.712	0.210	0.325	0.387	0.425	-0.037	5	0.911
1.06	0.703	0.216	0.381	0.389	0.446	-0.057	6	0.871
1.79	0.712	0.632	0.325	0.576	0.425	0.150	3	1.354
2.435	0.756	1	0.05	1	0.344	0.655	1	2.9
1.55	0.764	0.495	0	0.497	0.333	0.164	2	1.493
1.5	0.751	0.467	0.081	0.484	0.352	0.131	4	1.373

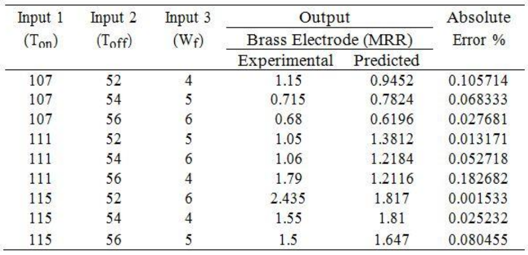
HB=Higher the better, LB= Lower the better

Appendix A.3. Multi-Objective Optimization using Grey Taguchi based MOORA of Diffused Coated wire



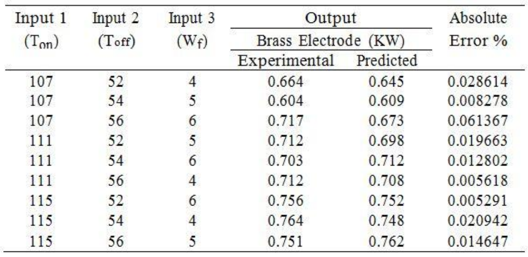
Diffused Coated wire								
MRR	KW	Normalization		$\zeta_i(k)$		y_i	Rank	Modified Coefficient Ratio
(HB)	(LB)	(HB)	(LB)	(HB)	(LB)			
0.875	0.639	0.217	1	0.389	1	-0.610	9	0.389
0.78	0.702	0.105	0.496	0.358	0.498	-0.139	8	0.720
0.69	0.736	0	0.224	0.333	0.391	-0.058	4	0.850
1.025	0.764	0.394	0	0.452	0.333	0.118	6	1.356
1.03	0.685	0.4	0.632	0.454	0.576	-0.121	7	0.789
0.895	0.709	0.241	0.44	0.397	0.471	-0.074	5	0.842
1.5	0.683	0.952	0.648	0.913	0.586	0.327	3	1.557
1.51	0.738	0.964	0.208	0.934	0.386	0.547	1	2.413
1.54	0.701	1	0.504	1	0.502	0.497	2	1.992

Appendix A.4. Comparison of error % between experimental and predicted values of MRR machined by Brass electrode



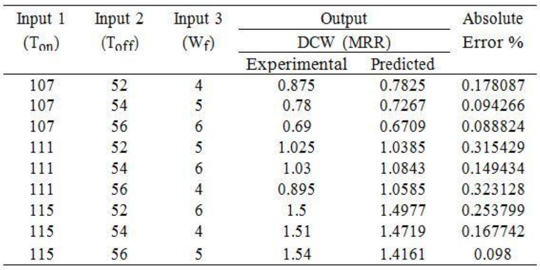
Input 1 (T_{on})	Input 2 (T_{off})	Input 3 (W_f)	Output		Absolute Error %
			Brass Electrode (MRR)		
			Experimental	Predicted	
107	52	4	1.15	0.9452	0.105714
107	54	5	0.715	0.7824	0.068333
107	56	6	0.68	0.6196	0.027681
111	52	5	1.05	1.3812	0.013171
111	54	6	1.06	1.2184	0.052718
111	56	4	1.79	1.2116	0.182682
115	52	6	2.435	1.817	0.001533
115	54	4	1.55	1.81	0.025232
115	56	5	1.5	1.647	0.080455

Appendix A.5. Comparison of error % between experimental and predicted values of KW machined by Brass electrode



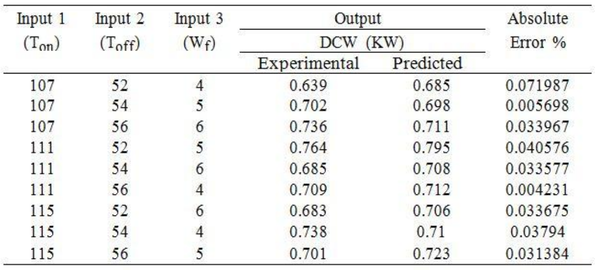
Input 1 (T_{on})	Input 2 (T_{off})	Input 3 (W_f)	Output		Absolute Error %
			Brass Electrode (KW)		
			Experimental	Predicted	
107	52	4	0.664	0.645	0.028614
107	54	5	0.604	0.609	0.008278
107	56	6	0.717	0.673	0.061367
111	52	5	0.712	0.698	0.019663
111	54	6	0.703	0.712	0.012802
111	56	4	0.712	0.708	0.005618
115	52	6	0.756	0.752	0.005291
115	54	4	0.764	0.748	0.020942
115	56	5	0.751	0.762	0.014647

Appendix A.6. Comparison of error % between experimental and predicted values of MRR machined by Diffused coated wire electrode



Input 1 (T_{on})	Input 2 (T_{off})	Input 3 (W_f)	Output		Absolute Error %
			DCW (MRR)		
			Experimental	Predicted	
107	52	4	0.875	0.7825	0.178087
107	54	5	0.78	0.7267	0.094266
107	56	6	0.69	0.6709	0.088824
111	52	5	1.025	1.0385	0.315429
111	54	6	1.03	1.0843	0.149434
111	56	4	0.895	1.0585	0.323128
115	52	6	1.5	1.4977	0.253799
115	54	4	1.51	1.4719	0.167742
115	56	5	1.54	1.4161	0.098

Appendix A.7. Comparison of error % between experimental and predicted values of KW machined by Diffused coated wire electrode



Input 1 (T_{on})	Input 2 (T_{off})	Input 3 (W_f)	Output		Absolute Error %
			DCW (KW)		
			Experimental	Predicted	
107	52	4	0.639	0.685	0.071987
107	54	5	0.702	0.698	0.005698
107	56	6	0.736	0.711	0.033967
111	52	5	0.764	0.795	0.040576
111	54	6	0.685	0.708	0.033577
111	56	4	0.709	0.712	0.004231
115	52	6	0.683	0.706	0.033675
115	54	4	0.738	0.71	0.03794
115	56	5	0.701	0.723	0.031384