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Performance of Zinc Coated Electrode Wire and Parametric Optimization During Profile Cutting of Die-Steel

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Abstract*: In this work, the effect of brass wire coated with zinc as electrode wire towards maximizing MRR and minimizing SR for the considered input parameters was studied in elaborate during profile cutting of tool steel AISI D3. Experiments were designed based on the $L_{18}(2^1,3^7)$ Taguchi's orthogonal array considering cutting speed, Ton and Toff, wire tension, servo feed rate and voltage, current and electrode feed rate. The outputs MRR and SR were analyzed and optimized using Grey Relational Analysis (GRA) simultaneously. For both SR and MRR, the drawn chart shows that, the raw data's lies within upper and lower control limits. The optimum input conditions obtained for higher MRR and lower SR were: 75% of cutting speed, 128 µsec of Ton, 54µsec of Toff, 190A of input current, electrode feed of 3 mm/min with 7 gm of electrode tension, 10V of servo voltage and 2060 mm/min of 10V. Execution of ANOVA on grey grade identifies that, wire tension was the parameter that influences more by 25.89%, followed by Ton and servo voltage by 21.37% and feed rate of wire by 11.89%, with an R2 value of 96.55%. For validating the results, confirmation experiment was also done.

Keywords: WEDM, Grey Relational Analysis, Taguchi's DoE, Profile Cutting, ANOVA.

I. INTRODUCTION

Wirecut- Electrical Discharge Machining (WEDM) is advancement of EDM, is a process of metal removing that utilizes thermal energy and uses an uninterruptedly moving electrode wire to eradicate material by means of controlled, rapid and discharges of repetitive sparks. For flushing the particles removed, a dielectric fluid is applied, apart from that, it is also used to regulate the spark discharge, and to cool the workpiece and wire electrode. In WEDM, both the workpiece and wire must be conductive to electricity [1].

In WEDM, as illustrated in Fig. 1, a supply reels supplies the electrode wire, which moves through the conductive workpiece and is taken by the take-up reel.

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The wire electrode is advanced gradually between the supply and take-up reals in order to compensate towards the wear that occurs in the wire electrode during at the cutting point.

In WEDM, with a series of spark discharges that happen between the workpiece and precisely placed wire that is moving, machining of materials takes place [2]. High frequency pulses are utilized to create discharges from the moving wire electrode towards the workpiece within a spark gap that is very small which is filled with insulated dielectric fluid, i.e., de-ionized water. The heat generated by spar ks, erodes away a minute amount of material by melting and vaporization from the workpiece. During the process, some amount of wire electrode material will also be eroded. These debris particles are removed from the zone of machining by flushing action with the aid of de-ionized water stream that flows through the bottom and top flushing nozzles with extreme pressures [3].

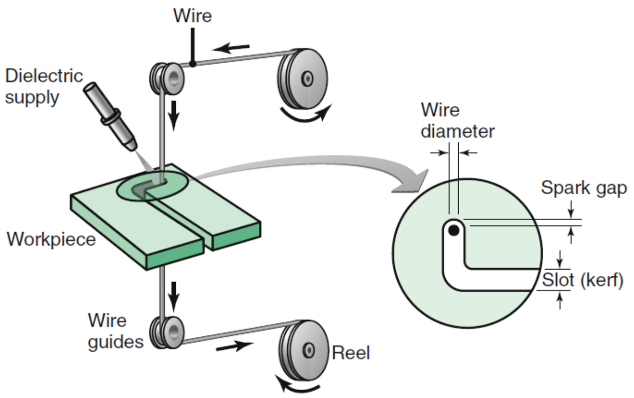

Fig. 1. WEDM process [4]

Tonday and Tigga [5] performed experimental investigation on WEDM while cutting Inconel 718 material considering Ton, Toff, cutting voltage, flushing pressure, and wire feed towards optimizing machining time and surface roughness considering L_{27} Taguchi's design of orthogonal array (OA) and found that, Ton, is most influential parameter for both outputs and kerf fluctuates with variations in the considered independent parameters during the process of machining. Experimental investigation on MRR and Ra of Inconel 625 were studied in WEDM procedure by adopting tow wire electrodes viz., untreated and cryogenically treated zinc coated wire [6], considering intensity of current, tool electrode, Ton, Toff, wire feed rate and tension, a suitable L_{18} OA was selected, observation shows that, the significant inputs that influences SR and MRR were Ton, wire electrode material and intensity of current. Cryogenic treated zinc coated wire, intensity of current and Ton are the significant inputs that influences the outputs and performance machining improves with cryogenically treated wire electrode.

Kumar et al. [7] analyzed and examined the impact of electrode in WEDM machinability of Inconel 718, considering L_{16} OA for input parameters Ton, current discharge, flushing pressure and wire speed and studied their influence on corner error and surface roughness. Zinc coated wire electrode provides improved effect on corner radius and SR than the uncoated brass wire. The Ton and discharge current are the highest influential factor that influences the response variables. Kumar et al. [8] conducted experimental studies considering L_9 OA for machining H13 tool steel using WEDM for parametric optimization, considering Ton, Toff and wire tension and speed as inputs and MRR, wire wear ratio and surface flatness as outputs, with zinc coated copper wire electrode. Chinnadurai and Vendan [9] performed WEDM machining using uncoated and zinc coated wire electrode during machining AISI 4140. Observation shows that, MRR was affected by current, Ton for uncoated brass wire, and for coated wire electrode, Ton, servo voltage and Toff are the influential parameters than govern the MRR. The best performances were provided while using wire electrode as zinc coated brass wire.

Kapoor et al. [10] studied the influence of different wire electrodes used in WEDM on the machining characteristics of AISI D3 die steel, considering brass wire, zinc material coated wire and composite wire along with Ton and peak current, over the outputs SR and cutting speed. The study found that, reduction in SR was possible with brass wire and improved cutting speed was possible with composite wire when compared with other wire electrodes. With brass wire, smooth surface is attained, whereas rough surface is produced with zinc coated electrode wire. Dhale and Kulkarni [11] studied the behavior of Inconel-718, with different wire electrodes in WEDM process and measured the performance measures such as MRR and surface finish, conducted experiments by varying Ton, Toff, wire tension, dielectric fluid flushing pressure and wire feed. The investigational output proves that, better MRR and SR was better. Improved MRR is possible with coated wire than uncoated wire, zinc coated wire gives better surface finish as compared to brass wire. Researches had also considered different wire electrodes during WEDM process parameter optimization purpose [12].

From the review of literature carried out, the conclusion was, no researcher had adopted most of the WEDM process parameters for optimization for their study and the works on brass wire coated with zinc is limited. Hence, an attempt was made to perform the WEDM studies using zinc coated wire electrode. In this work, the influence of wire electrode coated with zinc along with the effect of machining parameters were studied during the profile cutting of tool steel in WEDM. Experiments were formulated as per Taguchi's methodology and the outputs measured (MRR and SR) were analyzed using Grey Relational Analysis. The process capability of WEDM was studied using control chart.

II. MATERIALS & METHODOLOGY

A. AISI D3 Steel

In this work, AISI D3 high carbon, high chromium steel termed as tool grade was selected as workpiece. D3 steels were characterized with extreme hardness through oil hardening and due to the presence of carbides of chromium in their microstructure [13]. The elements present in AISI D3 steel is presented in Table I. D3 tool steels are specifically used as tooling and cold die materials and in trimming and blanking dies. A commercially available zinc coated brass wire is preferred as electrode with a diameter of 0.25 mm diameter. For experimentation purpose a plate of size 50×50×15 mm was used.

Table- I: AISI D3 steel composition

Element	C	Si	Mn	P	S	Cr	Fe
%	2.4	0.608	0.601	0.0303	0.0322	11.96	Reminder

B. Taguchi's Experimental Methodology

The method of examining and describing all possible situations in an experimental trial that comprises of various design parameters is known as Design of Experiments (DoE) [14]. Taguchi believed that the perfect practice to augment the quality of a product is to develop the product with inbuilt quality [15]-[17]. For achieving this quality, Taguchi planned investigational methods using specifically created arrays known as Orthogonal Arrays (OA) [18], [19]. Experimental design was made easier and consistent with the use of table designed using OAs. Taguchi established distinct OAs for his investigation that are purely constructed on Latin squares, with combination of considered input is a specific means, for various experimental trials [20]. Enhancing the design of a product suggests that finding the exact combination of input parameters or developing appropriate modifications to the machinery will provide better outcomes. Experiments designed based on OA reduces the variation in outputs due to properly controlled parameters.

For examining the machinability performance of D3 steel, a L_{18} OA was selected for multiple-level input factors [21] for dissimilar number of levels of input parameters for conducting trials, with the aid of Minitab-18 a statistical analysis software in which one parameter varies through two level and other selected parameters were varied by three level values. From Taguchi's OA for multi-level model, the various combination of input parameter selected for machining designed as per Latin square is given in Table II.

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Table- II: Taguchi L_{18} OA

Trial No	Cutting Speed (%)	Ton (µsec)	Toff (µsec)	Input Current (Amp)	Wire Feed (mm/min)	Wire Tension (gm)	Servo Volt (Voltage)	Servo Feed rate (mm/min)
1	70	126	48	190	3	7	10	2060
2	70	126	51	210	4	9	15	2080
3	70	126	54	230	5	11	20	2100
4	70	127	48	190	4	9	20	2100
5	70	127	51	210	5	11	10	2060
6	70	127	54	230	3	7	15	2080
7	70	128	48	210	3	11	15	2100
8	70	128	51	230	4	7	20	2060
9	70	128	54	190	5	9	10	2080
10	75	126	48	230	5	9	15	2060
11	75	126	51	190	3	11	20	2080
12	75	126	54	210	4	7	10	2100
13	75	127	48	210	5	7	20	2080
14	75	127	51	230	3	9	10	2100
15	75	127	54	190	4	11	15	2060
16	75	128	48	230	4	11	10	2080
17	75	128	51	190	5	7	15	2100
18	75	128	54	210	3	9	20	2060

C. Multi-Criteria Optimization Method

Grey Relational Analysis (GRA) is implemented for perceiving the ideal assemblage of input factors for attaining improved responses [22]-[24]. GRA is applied for assessing the dependent parameter influence with meager data information [25]. In grey approach, pre-processing of raw data's is made initially for further analysis, pre-processing is done by converting the data points to some type of indices for quantification purposes through normalizing procedure [26]. The experimental output values should be converted to decimal values between zero and one for assessing in normalizing stage [27]. In normalizing, for larger-the-better condition, the original raw data should be converted using the formulae;

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (1)$$

where $x^o{}_i$ (k) is raw data, $x^*{}_i$ (k) corresponds to data subsequent to normalization, max $x^o{}_i$ (k) is higher value of data and min $x^o{}_i$ (k) is the lower data value. For performing normalizing responses that falls under lower-the-better category, the general formulae used is:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$$

Following normalizing, determination of grey coefficient is carried out for determining the relationship that exists between ideal and real values of normalization [28], the formulae used for finding grey coefficient is,

$$\zeta_i(k) = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{0i}(k) + \zeta.\Delta_{\max}} \quad (3)$$

Δ_{oi} (k) is deviation of normalized values for the ideal value of one, taken as reference value, provided as,

$$\Delta_{0i}(k) = \left\| x_0^*(k) - x_i^*(k) \right\| \quad (4)$$

$$\Delta_{\max} = \max_{\forall j \varepsilon i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|,$$
$$\Delta_{\min} = \min_{\forall j \varepsilon i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \quad (5)$$

ζ is identification coefficient, usually $\zeta \varepsilon$ lies in the range of 0 to 1 and normally ζ is considered as 0.5. After calculating grey coefficient value, the corresponding grade values were determined by considering the mean values of grey coefficient equivalent to experimental trials as,

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} {}_i\zeta_i(k) \quad (6)$$

D. Experimental Setup

Experiments were performed on computer-controlled Electronica ELCUT WEDM machine as per the formulated L_{18} OA and each experiment was replicated thrice for finding reliable outputs. After carrying out the machining, SR measurement was performed on surface of specimens with the help of Surfcorder SE1200 with specifications: 520 µm and 25 mm measuring range in vertical and horizontal directions with 0.008 µm resolution and 0.8 mm cut-off with gaussian type filter. Through loss of volume, MRR was calculated with the consideration of machining time. MRR is calculated using the formulae;

$$MRR = \frac{Wt.\ before\ \mathrm{m/c}\ -\ Wt.\ after\ m/c}{M/c\ time\ \times\ Density}\ (mm^3/\min) \quad (7)$$

III. RESULT AND DISCUSSIONS

As per L_{18} Taguchi's design, experiments were conducted, and the MRR and SR was determined from the volume loss and roughness on the machined surface, as presented in Table III. Observation shows that, with higher cutting speed, both MRR and SR increases [29]. With increase in Ton, MRR increases considerably, but SR increases up to 127 µsec and with further increase in Ton to 128 µsec, SR reduces. With higher Toff, MRR increases abruptly [30] but SR increases up to 51 µsec, afterward SR decreases. Similarly, with higher input current, MRR increases but SR increases initially and afterwards it reduces considerably.

With higher wire feed, SR increases drastically [31], but MRR reduces until 4 mm/min and then upsurges with higher feed rate of wire electrode.

Table- III: Output response of WEDM with zinc coated wire

Exp. No	Output Responses	
	MRR (mm^3/min)	*SR (μm)*
1	12.390	1.827
2	11.745	3.076
3	12.048	2.664
4	11.619	2.763
5	12.619	2.786
6	12.649	2.607
7	11.169	2.660
8	13.169	2.181
9	15.212	2.531
10	13.636	2.715
11	12.623	2.687
12	14.182	2.611
13	14.442	2.811
14	14.701	2.604
15	12.039	2.969
16	13.762	2.503
17	14.762	2.698
18	15.429	2.226

With higher wire tension, SR increases significantly, but MRR tends to reduce. SR become higher with higher values of servo voltage to 15 V, afterwards SR decreases, whereas for MRR, initially MRR decreases until 15 V, then it tends to increase with higher servo voltage to 20 V. With higher servo feed, SR tends to increase, but MRR increases with change in servo feed rate up to 2080 mm/min, with further increase to 2100 mm/min, MRR tends to reduce.

For assessing the process control and stability, the statistical tool normally used is X-bar chart [32], which can identify, whether the process is foreseeable and steady [33]. Fig. 2 shows the control chart (X-bar) for MRR, where the upper limit is 16.151 mm^3/min and lower limit is 10.316 mm^3/min. It was observed that, all the experimental data points were well scattered within the control limits, thereby the stable experimental readings were evaluated. Likewise, control chart obtained for SR is presented in Fig. 3, having higher control limit of 3.395 microns and lower control limit of 1.819 microns, all the 18-trial data were placed well within control limits.

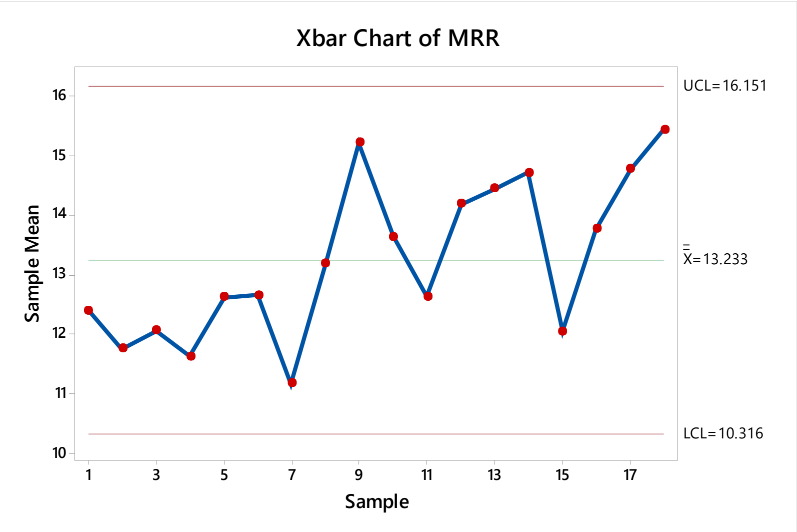

Fig. 2. Control chart developed for MRR

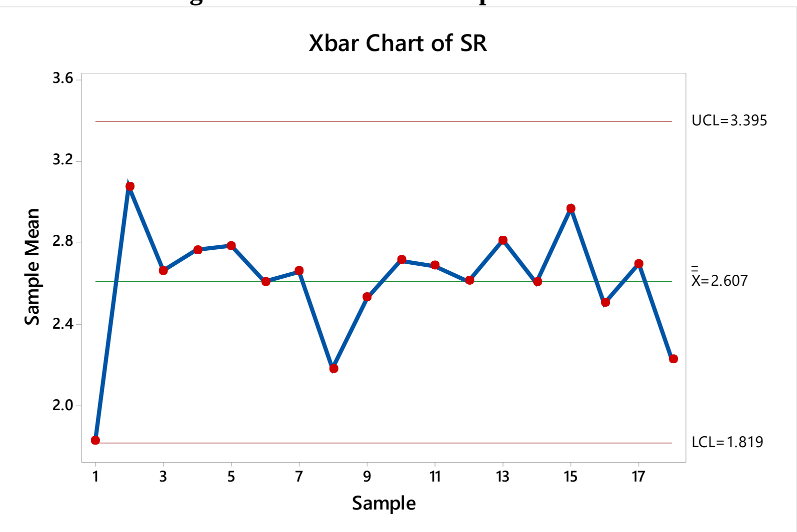

Fig. 3. Control chart developed for SR values

For optimizing SR and MRR simultaneously, GRA was applied, for normalizing raw data's of MRR and SR which should be maximum and minimum, for which formulae given in Equ. (1) and Equ. (2) were used. Following the normalizing sequence, deviation sequence was calculated, to know how much the normalized values had deviated from the ideal value of 1, as displayed in Table IV.

Table- IV: Normalizing and Deviation sequence in GRA

Trial No	Normalizing Sequence		Deviation Sequence		Grey Relational Coefficient		Grey Relational Grade
	MRR	*SR*	*MRR*	*SR*	*MRR*	*SR*	
1	0.287	1.000	0.713	0.000	0.412	1.000	0.706
2	0.135	0.000	0.865	1.000	0.366	0.333	0.350
3	0.206	0.330	0.794	0.670	0.386	0.427	0.407
4	0.106	0.251	0.894	0.749	0.359	0.400	0.379
5	0.340	0.232	0.660	0.768	0.431	0.394	0.413
6	0.347	0.376	0.653	0.624	0.434	0.445	0.439
7	0.000	0.333	1.000	0.667	0.333	0.428	0.381
8	0.469	0.717	0.531	0.283	0.485	0.638	0.562
9	0.949	0.436	0.051	0.564	0.908	0.470	0.689
10	0.579	0.289	0.421	0.711	0.543	0.413	0.478
11	0.341	0.311	0.659	0.689	0.432	0.421	0.426
12	0.707	0.372	0.293	0.628	0.631	0.443	0.537
13	0.768	0.212	0.232	0.788	0.683	0.388	0.536
14	0.829	0.378	0.171	0.622	0.745	0.446	0.595
15	0.204	0.086	0.796	0.914	0.386	0.354	0.370
16	0.609	0.459	0.391	0.541	0.561	0.480	0.521
17	0.843	0.303	0.157	0.697	0.762	0.418	0.590
18	1.000	0.681	0.000	0.319	1.000	0.610	0.805

Table IV presents the grey coefficient values obtained from the deviation sequence as given in Equ. (3). By taking mean grey coefficient values, corresponding to independent level values of input factors, GRGs were obtained and it was noticed that, for the experimental trial 18, higher value of GRG was obtained. For plotting the GRG response plot, mean grey grade that corresponds to individual level values were taken as presented in Fig. 4, based on the calculation of response table as in Table V. Optimum level values evolved from response table and response plot were selected based on higher values of grey relational grade, optimum settings identified were: 75% of cutting speed, 128 µsec of Ton, 54µsec of Toff, 190 A of input current, 3 mm/min of wire feed rate, 7 gm of tension of wire electrode, 260 mm/min and 10V of servo feed rate and voltage.

Interaction graph drawn for the obtained GRG to study the combinatory influence one parameter over another parameter [34] is given in Fig. 5. Observation shows that, in between cutting speed and input current, cutting speed and wire tension, a significant interaction exists, represented by non-parallel lines. In between T_{on} and wire tension, input current, servo feed and T_{off} a considerable interaction was observed. A combined effect between T_{off} and electrode tension and current and T_{off} and servo feed was observed through non-parallel lines. In between input current and feed rate of wire electrode a considerable interaction effect was observed, but with other input parameters no significant effect was observed. Among wire feed and tension, feed rate of the wire electrode and servo voltage and between wire feed and servo feed a significant interaction exists. Combined effect of wire tension and servo feed and between servo voltage and servo feed was higher.

Table- V: Mean level values of GRG

Factors	Level 1	Level 2	Level 3	Max - Min
Cutting Speed	0.481	0.540	-	0.059
Ton	0.484	0.455	0.591	0.136
Toff	0.500	0.489	0.541	0.052
Input Current	0.527	0.504	0.500	0.026
Wire Feed	0.559	0.453	0.519	0.106
Wire Tension	0.562	0.549	0.419	0.142
Servo Volt	0.577	0.435	0.519	0.142
Servo Feed rate	0.556	0.493	0.482	0.074

A statistical approach for evaluating the amount of variation between sets of data is Analysis of Variance (ANOVA), which is a needful tool identified by researchers for evaluating the dependent variables based on the influence of independent variables [35]. From the statistical tool ANOVA executed on GRG, it was identified that, wire tension was the most influential parameters contributing by 25.89%, followed by Ton and servo voltage by 21.37% and feed rate of wire by 11.89%. With 95% confidence level of ANOVA, an error of 3.45% was obtained, thereby producing a better model as displayed in Table VI. The R^2 value of the developed model is 96.55%, which is a good one. The influence of different independent parameters on grey grade determined is presented in Fig. 6.

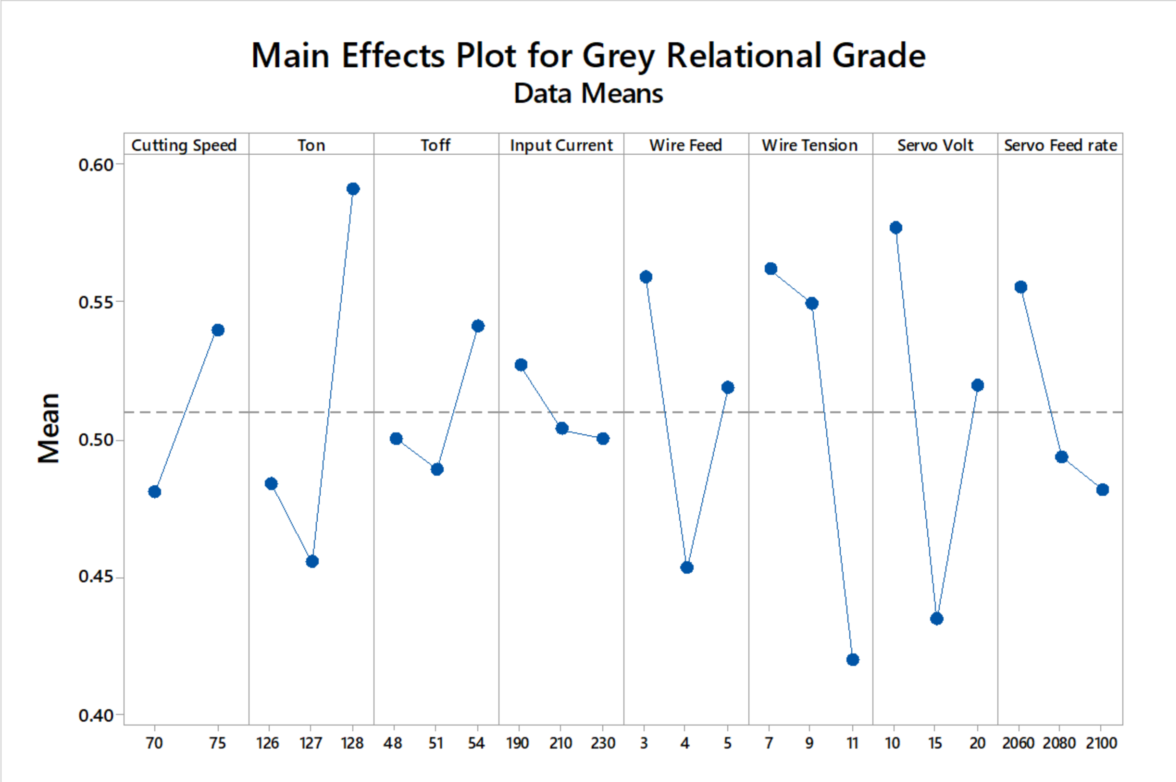

Fig. 4. Main effect plot for GRA Grade

Table- VI: ANOVA for Grey relational grade

Source	DoF	Adj. SS	Adj. MS	F Value	P Value	% Contribution
Cutting Speed	1	0.0157	0.0157	3.169	0.217	5.46%
Pulse ON-Time	2	0.0614	0.0307	6.200	0.139	21.37%
Pulse OFF-Time	2	0.0090	0.0045	0.907	0.524	3.13%
Input Current	2	0.0025	0.0012	0.249	0.801	0.86%
Wire Feed rate	2	0.0342	0.0171	3.451	0.225	11.89%
Wire Tension	2	0.0744	0.0372	7.511	0.117	25.89%
Servo Voltage	2	0.0614	0.0307	6.201	0.139	21.37%
Servo Feed rate	2	0.0190	0.0095	1.913	0.343	6.59%
Error	2	0.0099	0.0050	1.000		3.45%
Total	17	0.2875	0.0169			100.00%

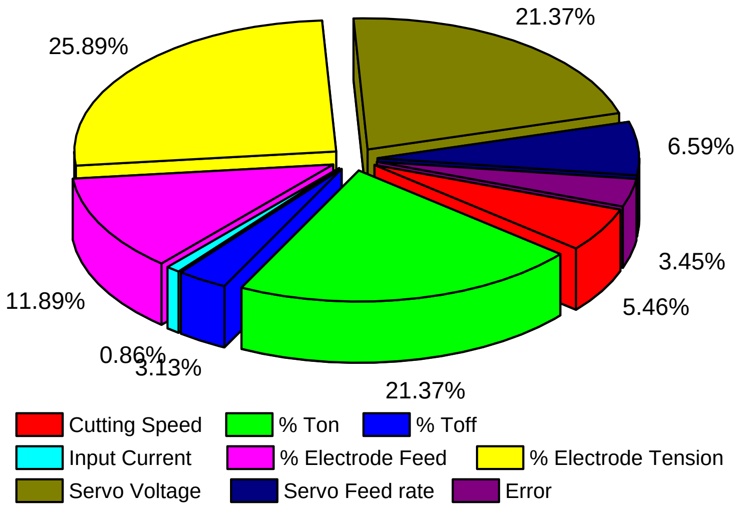

Fig. 6. Contribution of dependent parameters on GRG

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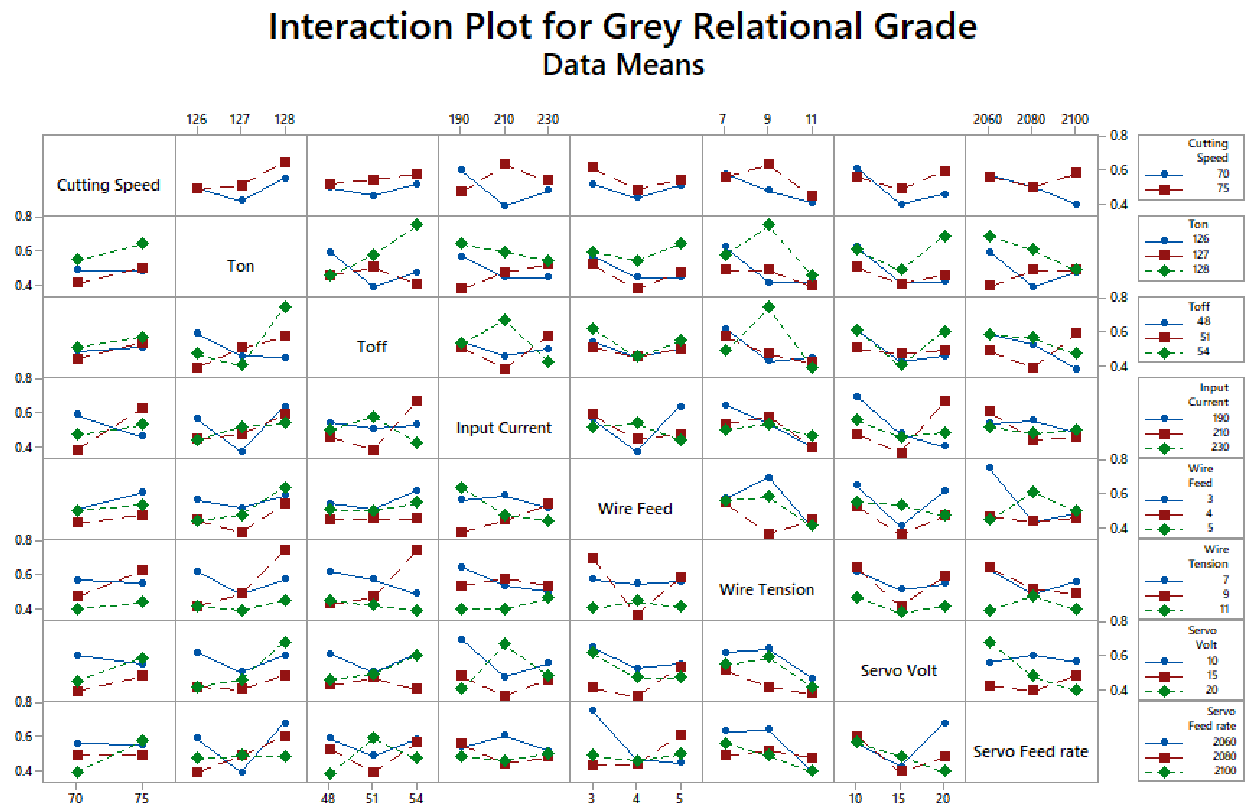

Fig. 5. Interaction plot for GRG

Surface plots are figures of 3D in nature, relatively displaying the data points of individuals, these plots of surface present a functional association that exists among the selected dependent variable (Y), and two input independent variables such as X and Z [36]. The 3D response plot is an alternative and identical design to the contour plot. A response surface is a geometric illustration attained once an output parameter is designed as a relationship with one or more quantitative independent factors [37]. Response surface plots were drawn for the output responses SR and removal of material from workpiece for the most significant parameters based on the ANOVA table. Fig. 7 shows the surface plot drawn between Ton and wire feed and between Ton and wire tension for variation in MRR. Observation shows that, with increase in Ton, MRR tends to shoots up in a linear manner and with higher values of tension in wire electrode, MRR tends to reduce in a curvilinear condition, similarly with higher wire feed rate, MRR tends to increase in a non-linear way. Higher Ton and feed rate of wire electrode produce lower MRR, whereas higher Ton and lower wire tension produces a higher MRR.

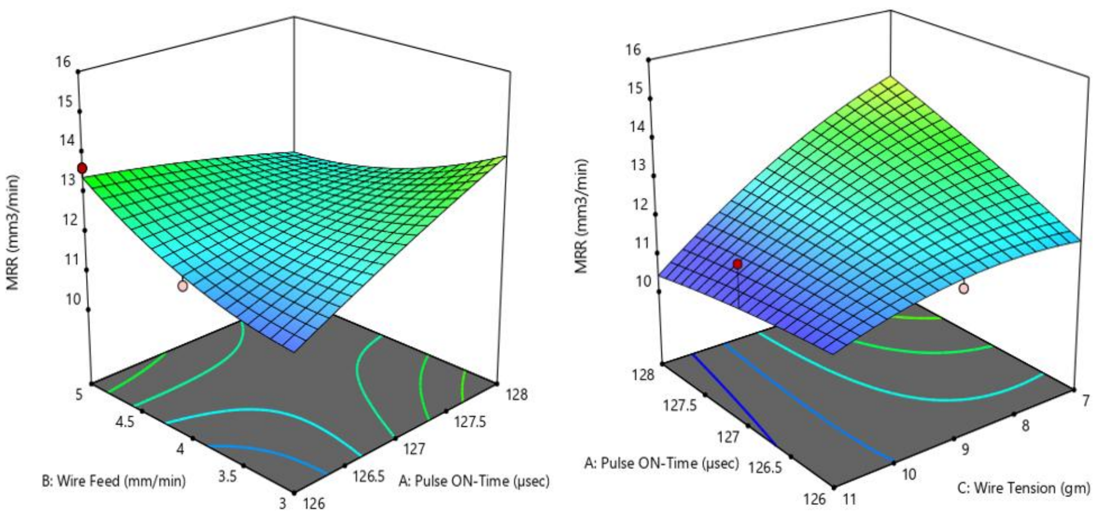

Fig. 7. Surface plot for MRR over wire tension, Ton and wire feed

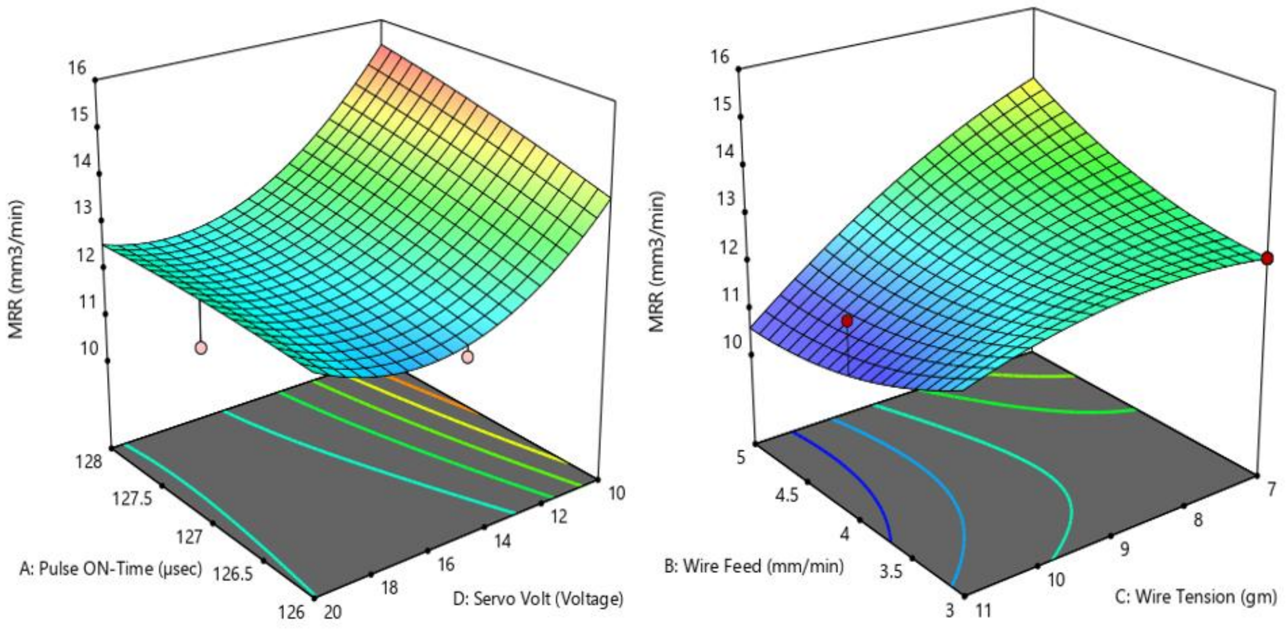

Fig. 8. Surface plot for MRR over Ton, wire feed and tension and servo voltage

Fig. 8 presents the 3D plot for MRR between Ton and servo voltage and between tension in wire and feed rate of wire. With increase in servo voltage, MRR tends to reduce in a concave manner, with a non-linear relationship. Higher Ton and servo voltage produce a higher MRR, and similarly higher MRR was developed for lower wire tension and higher feed rate of wire. Effect of electrode feed rate and servo voltage, and between servo voltage and tension in wire electrode towards MRR is presented in Fig. 9. Observation made was, maximum MRR was achieved with lower servo voltage values and extreme feed rate of wire electrode. With lower wire tension and lower servo voltage, higher values of MRR was achieved.

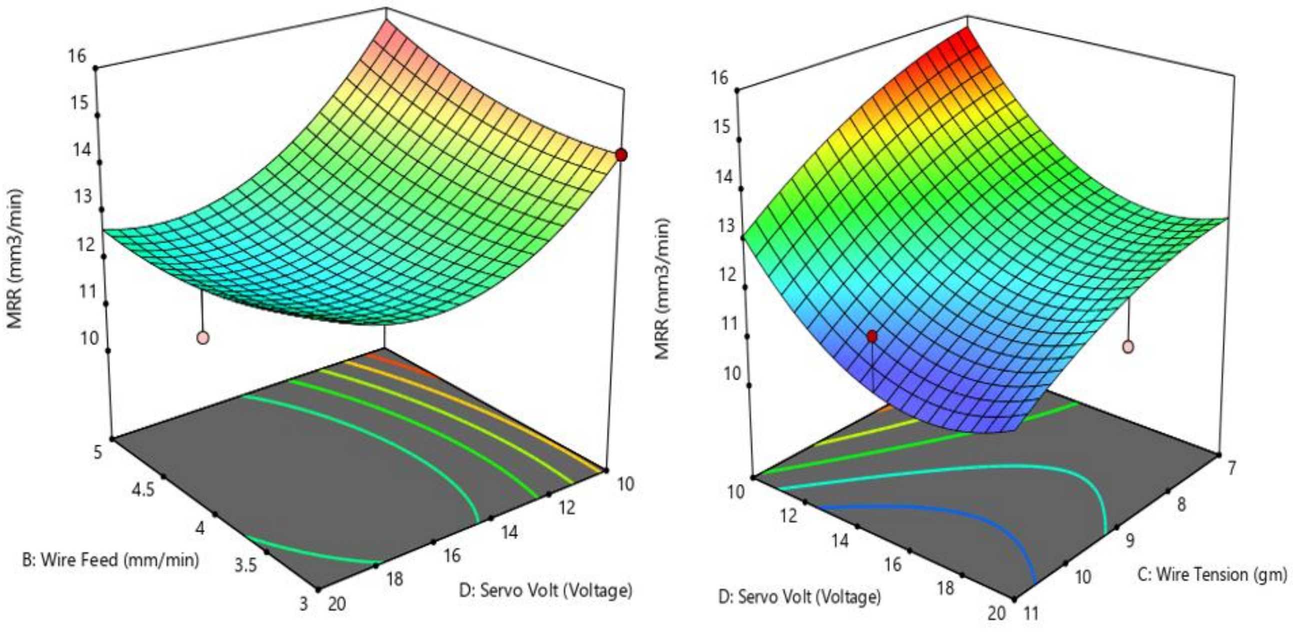

Fig. 9. Surface plot of MRR for servo volt, wire tension and feed rate

A min-max condition was achieved with Ton and feed rate of wire for surface roughness, as presented in Fig. 10. SR increases up to certain value of Ton and wire feed rate, afterwards it tends to reduce. With higher tension in the wire electrode, SR tends to increase. Higher SR was sensed with moderate values of Ton and wire feed rate. For moderate value of Ton and wire tension, higher SR was achieved.

Fig. 11 presents the surface plot for SR for variation in the significant input parameters. With increase in servo voltage, SR tends to reduce in a convex manner. Lower values of servo voltage produce higher SR, along with a moderate value of Ton. Lower tension of wire electrode and higher electrode feed produces a significant increase in SR.

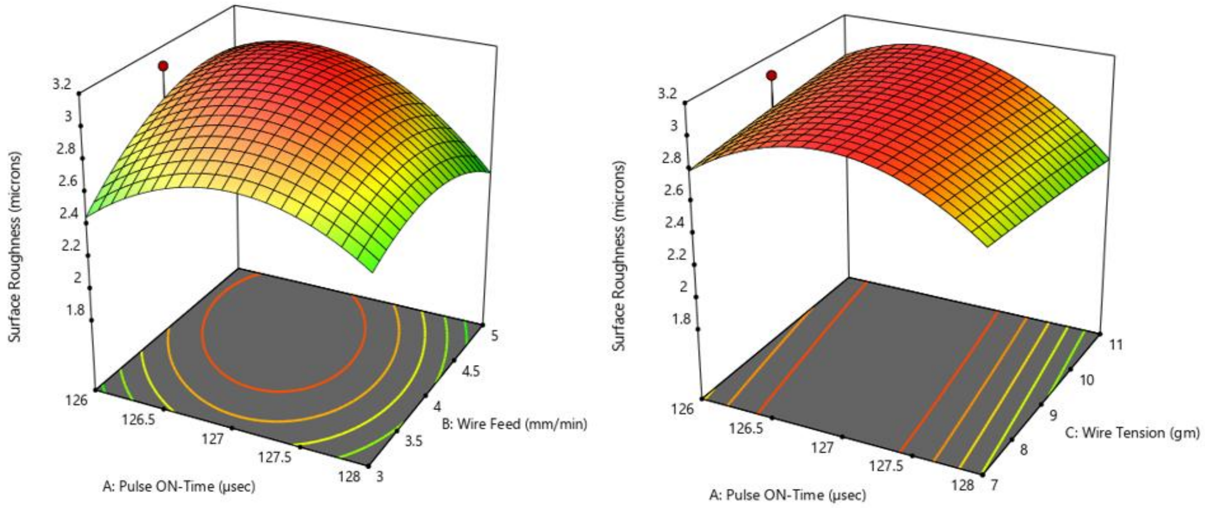

Fig. 10. Surface plot of SR for wire feed, tension and Toff

The surface plot of SR for various combinations of servo voltage and wire feed and between servo voltage and tension of wire is presented in Fig. 12. Observation shows that, lower feed rate of wire and higher-level value of servo voltage produces lower SR, similarly, lower value of wire tension and higher-level value of servo voltage produces a reduced SR.

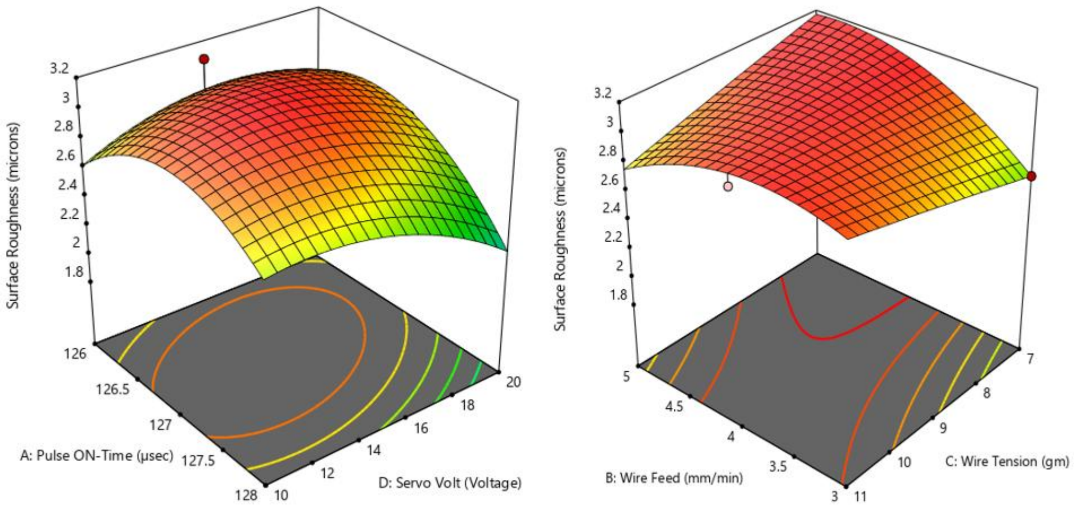

Fig. 11. Surface plot of SR for servo volt, pulse-on time, wire tension and wire feed

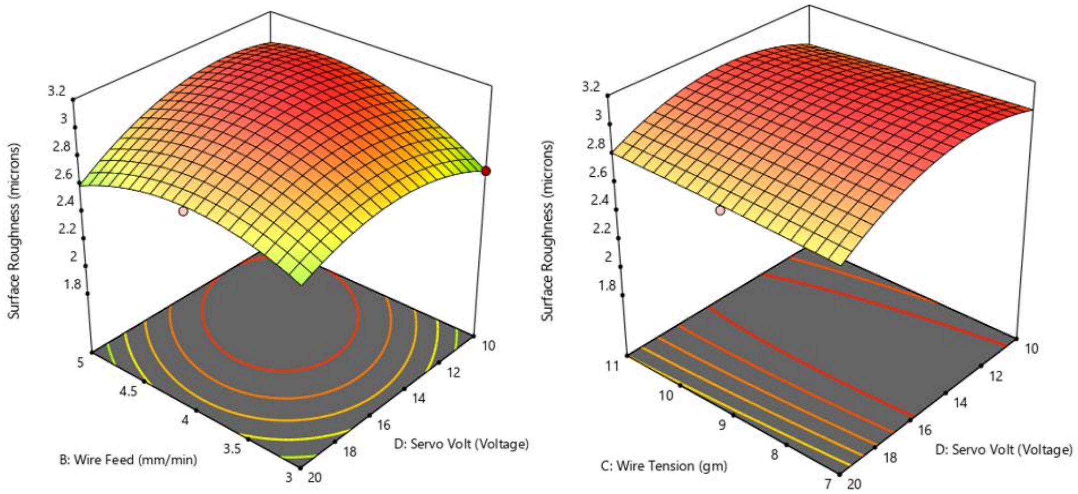

Fig. 12. Surface plot of SR for servo volt, wire tension and wire feed

A. Predictive model for Grey Grade

From the known ideal input factors, the GRG prediction was done for zinc coated wire electrode as given in Equ. (8) [38], [39].

$$\mu_{predicted} = V_{2m} + Ton_{3m} + Toff_{3m} + I_{1m} + WF_{1m} + WT_{1m} + SV_{1m} + SF_{1m} - 7\mu_{mean} \quad (8)$$

where, V_{2m}, Ton_{3m}, $Toff_{3m}$, I_{1m}, WF_{1m}, WT_{1m}, SV_{1m} and SF_{1m} and are the mean values of GRG corresponding to optimal individual levels and μ_{mean} is the mean value of obtained GRG for all the 18 experiments. At optimal condition, the value of predicted mean ($\mu_{predicted}$) is calculated as 0.883.

B. Confirmation Experiment

For confirming the effectiveness of the obtained optimum input parameters level settings, a validation experiment was made with identical investigational state and outputs obtained are tabulated in Table VII. For the obtained outputs MRR and SR, the equivalent GRG was calculated and is compared with the predicted GRG and the error deviation was calculated, as given in Table 7. A variation of 1.13% was obtained between the experimental and predicted GRG, and it was understood that GRA produces a better solution for multi-objective optimization.

Table- VII: Comparison of obtained GRGs

Measured outputs	Exp. values	GRG_Experimental	GRG_Predicted	% of Error
MRR (mm^3/min)	15.189	0.893	0.883	1.13%
SR (microns)	1.906			

IV. CONCLUSIONS

Optimizing the output responses during WEDM profile cutting of D3 steel zinc coated electrode wire towards MRR and SR considering $L_{18}(2^1,3^7)$ OA was achieved. From investigational examination, the following inferences were made.

- Higher SR and MRR was achieved with higher cutting speeds. With increase in Ton and Toff, MRR increases considerably, but SR increases until the moderate level value, afterwards it tends to reduce. Similarly, with higher input current, MRR increases but SR increases initially and afterwards it reduces considerably. With higher wire feed, SR increases drastically, but MRR reduces initially, afterwards shoots up with additional rise in wire feed rate. Higher wire tension produces lower MRR and higher SR. A max-min situation arises for MRR and SR when servo voltage is changed. Increasing the servo feed rate increases the SR, but MRR increases with change in servo feed rate up to 2080 mm/min.
- Control chart drawn for SR and MRR identifies that, all the data points were scattered between the two control limits values, thereby the steadiness in experimental trials were proved.
- The optimal settings of level values of independent input parameters identified were: 75% of cutting speed, 128 µsec of Ton, 54µsec of Toff, 190 A of input current, 3 mm/min of wire feed rate, 7 gm of tension of wire electrode, 260 mm/min and 10V of servo feed rate and voltage.
- Interaction plot shows that, between cutting speed and input current, cutting speed and wire tension, a significant interaction exists. A higher combinatory effect was observed between pulse on-time and several inputs (Toff, wire tension, input current, servo feed). Among wire feed and current a substantial collaboration effect was detected, but with other input parameters no significant effect was observed. Combined effect of wire tension and servo feed rate and between servo voltage and servo feed rate was higher.
- From ANOVA executed on GRG, it was identified that, wire tension was the utmost significant factor contributing by 25.89%, followed by Ton and servo voltage by 21.37% and wire feed rate by 11.89% with an R^2 value of 96.55%.
- From the confirmation experiment it was found that, a variation of 1.13% was achieved between the predicted and experimental GRGs, and it was understood that GRA produces a better solution for multi-objective optimization.

REFERENCES

1. R. H. Todd, D. K. Allen, L. Alting, Manufacturing Processes Reference Guide, New York: Industrial Press Inc., 1994.
2. M. P. Groover, *Fundamentals of Modern Manufacturing - Materials, Processes and Systems*, New York: John Wiley & Sons, Inc., 2010.
3. B. Bhattacharyya, B. Doloi, *Modern Machining Technology: Advanced, Hybrid, Micro Machining and Super Finishing Technology*, London: Academic Press, Elsevier, 2020.
4. S. Kalpakjian, S. R. Schmid, *Manufacturing process for engineering materials*, South Asia: Pearson education, 2009.
5. H. R. Tonday, A. M. Tigga, "An empirical evaluation and optimization of performance parameters of wire electrical discharge machining in cutting of Inconel 718," Measurement, vol. 140, 2019b, pp. 185-196.
6. A. Goyal, "Investigation of material removal rate and surface roughness during wire electrical discharge machining (WEDM) of Inconel 625 super alloy by cryogenic treated tool electrode," Journal of King Saud University – Science, vol. 29, no. 4, pp. 528-535.
7. A. Kumar, K. Abhishek, K.Vivekananda, K. P. Maity, "Effect of wire electrode materials on die-corner accuracy for Wire Electrical Discharge Machining (WEDM) of Inconel 718," MaterialsToday: Proceedings, vol. 5, no. 2, 2018, pp. 12641-12648.
8. P. Kumar, B. Bhushan, R. Gupta, "Response of Wire Electrical Discharge Machining For H13 Using Taguchi L_9 Array," Pulse, vol. 50, no. 1, 2013, pp. 907-912.
9. T. Chinnadurai, S. A. Vendan, “Contemplating the Performance Measures of Wire Cut EDM Based on Process Parameters for AISI 4140," MaterialsToday: Proceedings, vol. 2, no. 4, 2015, pp. 1067-1073.
10. J. Kapoor, J. S. Khamba, S. Singh, "Effect of Different Wire Electrodes on the Performance of WEDM," Materials Science Forum, vol. 751, 2013, pp. 27-34.
11. S. Dhale, M. Kulkarni, "Effect of Electrode Coatings in Wire Electrical Discharge Machining of Inconel-718," IOSR Journal of Mechanical and Civil Engineering, vol. 13, no. 4, 2015, pp. 53-59.
12. K. Mohapatra, R. Dash, S. Sahoo, "Comparative study of wire electrodes in a wire edm gear cutting process using Grey MOORA method," International Journal for Technological Research in Engineering, vol. 6, no. 5, 2019, pp. 4911-4920.

13. V. Muthukumar, A. Suresh Babu, R. Venkatasamy, N. Senthilkumar, "An Accelerated Particle Swarm Optimization Algorithm on Parametric Optimization of WEDM of Die-Steel," Journal of The Institution of Engineers (India): Series C, vol. 9, no. 1, 2014, pp. 49-56, 2014.
14. D. C. Montgomery, *Design and Analysis of Experiments*, 8th edition, New York: John Wiley & Sons, Inc., 2013.
15. R.K. Roy, *Design of experiments using the Taguchi approach: 16 steps to product and process improvement*, New York: Wiley-Inderscience Publication, 2001.
16. R. K. Roy, *A Primer on the Taguchi Method*, 2nd edition, USA: Society of Manufacturing Engineers, 2010.
17. P.J. Ross, *Taguchi Techniques for Quality Engineering*, New Delhi: Tata McGraw Hill publishing company Ltd., 2005.
18. P. Sinha, R. Kumar, G. K. Singh, D. Thomas, "Multi-Objective Optimization of Wire EDM of AISI D3 Tool Steel Using Orthogonal Array with Principal Component Analysis," MaterialsToday: Proceedings, vol. 2, no. 4, 2015, pp. 3778-3787.
19. T. Tamizharasan, N. Senthilkumar, V. Selvakumar, S. Dinesh, "Taguchi's Methodology of optimizing turning parameters over Chip Thickness Ratio in machining P/M AMMC," SN Applied Sciences, vol. 1, no. 2, 2019, DOI: 10.1007/s42452-019- 0170-8.
20. N. Senthilkumar, T. Tamizharasan, "Experimental investigation of cutting zone temperature and flank wear correlation in turning AISI 1045 steel with different tool geometries," Indian Journal of Engineering & Materials Sciences, vol. 21, no. 2, 2014, pp. 139-148.
21. N. Senthilkumar, T. Ganapathy, T. Tamizharasan, "Optimization of Machining and Geometrical parameters in Turning process using Taguchi Method," Australian Journal of Mechanical Engineering, vol. 12, no. 2, 2014a, pp. 233-246.
22. S. Liu, J. Y. L. Forrest, *Advances in Grey Systems Research*, Berlin: Springer Verlag, 2010.
23. S. Liu, Y. Yang, J. Forrest, *Grey Data Analysis: Methods, Models and Applications*, Singapore: Springer Science + Business Media, 2017.
24. K. Ragupathy, C. Velmurugan, N. Senthilkumar, "Tribological and Heat Treatment Prediction of Stir Cast Al 6061/SiC/MoS_2 Composites Using Grey Relational Analysis," Journal of the Balkan Tribological Association, vol. 24, no 2, 2018, pp. 198-217.
25. N. Senthilkumar, V. Selvakumar, T. Tamizharasan, "Optimization and Performance Analysis of Uncoated and Coated Carbide Inserts during Hard Turning AISI D2 Steel Using Hybrid GRA-PCA Technique," Applied Mechanics and Materials, vol. 852, 2016a, pp 151-159.
26. R. Purohit, R. S. Rana, R. K. Dwivedi, D. Banoriya, S. K. Singh, "Optimization of Electric Discharge Machining of M2 Tool Steel Using Grey Relational Analysis," MaterialsToday: Proceedings, vol. 2, no. 4, 2015, pp. 3378-3387.
27. N. Senthilkumar, B. Deepanraj, K. Vasantharaj, V. Sivasubramanian, "Optimization and performance analysis of process parameters during anaerobic digestion of food waste using hybrid GRA-PCA technique," Journal of Renewable Sustainable Energy, vol. 8, 063107 (2016b); Doi: 10.1063/1.4972884.
28. V. Selvakumar, S. Muruganandam, T. Tamizharasan, N. Senthilkumar, "Machinability evaluation of Al–4%Cu–7.5%SiC metal matrix composite by Taguchi–Grey relational analysis and NSGA-II," Sadhana, vol. 41, no. 10, 2016, pp. 1219-1234.
29. R. Rao, P. Pawar, "Process parameters modeling and optimization of wire electric discharge machining," Advances in Production Engineering & Management, vol. 5, no. 3, 2010, pp. 139-150.
30. V. B. Patel, J. D. Patel, D. M. Kalpesh, "Selection Of The Wire Cut Electrical Discharge Machining Process Parameters Using Gra Method," International Journal of Advance Engineering and Research Development, vol. 1, no. 5, 2014, pp. 1-12.
31. T. Thankachan, K. Soorya Prakash, R. Malini, S. Ramu, P. Sundararaj, S. Rajandran, D. Rammasamy, S. Jothi, "Prediction of surface roughness and material removal rate in wire electrical discharge machining on aluminum based alloys/composites using Taguchi coupled Grey Relational Analysis and Artificial Neural Networks," Applied Surface Science, vol. 472, 2019, pp. 22-35.
32. L. A. Doty, *Statistical Process Control*, 2nd edition, New York: Industrial Press Inc., 1996.
33. D. C. Montgomery, *Introduction to Statistical Quality Control*, New York: John Wiley & Sons, Inc., 2019.
34. S. Sundaraselvan, N. Senthilkumar, "Surface Modification of AZ61 Magnesium alloy with nano-Al_2O_3 using Laser Cladding Technique: Optimization of wear properties through Hybrid GRA-PCA," International Journal of Rapid Manufacturing, vol. 8, no. 3, 2019, pp. 221-242.
35. G. Gamst, L. S. Meyers, A. J. Guarino, *Analysis of Variance Designs - A Conceptual and Computational Approach with SPSS and SAS*, London: Cambridge University Press, Cambridge, 2008.
36. N. Senthilkumar, T. Tamizharasan, "Impact of Interface Temperature over Flank Wear in Hard Turning using Carbide Inserts," Procedia Engineering, vol. 38, 2012, pp. 613-621.
37. K. Gajalakshmi, N. Senthilkumar, B. Prabu, "Multi-response Optimization of Dry Sliding Wear Parameters of AA6026 Using Hybrid Grey Relational Analysis Coupled with Response Surface Method," Measurement and Control, vol. 52, no. 5-6, 2019, pp. 540-553.
38. N. Senthilkumar, T. Tamizharasan, V. Anandakrishnan, "Experimental Investigation and Performance Analysis of Cemented Carbide Inserts of different geometries using Taguchi based Grey Relational Analysis," Measurement, vol. 58, 2014b, pp. 520-536.
39. S. Thirumalvalavan, N. Senthilkumar, "Experimental Investigation and Optimization of HVOF Spray parameters on wear resistance behaviour of Ti-6Al-4V Alloy," Comptes rendus de l'Academie bulgare des Sciences, vol. 72, no. 5, 2019, pp. 665-674.

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