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Multi response optimization of wire-EDM process parameters of ballistic grade aluminium alloy

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A B S T R A C T

In the current investigation, a multi response optimization technique based on Taguchi method coupled with Grey relational analysis is planned for wire-EDM operations on ballistic grade aluminium alloy for armour applications. Experiments have been performed with four machining variables: pulse-on time, pulse-off time, peak current and spark voltage. Experimentation has been planned as per Taguchi technique. Three performance characteristics namely material removal rate (MRR), surface roughness (SR) and gap current (GC) have been chosen for this study. Results showed that pulse-on time, peak current and spark voltage were significant variables to Grey relational grade. Variation of performance measures with process variables was modelled by using response surface method. The confirmation tests have also been performed to validate the results obtained by Grey relational analysis and found that great improvement with 6% error is achieved.

1. Introduction

Wire electrical discharge machining (WEDM) of ballistic grade aluminium alloy has been considered in this work. It is an Al–Mg–Si-based alloy (6063), which is having superior impact strength, corrosion resistance and low density. This alloy is promising for armour applications due to excellent properties (energy absorption, stiffness etc). WEDM plays significant role in cutting conductive materials to produce intricate profiles and complex shapes. The material removal takes place due to melting and evaporation of workpiece because of the heat produced by discharges. The wire cut electric discharge machine usually consists of a machine tool, a power supply unit and flushing unit. Wire travels through the workpiece from upper and lower wire guides. In wire-cut EDM process the spark is generated between continuously travelling wire and workpiece [1–5]. The most significant response variables in WEDM are material removal rate (MRR) surface roughness (SR) and gap current (GC) of workpiece. Spark gap voltage, discharge current, pulse on time and pulse off time are the machining variables which influence the performance measures. Tosun [1] evaluated the significance machine variables on responses i.e. kerf width and SR. Poros [2] developed a model correlating thermal properties of material and efficiency of machining. Buckingham pi theorem was employed to find the correlation between the variables used in the study. Tzeng et al. [3] studied the effect of machine variables on SR by employing Taguchi technique. Chiang [4] carried out Grey relational analysis to optimize wire-EDM with multi response measures such as MRR and SR. Kumar [5] employed Grey relational methodology to optimize input parameters of EDM to maximize MRR. The optimum machine variables were validated by performing confirmation experiments. Vijayan [6] performed multiobjective study to optimize factors of friction stir welding of aluminium 5083 alloy. Hsiao [7] considered Grey relational technique along with orthogonal array to optimize multiobjective performance characteristics of plasma arc welding. Somasekhar [8] presented the modelling and optimization of micro-EDM using back propagation and genetic algorithms. The neural net work model has been established and simulated using MATLAB. Lin et al. [9] attempted to improve the multiple response characteristics using Taguchi technique to optimize machine variables of EDM.

The aim of this study is to examine the effects of process variables on MRR, GC and SR of ballistic grade aluminium alloy. MRR can be referred as degree of production whereas surface roughness (SR) represents the measure of surface quality. Gap current (GC) is taken as a pulse of current to initiate cutting. The peak current is the

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amount of power used in WEDM and measures in unit of amperage. Gap current specifies the supply current to be placed on the gap. The greater this value is, the greater the electric discharge energy becomes. Based on the literature survey, several pilot experiments were performed to select the influencing factors on performance characteristics. The chosen machining variables are: pulse on-time (TON), pulse off-time (TOFF), peak current (IP) and spark voltage (SV). The Taguchi technique is a dominant experimental planning tool, uses efficient and orderly approach for obtaining optimum process variables. It is difficult to select suitable process variables for every material in EDM, and depend greatly on operator's skill. With a view to lessen this complexity, a simple statistically planned experiments is recommended for examining the influence of different process variables on MRR, SR and gap current and estimate optimum machining variables. In the current investigation, the Grey relational analysis is employed to evaluate multiobjective response characteristics to optimize WEDM process. An appropriate orthogonal array [10] is selected to conduct precise and accurate experiments. Confirmation experiments were then conducted based on statistical results.

2. Experimental details

2.1. Material and methods

The experiments were performed using CNC WEDM made ELECTRONICA. Ballistic grade aluminium alloy (0.45% Si, 0.3% Fe, 0.1% Mn, 0.5% Mg, 0.02% Zn, 0.02% Ti and Al remainder) with 240 mm × 80 mm × 30 mm size was used as cutting material. During the experiments 80 mm length was cut along the width of the workpiece (Fig. 1). The machining performance was evaluated by MRR, IG and SR.

The MRR was determined by the wire feed rate and dimensions of the workpiece. The surface roughness, usually expressed as an SR value in microns was measured by Taylor Hobson Surtronic 25 Roughness Checker. The gap current (GC) is read on an ammeter, which is integral part of the machine, in amperes.

2.2. Taguchi method and Grey-relational analysis

Two aspects employed in Taguchi method are (i) S/N ratio to estimate the quality [11–13] and (ii) orthogonal arrays to accommodate many factors affecting simultaneously to evaluate the machining performances. Using Taguchi technique, an L18 ($2^1 \times 3^3$) orthogonal arrays table was chosen (Table 2). In the present study all the designs, plots and analysis have been carried out using Minitab statistical software.

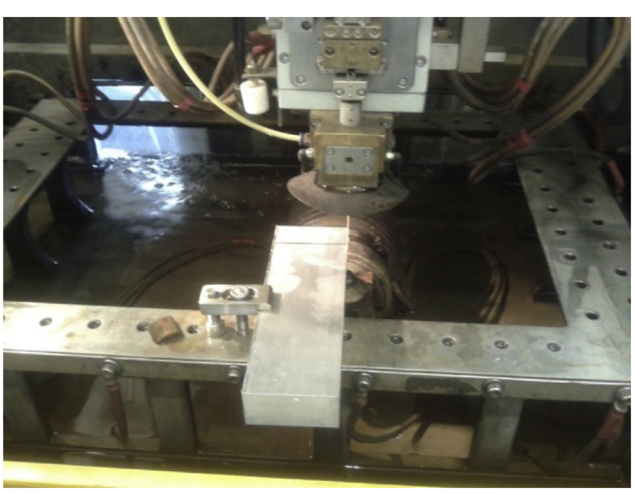

Fig. 1. Photograph of workpiece during machining.

Table 1
Input process parameters and their levels.

Parameters	Symbol	Level 1	Level 2	Level 3	Units
Pulse on time	TON	0.85	1.35	–	μs
Pulse off time	TOFF	18	36	56	μs
Peak current	IP	10	13	16	A
Spark voltage	SV	10	15	20	Volt

Grey relational analysis can transform multiple responses (MRR, SR and GC) into corresponding single response function. In Grey relational generation, the normalized data i.e. SR corresponding to lower-the-better (LB) criterion [7] can be expressed as:

$$x_i(k) = \frac{\max y_i\,(k) \;\; - y_i\,(k)}{\max y_i(k) \;-\; \min y_i(k)} \tag{1}$$

Similarly, the normalized data processing for MRR and GC corresponding to larger-the-better criterion can be expressed as

$$y_i(k) = \frac{y_i(k) - \min y_i\,(k)}{\max y_i(k) \;-\; \min y_i\,(k)} \tag{2}$$

Grey relational generation is tabulated in Table 4. After averaging the Grey relational coefficients (ζ) (Table 5), the Grey relational grade γ_i [8] (Table 6) can be calculated as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{3}$$

where n is the number of process responses.

3. Results and discussion

The results of performance measures MRR, SR and Gap current are obtained for 18 experimental trials of WEDM as recommended by Mahapatra and Patnaik [14] and given in Table 1. The ANOVA results are presented in Tables 3a–c. Taguchi method is adopted to study the effect of different machining variables viz., TON, TOFF, IP, and SV on MRR. MRR is directly proportional to the power supplied during this pulse-on time (TON). As the pulse-off time (TOFF) is decreased, more sparks will be generated. It is attributed to higher

Table 2
Experimental design using L18 orthogonal array.

Expt. no	TON	TOFF	IP	SV	MRR (mm^3/min)	SR (μm)	GC (A)
1	0.85	18	10	10	12.42	1.84	2.1
2	0.85	18	13	15	13.87	2.31	2.9
3	0.85	18	16	20	14.45	2.79	3.4
4	0.85	36	10	10	11.21	1.75	3.1
5	0.85	36	13	15	12.95	1.98	2.4
6	0.85	36	16	20	14.17	2.89	1.8
7	0.85	56	10	15	13.54	1.54	2.3
8	0.85	56	13	20	13.74	2.47	2.6
9	0.85	56	16	10	13.48	2.61	2.8
10	1.35	18	10	20	13.11	1.94	3.2
11	1.35	18	13	10	13.27	3.21	2.7
12	1.35	18	16	15	15.47	3.64	3.6
13	1.35	36	10	15	14.19	2.76	2.9
14	1.35	36	13	20	14.91	2.87	3.1
15	1.35	36	16	10	15.12	3.04	3.5
16	1.35	56	10	20	13.41	1.39	2.5
17	1.35	56	13	10	13.97	3.29	3.4
18	1.35	56	16	15	14.42	3.85	3.1

Table 3a
Analysis of variance for MRR.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
TON	1	1.478	1.478	1.478	8.28	0.016
TOFF	2	0.005	0.005	0.0027	0.02	0.985
IP	2	2.939	2.939	1.469	8.23	0.008
SV	2	1.093	1.093	0.546	3.06	0.092
Error	10	1.786	1.786	0.178		
Total	17	7.303				

Table 3b
Analysis of Variance for SR.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
TON	1	18.453	18.453	18.452	8.15	0.017
TOFF	2	1.26	1.26	0.629	0.28	0.763
IP	2	67.339	67.339	33.669	14.86	0.001
SV	2	2.674	2.674	1.337	0.59	0.572
Error	10	22.653	22.653	2.265		
Total	17	112.379				

Table 3c
Analysis of variance for gap current.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
TON	1	12.321	12.321	12.321	4.44	0.061
TOFF	2	1.363	1.363	0.681	0.25	0.787
IP	2	2.741	2.741	1.37	0.49	0.625
SV	2	1.027	1.027	0.513	0.18	0.834
Error	10	27.781	27.781	2.778		
Total	17	45.233				

thermal power with increase in TON leading to a faster cutting rate. This led to improvement in MRR. It is observed that the pulse on time ($p = 0.016$) and peak current ($p = 0.008$) have strong effect on MRR. It is suggested to apply the parameters TON and IP at levels 2 and 3 respectively for achieving maximum MRR. Similarly, it is recommended to use the parameters TON and IP at levels 1 and 1 respectively for obtaining minimum SR.

The response function [15] indicating each of the four responses can be expressed as follows:

$$y = f(\text{TON},\ \text{TOFF},\ \text{IP},\ \text{SV})$$

Here Y is response characteristic.

Table 4
Grey relational generation.

Ex. no	MRR	SR	GC
1	0.28404	0.817073171	0.166667
2	0.62441	0.62601626	0.611111
3	0.76056	0.430894309	0.888889
4	0	0.853658537	0.722222
5	0.40845	0.760162602	0.333333
6	0.69484	0.390243902	0
7	0.54695	0.93902439	0.277778
8	0.5939	0.56097561	0.444444
9	0.53286	0.504065041	0.555556
10	0.44601	0.776422764	0.777778
11	0.48357	0.260162602	0.5
12	1	0.085365854	1
13	0.69953	0.443089431	0.611111
14	0.86854	0.398373984	0.722222
15	0.91784	0.329268293	0.944444
16	0.51643	1	0.388889
17	0.64789	0.227642276	0.888889
18	0.75352	0	0.833333

Table 5
Grey relational coefficient of each performance characteristics.

Ex. no	MRR	SR	GC
1	0.411197	0.732143	0.375
2	0.571046	0.572093	0.5625
3	0.67619	0.467681	0.818182
4	0.333333	0.773585	0.642857
5	0.458065	0.675824	0.428571
6	0.620991	0.450549	0.333333
7	0.524631	0.891304	0.409091
8	0.551813	0.532468	0.473684
9	0.51699	0.502041	0.529412
10	0.474388	0.691011	0.692308
11	0.491917	0.403279	0.5
12	1	0.353448	1
13	0.624633	0.473077	0.5625
14	0.791822	0.453875	0.642857
15	0.858871	0.427083	0.9
16	0.508353	1	0.45
17	0.586777	0.392971	0.818182
18	0.669811	0.333333	0.75

The second order response surface models [16] for various performance measures are given as follow:

$$\begin{aligned}\text{MRR} = {} & 14.006 + 0.3808\ \text{TON} - 0.0523\ \text{TOFF} + 0.6661\ \text{IP} \\ & + 0.3622\ \text{SV} + 0.026\ \text{IP}^2 + 0.1229\ \text{TON}\cdot\text{IP} \\ & - 0.227\ \text{TOFF}\cdot\text{IP}\end{aligned} \tag{4}$$

$$\begin{aligned}\text{SR} = {} & -1.3828 + 5.219\ \text{TON} - 0.0381\ \text{TOFF} + 0.05269\ \text{IP} \\ & - 0.09328\ \text{SV} - 0.0883\ \text{TON}\cdot\text{IP} - 0.0694\ \text{TON}\cdot\text{SV} \\ & + 0.0358\ \text{IP}\cdot\text{SV}\end{aligned} \tag{5}$$

$$\begin{aligned}\text{GC} = {} & 1.1741 - 4.1136\ \text{TON} + 0.07912\ \text{TOFF} + 0.2181\ \text{IP} \\ & + 0.0666\ \text{SV} + 0.3271\ \text{TON}\cdot\text{IP} + 0.02591\ \text{TON}\cdot\text{SV} \\ & - 0.0124\ \text{IP}^2\end{aligned} \tag{6}$$

Figs. 2 and 3 illustrate the response surface of MRR, varying the parameters of pulse on time, peak current and spark voltage. It is observed from the figure that MRR increases with higher TON and spark voltage levels. Also in the higher levels of peak current by raising the spark voltage levels, the MRR increases. At higher peak current, more discharge energy is induced which causes overcuts

Table 6
Grey relational grade of performance characteristic.

Ex. no	Grade	S/N ratio
1	0.506113	−5.91505
2	0.568546	−4.90468
3	0.654018	−3.68821
4	0.583258	−4.68278
5	0.52082	−5.66625
6	0.468291	−6.58968
7	0.608342	−4.31704
8	0.519322	−5.69127
9	0.516148	−5.74452
10	0.619235	−4.16288
11	0.465065	−6.64972
12	0.784483	−2.10833
13	0.553403	−5.13916
14	0.629518	−4.01984
15	0.728651	−2.74960
16	0.652784	−3.70460
17	0.59931	−4.44697
18	0.584382	−4.66607

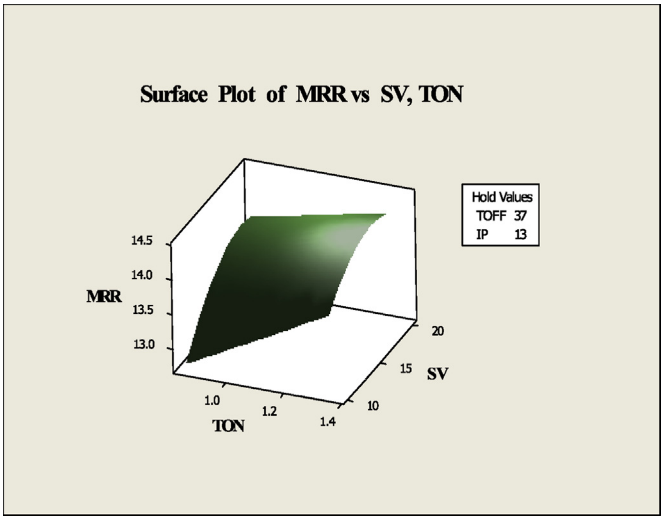

Fig. 2. Response surface of MRR vs. pulse on time and spark voltage.

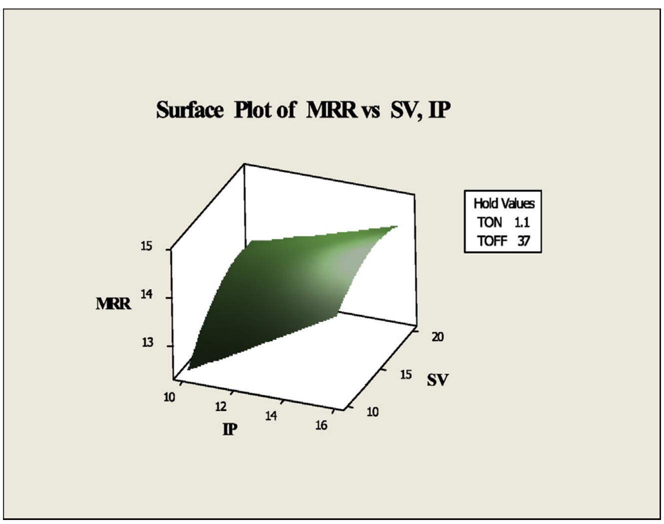

Fig. 3. Response surface of MRR vs. peak current and spark voltage.

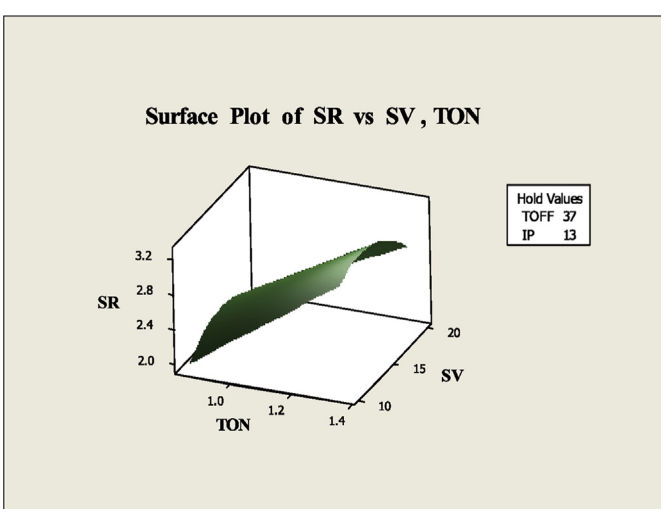

Fig. 4. Response surface of SR vs. spark voltage and pulse on time.

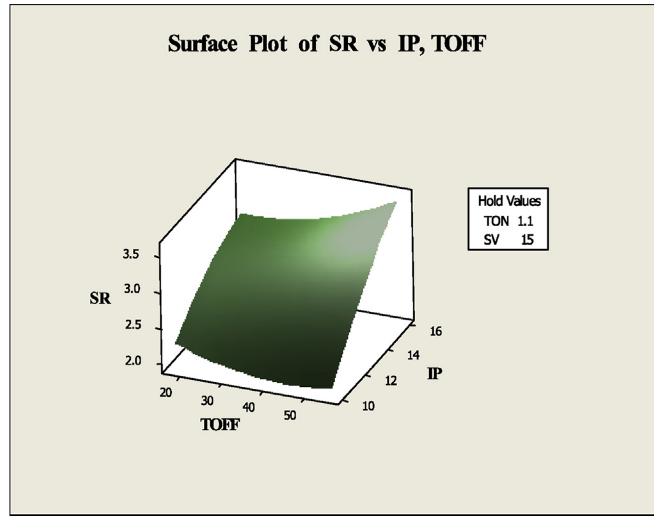

Fig. 5. Response surface of SR vs. peak current and pulse off time.

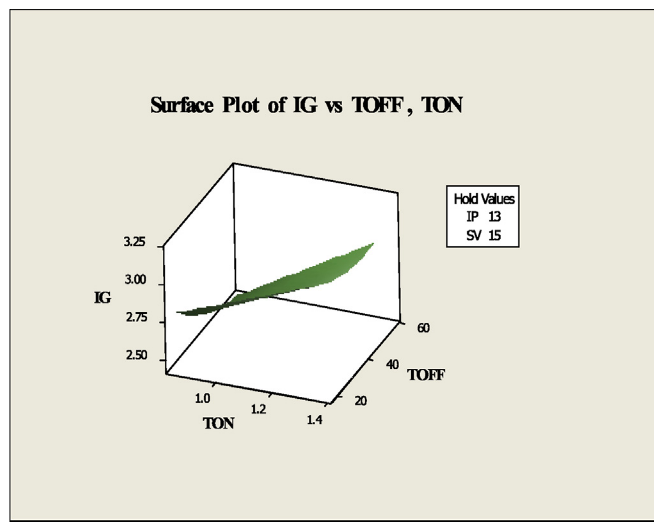

Fig. 6. Response surface of IG vs. pulse off time and pulse on time.

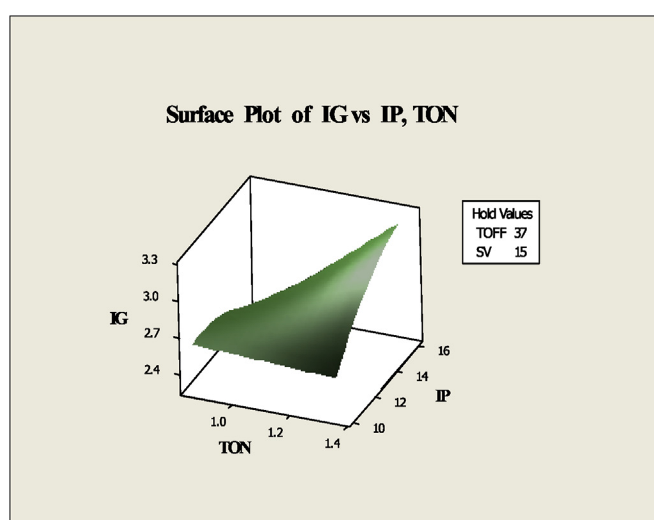

Fig. 7. Response surface of IG vs. peak current and pulse on time.

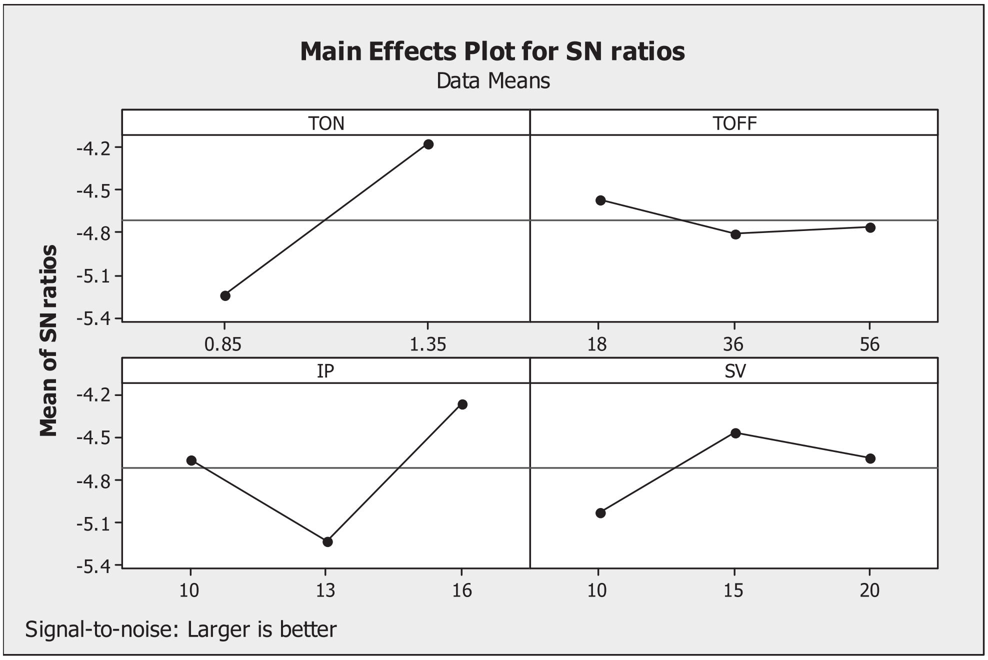

Fig. 8. Effect of process parameters on Grey relational grade.

and produces larger chips. The higher the peak current, the smaller is the machining time, as the machining rate is proportional to peak current. MRR increases as the supplied energy increases. It directly depends on the number of sparks generated per second. Higher TON specifies the discharge energy induced for a longer time which results in large craters.

Figs. 4 and 5 demonstrate the response surface of SR in function of the variables of SV, TON, IP and TOFF, while TOFF and SV remain stable in their middle values. It has been understood that by decreasing the TON and IP values, the SR minimizes. It has been noticed that at higher peak current, machined surface shows a higher SR due to uneven machined surface. On the other hand lower peak current produces little MRR and cause longer machining time. To achieve more MRR, higher TON and IP should be chosen. But, this will deteriorate the quality of the surface due to deeper and wider craters produced by sparks. Increasing TON from

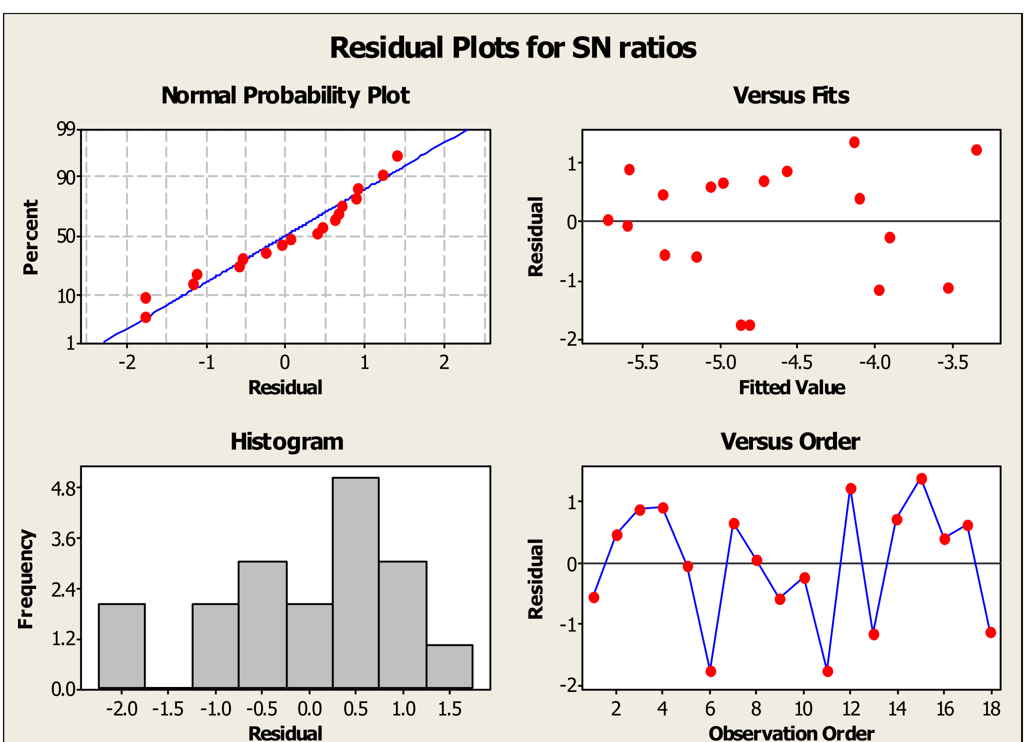

Fig. 9. Residual plots for Grey relational grade.

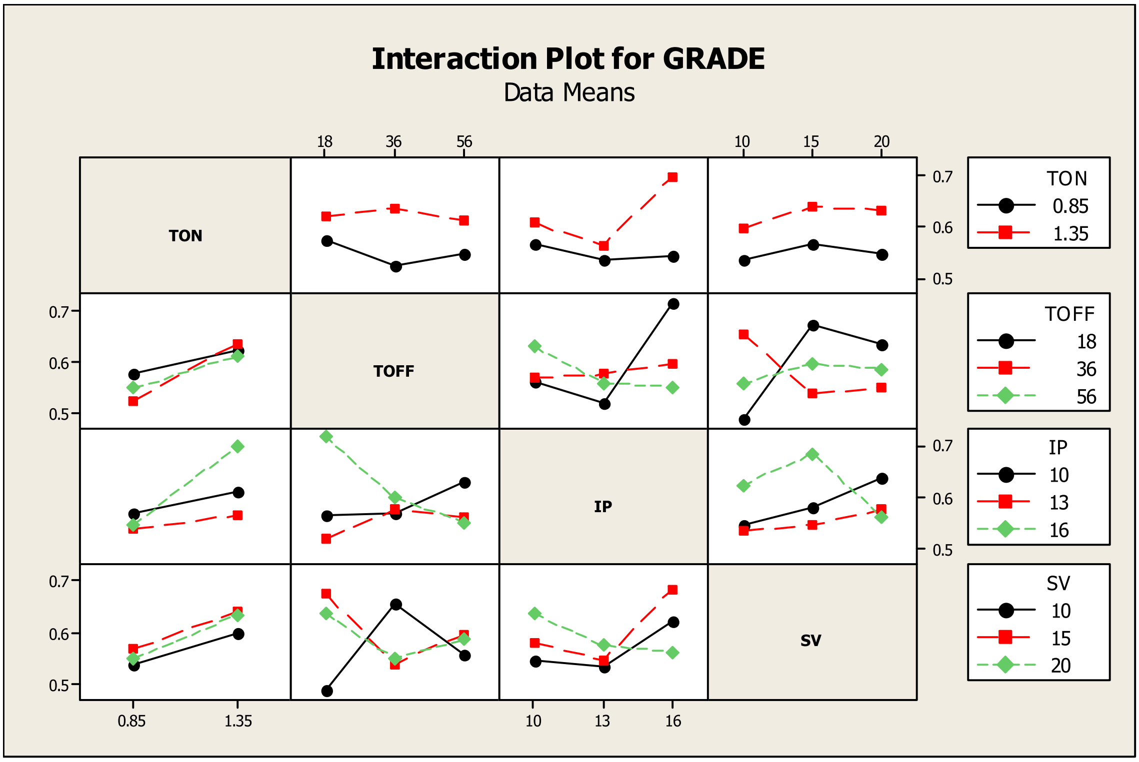

Fig. 10. Interaction effects of parameters on Grey relation grade.

Table 7
Results of the confirmation experiments.

Performance responses	Optimum set of parameters	Predicted optimum value	Experimental optimum value
Overall Grey relational grade	TON (2), TOFF (1), IP (3) and SV (2)	0.8154	0.8378

0.85 to 1.35 μs generates more discharge energy, which results into formation of larger craters on the machined surface. Also, breakage of wire occurred at higher discharge energy levels due to more temperatures. Reduction of tensile strength at elevated temperature causes softening of wire. The wire breakage was prevented by setting low wire tension and high flushing pressure to enhance cutting efficiency.

Figs. 6 and 7 show the response surface of GC of pulse off time, pulse on time and peak current. It has been observed that GC increases with increase in pulse on time and peak current.

The Grey relational grade has been treated as the performance measure for multi response optimization case and evaluated using Taguchi technique [17]. It has been noticed that the TON, IP and SV have significant effect on Grey relational grade. The graphical illustration of parameters is given in Fig. 8. Analysis of factors contributes to fix the optimal process parameters for maximum Grey relational grade as TON 2, TOFF 1, IP 3 and SV 2.

Fig. 9 illustrates that the residuals follow an approximately straight line in normal probability plot. Residuals possess constant variance as they are scattered randomly around zero in residuals versus the fitted values. Since residuals exhibit no clear pattern, there is no error due to time or data collection order. The strongest interactions between various parameters can be observed from Fig. 10.

The confirmation test [18] is an essential step for validating conclusions drawn from the experimental results. The optimum response characteristics at various levels of significant variables have been shown in Table 7.

4. Conclusions

An application of Taguchi technique coupled with Grey relational analysis to optimize the input variables of WEDM on MRR, SR and GC of ballistic grade aluminium alloy has been studied. Optimization of the complex multiobjective responses can be simplified through this technique. The conclusions are as follows:

- Results confirm that TON, IP and SV are significant variables to Grey relational grade.
- Mathematical models were developed using response surface method for MRR, SR and IG to determine the relation between machine variables and performance measures.
- Optimum response characteristics such as MRR, SR and GC are improved with 6% error by employing Grey relational analysis.

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