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Optimization of Wire-EDM Process Parameters on Machining Die Steel DC53 using Taguchi – GRA Methodology

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Abstract: This research paper represents the parametric optimization of Wire Electrical Discharge Machining (WEDM) on machining die steel DC53. For problem formulation of this research work, literature survey has been carried out. The objective of the present work was to investigate the effects of the various WEDM process parameters using Taguchi and Grey Relation Analysis (GRA) on the machining quality and to obtain the optimal sets of process parameters so that the quality of machined parts can be optimized. The machining parameters selected for optimization in present research are Pulse On time, Pulse Off time and Wire Feed. A series of nine experiments were conducted using Wire EDM. The Analysis of Variance (ANOVA) was employed to analyze the influence of these parameters on Material Removal Rate (MRR) and Surface Roughness during machining process. The influences of different process parameters on die steel DC53 were compared. Confirmation experiments were performed for finding the validation of results and a good agreement is found between the predicted and experimental results. The results showed that the input parameters setting of Pulse on time at 100 µs, pulse off time at 40 µs and wire feed at 6 mm/min have given the best results for simultaneous optimization of Material Removal Rate and Surface Roughness.
Keywords: WEDM, Optimization, Die Steel DC53, Taguchi, GRA, ANOVA, Pulse On time, Pulse Off time, Wire Feed, MRR, Surface Roughness

I. INTRODUCTION

Wire Electric Discharge Machining (WEDM) is an unconventional process of material removal from electrically conductive materials to produce parts with intricate shapes and profiles (Fig. 1). This process is done by using a series of spark erosion. These sparks are produced between the work piece and a wire electrode (usually less than 0.30 mm diameter) separated by a dielectric fluid and erodes the work piece to produce complex shapes according to a numerically controlled pre-programmed path. The sparks produce heating and melt work piece surface to form debris which is then flushed away by dielectric pressure. During the cutting process there is no direct contact between the work piece and the wire electrode. Wire Electrical Discharge Machining (WEDM) has become an important non-traditional machining process because it can be used on materials like titanium alloys and zirconium which cannot be machined by conventional machining processes. The development of new advanced engineering materials, need to meet demand for precise and flexible prototype and low-volume production of components have made wire electrical discharge machining an important manufacturing process.

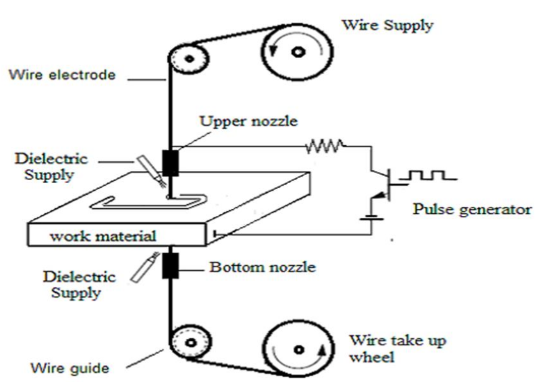

Fig. 1. Schematic Diagram of WEDM (Shinde & Shivade, 2014)[1]

The basic mechanism of metal removal in WEDM is identical to conventional EDM. Instead of moving electrode (as in EDM), the electrode in this process is a moving wire of copper or brass. A vertically oriented wire is fed into the work piece which is continuously travelling from a supply spool to a take up spool. For this purpose a hole is pre-drilled in the work piece, through which the wire electrode will pass. A constant gap between tool and work piece is maintained with the help of computer controlled positioning system. This process gives a high degree of accuracy and a good surface finish. In addition, the WEDM process is able to machine exotic and high strength and temperature resistant materials and eliminates the geometrical changes occurring in the machining of heat-treated steels.

II. LITERATURE REVIEW

Over the years researchers have used various approaches to improve the performance characteristics of WEDM process. Lee and Li [2] presented a study on the surface integrity of tungsten carbide composite machined on sinking EDM. They reported that, the surface roughness is a function of two main parameters namely peak current and pulse duration. Tosun [3] studied cutting performance parameters like surface roughness and cutting speed using brass wire of 0.25 mm diameter and AISI 4140 steel as the tool and work material respectively. The variation of performance parameters was modeled using regression analysis method. Chiang and Chang [4] employed grey relational analysis to optimize the WEDM parameters for Al_2O_3 particle reinforced material with two performance characteristics namely material removal rate and surface roughness.

Kanlayasiri and Boonmung [5] investigated machining of DC53 die steel by varying the process parameters to investigate their effects on surface roughness. Esme et.al [6] Presented factorial design and neural network (NN) techniques for modeling and predicting the surface roughness of AISI 4340 steel. Mathematical relation between the surface roughness and WEDM cutting parameters were established by regression analysis method. Kumar et.al [7] demonstrated optimization of WEDM process parameters of Incoloy800 super alloy with multiple performance characteristics such as Material Removal Rate (MRR), surface roughness and kerf based on the Grey-Taguchi Method. Pasam [8] studied WEDM of Ti6Al4V. The behavior of input parameters on surface finish was studied using Taguchi parameter design. To establish relationship between control parameters and surface finish as a process response, regression analysis was used. Rao et.al [9] considered WEDM of Al-24345 for their study.

Taguchi's L18 orthogonal array was used in experimentation. Multiple linear regression models have been developed for relating the process and machining performances. The response of MRR and surface roughness was considered for improving the machining efficiency. Kumar et.al [10] reported an investigation on WEDM of pure titanium (grade-2). An attempt has been made to model the response variable i.e. surface roughness in WEDM process using response surface methodology.

Kumar and Singh [11] studied WEDM of Skd 61 alloy. Experimentation was completed using Taguchi's L18 orthogonal array under different parametric conditions. The results obtained were analyzed for selection of an optimal combination of WEDM parameters to achieve better surface finish. Dharmender et.al [12] studied the effect of different process parameters on surface roughness using Brass wire and En31Tool Steel as the tool and work material respectively. Taguchi's L9 orthogonal array was chosen for experimentation in their study.

Rajyalakshmi and Ramaiah [13] carried out an experimental investigation on the influence of cutting parameters of WEDM during the machining of Inconel825. The response of surface roughness is considered for improving the machining efficiency. Yadav et.al [14] studied the effect of WEDM parameters on AISI D3 steel. They reported that, there is decrease in surface roughness with increase in wire feed rate and for a fixed value of pulse on time, gap voltage should be higher for better surface finish. Singh et.al [15] performed experiments on die steel DC53 using two different wires, namely cryogenically treated zinc coated diffused brass wire and the other a plain brass wire. Input parameters such as pulse duration, pulse interval and wire feed rate were chosen.

III. EXPERIMENTAL PROCESS

The objective of this research is to optimize the different process parameters by using Taguchi and Grey relation analysis. This optimization will result to maximization of metal removal rate and minimization of surface roughness. Taguchi technique was used to obtain single response optimization and Grey Relational Analysis was used for multi response optimization.

A. Machine Tool

The experiments are carried out on a wire-cut EDM machine (Model DK77) of Zhongyuan Machine Tools Ltd. (Fig. 2). The WEDM machine tool has the following specifications given in Table 1.

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Table 1. Specification of WEDM Machine

1.	Design	Fixed Column, Moving Table
2.	Table size	440 x 650 mm
3.	Max. work piece height	200 mm
4.	Max. work piece weight	500 kg
5.	Main table traverse (X, Y)	300, 400 mm
6.	Auxiliary table traverse (u, v)	80, 80 mm
7.	Max. taper cutting angle	±20°/50 mm
8.	Max. wire spool capacity	6 kg
9.	Wire electrode diameter	0.15, 0.20,0.25 mm
10.	Control Mode	Open-loop, Step motor drive
11.	Interpolation	Linear & Circular
12.	Least command input (X, Y, u, v)	0.0005mm
13.	Input Power supply	3 phase, AC 380 V, 50 Hz
14.	Average power consumption	6 to 7 KVA
15.	Dielectric	Deionised water

Fig. 2. Pictorial View of WEDM Machine

B. Work Piece Material

The work material selected for the study is Die Steel DC53 which has high tensile strength, shock resistance, good ductility and wear resistance. DC53 is an improvement over alloy tool steel D2.It has wide industrial applications like punching dies, rotor plates, cold forging dies, forming dies etc. The chemical composition of die steel DC53 is represented in Table 2.

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Table 2. Chemical Composition of Die Steel DC53

Constituent	C	Si	Mn	Cr	P	S	Mo	V
%age Composition	0.90-1.10	0.80-1.20	≤0.40	7.50-8.50	≤0.03	≤0.03	1.80-2.20	0.20-0.50

Fig. 3. Picture of Work Piece

C. Parameters Considered

Figure 4 shows the process and performance parameters considered for the present study.

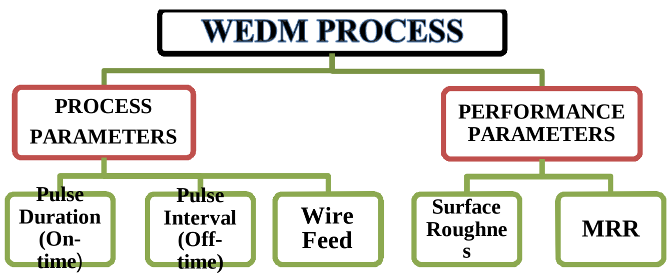

Fig. 4. Process and Performance Parameters of WEDM

The range of input process parameters are indicated in Table 3. The fixed process parameters are presented in Table 4.

Table 3. Range of Input Process Parameters

Sr. No.	Process Parameters	Symbols Used	Units	Range Used
1.	Pulse On Time	T_{on}	µs	100-120
2.	Pulse Off Time	T_{off}	µs	40-60
3.	Wire Feed Rate	WF	m/min	4-8

Table 4. Fixed Process Parameters

S. No.	Process Parameters	Value
1.	Work material	Die steel DC53
2.	Cutting tool	Brass wire of diameter 0.15 mm
3.	Servo Feed	2050 unit
4.	Peak current	150 A
5.	Flushing Pressure	1 unit (15 kg/cm)
6.	Peak Voltage	2 units (110 volt DC)
7.	Dielectric Fluid	De-ionised Water
8.	Conductivity of Dielectric	20 mho
9.	Work Piece Height	16 mm

D. Experimental Data

The experimental work is carried out using Taguchi methodology. Taguchi's L9 orthogonal array was chosen for the design of experiments. 'MINITAB-16' was used to create the experimental design. The experimental design according to Taguchi methodology along with the response data is shown in Table 5.

Table 5. Experimental Design according to Taguchi with Response Data

	Factor1	Factor2	Factor 3	Response 1	Response 2
Run	A:Pulse on Time (T_{on})	B:Pulse off Time (T_{off})	C:Wire Feed Rate (WF)	MRR	Surface Roughness
	µs	µs	mm/min	mm^3/min	µm
1.	100	40	4	3.869	1.01
2.	100	50	6	4.760	1.09
3.	100	60	8	5.671	1.56
4.	110	40	6	6.199	1.25
5.	110	50	8	2.675	1.09
6.	110	60	4	8.564	1.95
7.	120	40	8	3.468	1.25
8.	120	50	4	4.986	1.43
9.	120	60	6	9.243	2.25

Figure 5 shows the specimen cut out from the work piece using different settings.

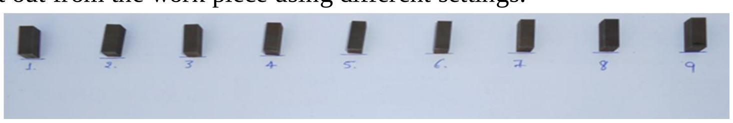

Fig. 5. Actual Picture of Specimen

IV. RESULT ANALYSIS

After conducting experiments with different values of input process parameters, the values of performance parameters were recorded and plotted. The analysis of the results obtained has been performed according to the standard procedure recommended by Taguchi.

A. Single response optimization

1) *Evaluation of S/N Ratio:* The S/N ratio is obtained using Taguchi's methodology. Here, the term 'signal' (S) represents the desirable value (mean) and the 'noise' (N) represents the undesirable value (standard deviation). There are various types of S/N ratios. As the objective was to optimize the response variables, larger-the-better type and lower-the-better type S/N ratio was selected for MRR and surface roughness respectively. The values of S/N ratio of MRR and Surface Roughness corresponding to different experimental runs have been tabulated in Table 6 along with the mean values and the values of S/N ratio of MRR and surface roughness.

Table 6. Data Summary for Material Removal Rate and Surface Roughness

S.NO.	MRR (mm^3/min)	MRR (S/N Ratio)	SR (µm)	SR (S/N Ratio)
1.	3.869	11.7520	1.01	-0.08643
2.	4.760	13.5521	1.09	-0.74853
3.	5.671	15.0732	1.56	-3.86249
4.	6.199	15.8464	1.25	-1.93820
5.	2.675	8.5465	1.09	-0.74853
6.	8.564	18.6535	1.95	-5.80069
7.	3.468	10.8016	1.25	-1.93820
8.	4.986	13.9550	1.43	-3.10672
9.	9.243	19.3163	2.25	-7.04365
Average	5.492778	14.16629	1.43111	2.80816

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2) *Response Analysis:* The main effect of response variables is shown in Figure (6 - 9).

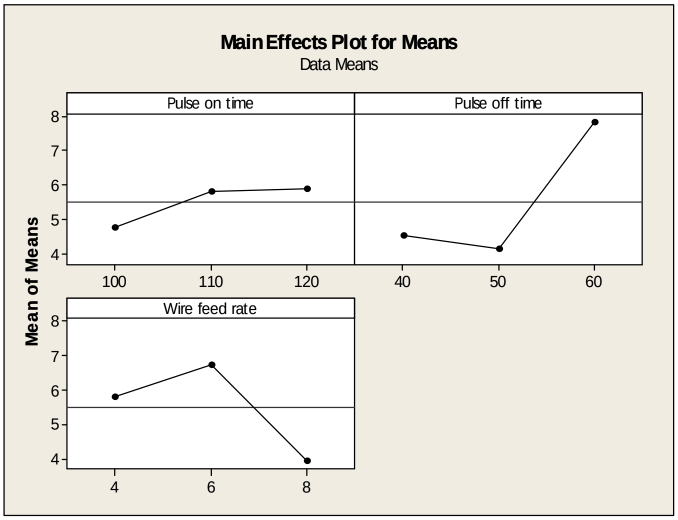

Fig. 6. Effects of Process Parameters on Material Removal Rate (Means)

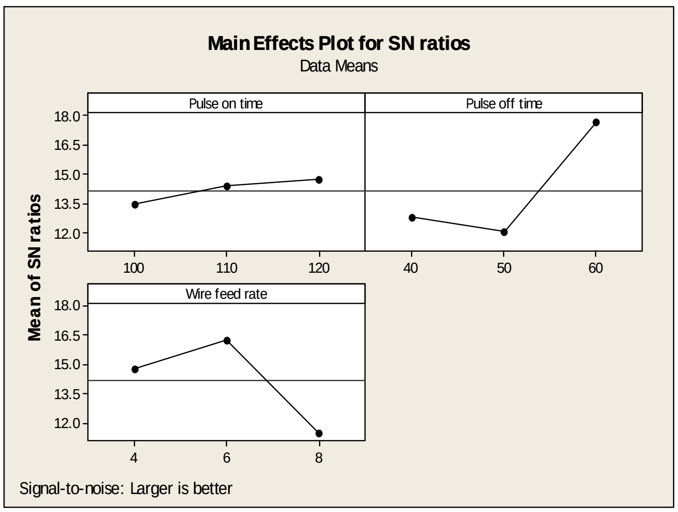

Fig. 7. Effects of Process Parameters on Material Removal Rate (S/N Ratio)

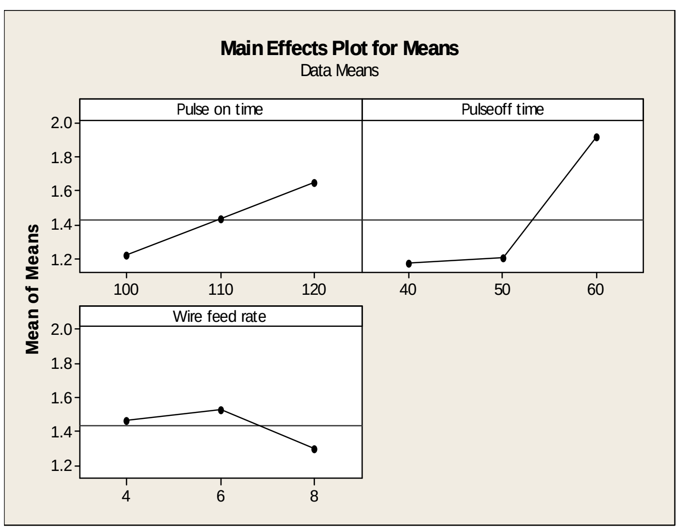

Fig. 8. Effects of Process Parameters on Surface Roughness (Means)

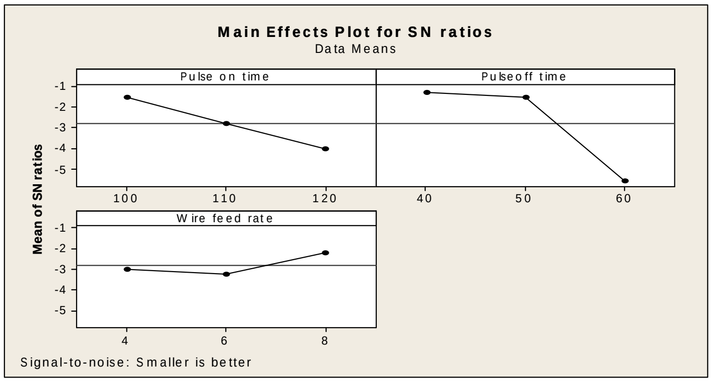

Fig. 9. Effects of Process Parameters on Surface Roughness (S/N Ratio)

3) *ANOVA for Single Response Optimization:* The Analysis of Variance ANOVA (general linear model) for raw data and S/N data has been performed. The ANOVA for Means & S/N data are given in Tables 7-10.

Table 7. Analysis of Variance for Material Removal Rate (Means)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%age contribution
T_{on}	2	2.3837	2.3837	1.1919	9.95	0.091	6.07%
T_{off}	2	24.7049	24.7049	12.3524	103.09	0.010	62.92%
WF	2	12.1689	12.1689	6.0844	50.78	0.019	30.99
Residual Error	2	0.2397	0.2397	0.1198			
Total	8	39.4971					
DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, P < 0.05 - determines significance of a factor at 95% confidence level							

Table 8. Analysis of Variance for Material Removal Rate (S/N ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%age contribution
T_{on}	2	2.426	2.426	1.213	0.51	0.661	2.55%
T_{off}	2	56.507	56.507	28.253	11.92	0.077	59.65%
WF	2	35.784	35.784	17.892	7.55	0.117	37.78%
Residual Error	2	4.740	4.740	2.370			
Total	8	99.457					

Table 9. Analysis of Variance for Surface Roughness (Means)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%age contribution
T_{on}	2	0.26882	0.26882	0.134411	132.93	0.007	18.79%
T_{off}	2	1.07722	1.07722	0.538611	532.69	0.002	75.32%
WF	2	0.08402	0.08402	0.042011	41.55	0.024	5.87%
Residual Error	2	0.00202	0.00202	0.001011			
Total	8	1.43209					

Table 10. Analysis of Variance for Surface Roughness (S/N Ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%age contribution
T_{on}	2	9.1068	9.1068	4.5534	51.05	0.019	20.09%
T_{off}	2	34.3672	34.3672	17.1836	192.65	0.005	75.82%
WF	2	1.8487	1.8487	0.9244	10.36	0.088	04.07%
Residual Error	2	0.1784	0.1784	0.0892			
Total	8	45.5010					

4) *Confirmation Experiment for Single Response Optimization:* In order to validate the results obtained, three confirmation experiments were conducted for each of the response characteristics (MRR and SR) at optimal levels of the process variables. The average values of the characteristics were obtained and compared with the predicted values. The results are given in Table 11.

Table 11. Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments

Performance Measures / Responses	Optimal Set of Parameters	Predicted Optimal Value	Predicted Confidence Intervals at 95% Confidence Level	Experimental Value
MRR	$A_3B_3C_2$	9.473 mm^3/min	CI_{CE} : 8.04 < μ_{MRR} < 11.43	9.243 mm^3/min
Surface Roughness	$A_1B_1C_3$	0.8278 µm	CI_{CE} : 0.6728 < μ_{SR} < 0.983	0.795 µm

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B. Multi response optimization

Taguchi's method focuses on products with single quality characteristic for determining the optimal settings of controllable parameters. But most products have several quality characteristics of interest. A single setting of the process parameter may be optimal for one characteristic but not for the other one. In such cases, grey relational analysis is brought into use.

1) *Grey Relational Analysis:* The theory of grey system which was proposed by Deng[16-17]. It makes use of grey relational generation and the grey relational coefficient to handle the uncertain systematic problem under the status of only partial known information. Therefore, the grey relational coefficient can express the relationship between the desired and actual experimental results. The use of Taguchi method with the grey relational analysis can greatly simplify the optimization of process parameters for multiple-performance characteristics. Antony J [18] attempted simultaneous optimization of multiple quality characteristics in manufacturing processes using Taguchi's quality loss function. In GRA, grey relational coefficient for different characteristics is calculated and their average is called grey relational grade which is used as a single response for the Taguchi's experimental plan. Table 12 shows the mean values and S/N ratios of MRR and Surface Roughness. Table 13 shows the grey relational grade for each experiment using L9 orthogonal array. Higher grey relational grade represents that the corresponding elemental result is closer to the ideally normalized value.

Table 12. Mean Value and S/N ratio of Experimental Results

Mean and S/N ratio of Experimental Results				
Exp. No.	MRR	S/N ratio (dB)	SR	S/N ratio(dB)
1.	3.869	11.7520	1.01	-0.08643
2.	4.760	13.5521	1.09	-0.74853
3.	5.671	15.0732	1.56	-3.86249
4.	6.199	15.8464	1.25	-1.93820
5.	2.675	8.5465	1.09	-0.74853
6.	8.564	18.6535	1.95	-5.80069

7.	3.468	10.8016	1.25	-1.93820
8.	4.986	13.9550	1.43	-3.10672
9.	9.243	19.3163	2.25	-7.04365
Average	5.492778	14.16629	1.431111	-2.80816

Table 13. Grey Relational Coefficient and Grey Relational Grade

S. No.	Grey Relational Coefficient		Grey Relational Grade
Comparability Sequence	MRR	SR	
1.	0.415848	1	0.707924
2.	0.48299	0.8401	0.661545
3.	0.559296	0.479499	0.519398
4.	0.608133	0.652601	0.630367
5.	0.333333	0.8401	0.586717
6.	0.890405	0.378403	0.634404
7.	0.387414	0.652601	0.520007
8.	0.501098	0.535261	0.51818
9.	1	0.333333	0.666667

2) *ANOVA for Multi Response Optimization:* The purpose of Analysis of Variance (ANOVA) is to investigate the parameters, whose combination to total variation is significant. The ANOVA for grey relational grade has been tabulated in Table 14.

Table 14. Analysis of Variance for Grey Relational Grade

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.006307	0.006307	0.003153	0.44	0.695
B	2	0.001421	0.001421	0.000710	0.10	0.910
C	2	0.019454	0.019454	0.009727	1.36	0.424
Residual Error	2	0.014344	0.014344	0.007172		
Total	8	0.041525				

The graphs of grey relational grade are shown in Figure 10. It clearly shows that pulse on time, pulse off time and wire feed are the dominant parameters that affect grey relational grade and hence contributes in optimizing material removal rate and surface roughness to improve machining quality.

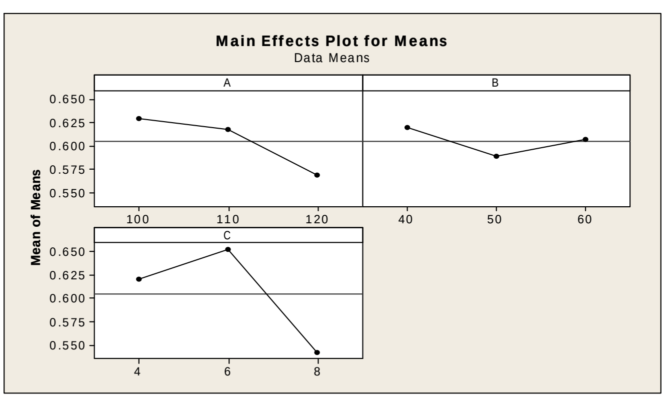

Fig. 10. Graphs of Grey Relational Grade

3) *Confirmation Experiment for Multi Response Optimization:* In order to validate the results obtained, three confirmation experiments were conducted for each of the response characteristics (MRR and SR) at optimal levels of the process variables. The average values of the characteristics were obtained and compared with the predicted values. The results are given in Table 15.

Table 15. Predicted and Confirmation Experiments Results of Multi Response Optimization at Optimal Setting

Response	Optimal Condition	Predicted Value	Experimental Value	CI_{CE}
Grey Relational Grade (GRG)	$A_1 B_1 C_2$	0.6919	------	-------
Material Removal Rate		5.027 mm^3/min	6.54 mm^3/min	$3.337 < \mu_{MRR} < 6.72$
Surface Roughness		1.06 μm	0.972 μm	$0.905 < \mu_{SR} < 1.215$

V. CONCLUSION

The following conclusions are drawn based on the results obtained for performance characteristics studied in this research work namely, MRR and Surface Roughness. In this study, all three process parameters affect the performance parameters. All the selected parameters significantly affect the MRR. Pulse off time has emerged as most significant with a percentage contribution of 62.92 % followed by Wire Feed (30.99 %) and Pulse on time (6.07%). The process parameters settings of Pulse on time at 120 μs, Pulse off time at 60 μs and Wire Feed at 6mm/min have given the optimum results for MRR. All the selected parameters affect the Surface Roughness significantly. Pulse off time has emerged as most significant with a percentage contribution of 75.32% followed by Pulse on time (18.79%) and Wire Feed (5.87 %). The process parameters settings of Pulse on time at 100 μs, Pulse off time at 40 μs, and Wire Feed at 8 mm/min have given the optimum results for Surface Roughness.

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