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RESEARCH ARTICLE

Investigation of aluminum alloy 6061 in Wire-EDM regarding surface roughness and material removal rate by adopting optimization techniques

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ABSTRACT - Wire-electric discharge machining offers a number of benefits in comparison to traditional manufacturing processes likewise, no obvious mechanical cutting traces also hard and rigid materials can be processed perfectly in WEDM. Since, aluminum alloys are used in aerospace, shipbuilding, breathing gas cylinders for scuba diving, surgical components and automotive industry for their high-strength-to-weight ratio, accurate shapes and dimensions. Through this method, complicated structures made of aluminum alloy are produced in a single setup with incredibly tight tolerances. The present investigation explores WEDM for AA6061 to optimize different process variables for attaining performance measures in terms of maximum MRR and minimum SR. Taguchi's L18 OA matrix, S/N ratio, ANOVA and Grey Relational Analysis were employed to optimize SR and MRR. It has been noted from ANOVA that pulse on time and peak current are the most influential aspects for MRR and SR with their contributions of 13.33% and 16.25% respectively. Further, the best possible considered parameters setting has been established by applying GRA for MRR and SR are, pulse on time-50μs, pulse off time-13μs and peak current-4 amp.

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1.0 INTRODUCTION

Wire-electric discharge machining (WEDM) is a non-traditional machine that is great for producing intricate or complex shapes that are difficult to machine with a traditional machine. Since the last decade, all types of conductive materials have been machined through the process. The wires used in WEDM are copper, tungsten, and brass, with a width of 0.005 to 0.3 mm. The wire electrode and the workpiece serve as cathode and anode respectively, with a gap between them. Deionized water acts as a dielectric fluid between the wire and the workpiece. More electrons are created when a wire strikes a de-ionized water molecule, and this process moves towards the anode because the electron's kinetic energy is transformed into thermal energy, creating a spark. Because of this movement, the material melts and vaporizes due to electric discharges, and the debris is ejected and flushed away by dielectric fluid. A computer-controlled positioning system continuously maintains this. Therefore, the main objective is to minimize surface roughness (SR) and the maximize material removal rate (MRR). The machining parameter settings rely heavily on the knowledge of operators and the machining parameter tables given by machine tool manufacturers [1 – 4].

WEDM is a versatile CNC machine utilized for many materials such as steels and its alloys, titanium alloys,aluminum alloys and MMC based on aluminum alloys. Several input parameters of WEDM have been analyzed, especially, Pulse on Time (T_{ON}), Pulse off Time (T_{OFF}) and Peak current (I_P) for attaining minimal SR and maximal MRR substantially along with kerf width, cutting speed, Work Feed Ratio (WFR), dimensional accuracy and surface characteristics. Therefore, several researchers have attempted to optimize its parameters for attaining the set goals for different materials and alloys. A summary of the researchers who studied the above stated materials is described as follows.

Durairaj et al. [5] analyzed SS304 to optimize the variables like gap voltage, wire feed, T_{ON}, T_{OFF} along with some fixed variables for attaining minimum kerf width and SR in WDEM by implementing Taguchi's L16 orthogonal array(OA), Grey Relational Analysis (GRA) and ANOVA. Similarly, a report by Lodhi et al. [1] investigated the surface roughness of AlSl D3 steel in WEDM by taking specifications like T_{ON}, T_{OFF}, I_P along with wire feed. The Taguchi's L9 OA, S/N ratio and ANOVA were utilized for optimizing the results. It is found that the discharge current has the highest impact on SR. In addition, Singha et al. [6] and Manjaiah et al. [7] investigated the process parameter for AISI D2 steels in WEDM to see the impact on SR and MRR by adopting Taguchi's OA approach, ANOVA in conjunction with Response Surface Methodology (RSM). The T_{ON} and servo voltage were the highly influencing factors for the results. Moreover, Goswami et al. [8] investigated the Nimonic 80-A alloy by considering input parameters of WEDM by adopting multi-response optimization technique to observe the impacts on the surface characteristics of the machined surface. Furthermore, Kumar et al. [9] investigated the parameters of WEDM on HSS M2 grade for optimizing the results for MRR, SR and kerf width by adopting RSM, GRA along with ANOVA. On the other hand, Marelli et al. [10] investigated

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the several input parameter of WEDM on super alloys by applying Taguchi's OA, ANOVA, GRA, Artificial Neural Network (ANN) and Principal Component Analysis (PCA) to optimize responses such as MRR and SR.

Several studies have focused on Titanium Alloys. Nourbakhsh et al. [11] examined the impact of several input variables of WEDM to determine the machining performance such as cutting speed, wire rapture, and surface characteristics of titanium alloy by using the Taguchi's L18 OA and ANOVA. Similarily, Silambarasan et al. [12] evaluated the various input specifications of WEDM for titanium grade 5 alloy to optimize SR and MRR by selecting L18 OA and Genetic Algorithm (GA) approaches. In addition, Magabe et al. [13] analyzed the efficacy of several input variables of WEDM on Ni55.8 titanium alloy for the responses MRR and SR by selecting L16 DOE, ANOVA and GA approaches. Moreover, Pramanik et al. [14] investigated the geometrical errors generated in form of holes by taking input variables such as WT, T_{ON}, and flushing pressure in WEDM for Ti6Al4V alloy by utilizing Taguchi DOE and ANOVA. On the contrary, Thangaraj et al. [15] analyzed the micro-titanium alloy's surface aspects in WEDM considering input factors for wire wear ratio, micro-hardness, and recast layer thickness by utilizing the Taguchi–GRA-based approach. Dheeraj et al. [16] evaluated the several factors of WEDM for titanium superalloy to optimize SR and MRR by adopting Taguchi's L18 OA Method coupled with GRA. The results show that the I_P and T_{OFF} influence the process performance.

Several researchers further examined Aluminum Alloys, for example Selvakumar et al. [17] investigated experimentally AA 5083 by considering input parameters of WEDM by utilizing Taguchi's L9 OA and Pareto optimality approach to obtaine the best combination of a variable for the responses SR and cutting speed. Thereafter, Bobbili et al. [18] examined the outcome response of ballistic grade aluminum alloy in WEDM by considering input variables for outcomes MRR, SR and gap current (GC) by adopting multi-response optimization technique in conjunction with GRA. Further, Mohamed et al. [19] analyzed AA6082-T6 in WEDM to optimize T_{ON}, T_{OFF} and I_P for evaluating the outcome values of SR by adopting Taguchi's L9 OA. Additionally, Rana et al. [20] observed the impact of input factors like T_{ON}, T_{OFF} and spark gap voltage in WEDM for AA 2216 on cutting speed by adopting BBD array for RSM techniques. The outcomes show that pulse on time and spark gap voltage have notable effects on cutting speed. Moreover, Biswas et al. [21] studied experimentally AA7075 on WEDM for the outcomes like cutting speed and SR with input WEDM parameters. The Taguchi method L16 OA and MOGA has been adopted for machining process optimization**.** In addition to AA7075, Mandal et al. [22, 23] optimized the seven effective parameters of WEDM for V_C, corner error and SR by applying Taguchi's techniques, GRA and 3D surface topography for evaluating the features of the machined surfaces.

Although, few authors examined AA6061, Sunkara et al. [24] studied AA 6061 by optimizing several WEDM inputs to create multiple holes in the sheet. Taguchi's L16 OA, a regression equation and Genetic Algorithm were utilized for finding the process variable that yields the best results. Similarly, Babu et al. [25] studied the fluctuations of outcomes for MRR and SR in WEDM by altering significant variables T_{ON}, T_{OFF} and I_P in the case of AA6061 and the performance measures were examined individually by considering the Taguchi's method, S/N ratio and ANOVA. Further, Pramanik et al. [26, 27] optimized the value of various input parameters of WEDM for AA6061 to obtain the outcome response such as MRR, kerf width and SR by adopting optimization methods. In addition, Ishfaq et al. [28, 29] investigated the impact of several control variables of WEDM for AA 6061 for dimensional accuracy issues by adopting statistical techniques and SEM. The results show that corner errors at the top and bottom together with MRR and SR are highly affected by the parameters and pulse variations.

Moreover, some authors compared two different metals in WEDM. Akkurt [30] investigated the aluminum and AA6061 machined surfaces with different conventional and non-conventional processes for microstructures and hardness variations. The outcomes of machined surfaces are significantly influenced by the process variables. Tilekar et al. [31] analyzed aluminum and mild steel to compare their outcomes like SR and kerf width in WEDM by considering various parameters by implementing a single objective methodology. Similarly, Saif and Satyam [32] analyzed AA 5083 and AA 6061 to compare their outcomes like SR and MRR in WEDM by taking input variables T_{ON}, T_{OFF} and I_P keeping servo voltage as constant by adopting Taguchi's optimization technique. The results reveal that the T_{ON} and I_P have significant effects on SR and MRR. In addition, Shiuan et al. [33] optimized the machining parameters that satisfy the necessary machining properties for various workpiece materials by utilizing specific discharge energy (SDE), GA and ANN in WEDM for AA6061 and tool steel with unique SDE values.

Furthermore, Al-based MMC has been analyzed with varying compositions of alloying elements in WEDM. Shandilya et al. [34] examined the machinability of SiCp/6061 Al alloy in WEDM for four-process parameters to optimize output responses such as machining accuracy, quality of machined surface and wire breakage for smooth cutting. Similarly**,** Sivaprakasam [35] analyzed the input variables of Micro-WEDM for Aluminum Matrix Composite to optimize the MRR, kerf width (KW) and SR. Kumar et al. [36] studied Al (6351)/Boron carbide composite by considering several machining parameters and the boron carbide percentage to analyze the kerf width and SR through GRA and SEM. Further, Patel et al. [37] studied the various parameters, cutting wire properties, optimization techniques and their importance in WEDM for the prediction of many outputs. Praveen et al.[38] studied various aluminum-based MMC and their distinct optimization techniques in WEDM process parameters having extensive applications in many industries. On the contrary, Vishwakarma et al. [39] studied the various advanced recent materials viz. nanomaterial, ceramics, super alloys, and MMC's on various non-traditional machining to obtain the best MRR, SR, and dimensional accuracy with minimal tool wear. Karthik et al. [40] optimized the WEDM parameters to attain better surface finish, MRR, and reduced KW by using Taguchi's L18 OA for machining the most recent aluminum composites. Further, Kumar et al. [41] examined the process variables in WEDM for Aluminum hybrid composites to optimize the outcomes like MRR, SR and spark gap using EDS and SEM analysis.

From the above literature studies, it is evident that the WEDM has been utilized for several materials for their process optimization, with different methodologies to evaluate the expected responses. The Aluminum alloy and their MMC along with other materials have been investigated by many researchers in WEDM. However, not many studies have been done on AA6061 using two different optimization techniques. Therefore, the goal of the current work is to investigate the outcomes from two different optimization techniques to fill the research gap for AA6061.

2.0 MATERIALS AND METHODS

This segment provides information regarding material selected for investigation, along with its specifications, the CNC machine utilized for experimentation and tool details. Taguchi's L18 OA, ANOVA with GRA has been adopted to enhance the output responses like SR and MRR.

2.1 Material and Tool Descriptions

1) The AA6061 has a high strength-to-weight ratio, high surface finish,excellent corrosion resistance and a good workability alloy. It is made of an age-hardened aluminum alloy with silicon and magnesium as its main alloying components.
2) The experimental study has been accomplished on a CNC wire-cut EDM machine.The brass wire coated with a zinc layer having a 0.25 mm diameter and a 900 N/mm^2 tensile strength has been utilized during the experiment.
3) The dimension of the workpiece is 15×15×6 mm [9, 11, 16, 32]. A single workpiece and whole work plate are depicted in Figure 1 and Figure 2, respectively.
4) The chemical composition, physical and mechanical properties of AA6061 are listed in Table 1 and Table 2.
5) Table 3 illustrates the imperative input variables and their levels.

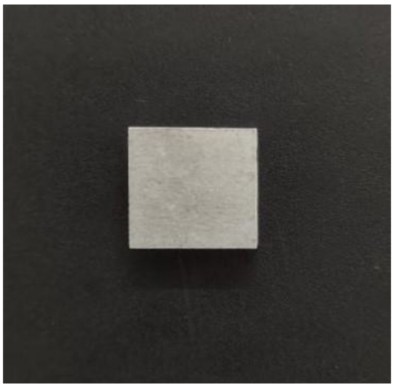


Figure 1. A machined workpiece

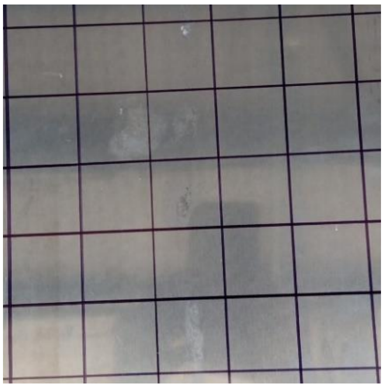


Figure 2. A work plate before machining

Table 1. The chemical compositions of AA6061 (wt%)

Components	Al	Mg	Si	Mn	Fe	Cu	Zn	Ti	Cr
Contents %	Bal	0.88	0.70	0.12	0.27	0.23	0.03	0.03	0.12

Table 2. The mechanical properties of AA6061 (wt%)

Material	Tensile strength	ProofStress	Elongation%	Thermalconductivity	Young modulas	Density	Melting point
AA6061	260-310 MPa	240-328MPa	10-14 %	167 W/m-K	68 GPa	2.70g/cc	585 ℃

Table 3. The basic input variables and its levels for AA6061

Symbols	Variables	Level 1	Level 2	Level 3	Units
A	Peak current (I_P)	3	4		Amp
B	Pulse-on Time (T_{ON})	50	60	70	µs
C	Pulse-off time (T_{OFF})	9	11	13	µs

3.0 METHODOLOGY

3.1 The Taguchi's Technique

Taguchi's technique is a statistical technique based on orthogonal array (OA) experiments and significantly reduces deviation for experiments with optimal control configurations to enhance the quality of produced items. The maximum possible signal to noise (S/N) ratios are the best level of control factor for this method. The desired result characteristics are a log function of the signal-to-noise ratios. The three S/N ratios, smaller is better, larger is better, and nominal is best are used to optimize the system. It is implied that for SR, smaller is better, and for MRR, larger is better [18].

3.2 The Design of Experiment (DOE)

The orthogonal arrays accommodate multiple factors that affect the performance of operations for optimization. The L18(2^1×3^2) OA table was selected which shows that T_{ON} and T_{OFF} varied for three levels and I_P varied for two levels [18]. The MINITAB-22 software was applied for analyzing the experimental results. The DOE of L18 OA is presented in Table 4.

Table 4. The DOE of Taguchi's L18 OA

Trial No.	Peak current (I_P)	Pulse-on Time (T_{ON})	Pulse-off time (T_{OFF})
1.	3	50	9
2.	3	50	11
3.	3	50	13
4.	3	60	9
5.	3	60	11
6.	3	60	13
7.	3	70	9
8.	3	70	11
9.	3	70	13
10.	4	50	9
11.	4	50	11
12.	4	50	13
13.	4	60	9
14.	4	60	11
15.	4	60	13
16.	4	70	9
17.	4	70	11
18.	4	70	13

3.3 The Surface Roughness (SR)

Surface finish refers to the process of altering the metal's surface which involves removing, reshaping and adding. Because of surface imperfections, this could create corrosion or crack initiation sites. The values of SR are calculated by applying a portable surface roughness tester, the MitutoyoSurfest SJ-2O1P.

3.4 The Material Removal Rate (MRR)

The difference between the workpiece's weight before and after the process, as well as the product of the procedure's duration and density, is used to calculate the material removal rate. For this specified research, Eq. (1) has been used for evaluating the material removal rate.

$$MRR = \frac{wt.\ before\,machining - wt.\ after\,machining}{time\ \times density} \tag{1}$$

3.5 The Experimental Outcomes of AA6061 as per L18 OA

The results obtained from the WEDM process parameter for SR and MRR as per Taguchi's L18 OA are presented in Table 5.

Table 5. The conducted test results of MRR and SR for AA6061

Trial No.	I_P	T_{ON}	T_{OFF}	Trial 1 (SR)	Trial 2 (SR)	Trial 3 (SR)	SR (µm)	MRR (mm^3/min)
1.	3	50	9	8.334	10.143	9.442	9.3060	12.4560
2.	3	50	11	8.079	9.764	10.759	9.5340	11.3703
3.	3	50	13	9.300	7.543	7.672	8.1716	11.4193
4.	3	60	9	8.613	7.563	9.538	8.5713	11.6264
5.	3	60	11	9.365	8.090	8.432	8.6290	11.6666
6.	3	60	13	10.291	10.758	8.144	9.7310	10.9262
7.	3	70	9	8.084	11.116	8.468	9.2220	11.8826
8.	3	70	11	10.191	9.177	9.492	9.6200	12.3679
9.	3	70	13	8.758	8.691	8.697	8.7153	13.4735
10.	4	50	9	10.231	7.643	10.016	9.2960	13.1676
11.	4	50	11	7.760	7.896	8.206	7.9183	11.0666
12.	4	50	13	7.457	8.765	7.861	8.0276	11.5148
13.	4	60	9	9.268	8.563	8.287	8.7060	10.9503
14.	4	60	11	8.394	9.307	8.419	8.7066	11.5363
15.	4	60	13	8.791	8.910	7.828	8.5096	12.1836
16.	4	70	9	8.634	8.434	9.514	8.8606	11.6756
17.	4	70	11	9.675	9.367	8.672	9.2380	11.8424
18.	4	70	13	6.976	9.749	8.473	8.3963	11.2980

3.6 The Grey Relational Analysis (GRA)

The GRA is a tool for evaluating how closely sequences approximate each other using the Grey relational grade [9]. In this method, the data are normalized between 0 and 1. The SR considering the lower the better has been expressed by Eq.(2).

$$xi(k) = \frac{\max yi(k) - yi(k)}{\max yi(k) - \min yi\,(k)} \tag{2}$$

Similarly, the normalized the data processing for MRR are considering the higher the better is expressed by Eq. (3).

$$xi(k) = \frac{yi(k) - \min yi(k)}{\max yi(k) - \min yi\,(k)} \tag{3}$$

where,
xi(k) = normalized value.
yi(k) = individual value in the column for the response *k*.
min *yi(k)* = smallest value in the column for the response *k*.
max *yi(k)* = largest value in the column for the response *k*.

After the normalized value, Grey relational coefficient (GRC) and Grey relational Grade (GRG) are calculated that can be expressed by Eqs. (4) and (5), respectively.

$$\mathcal{E}i = \frac{\min yi(k) + (0.5 * \max yi(k)}{yi(k) + (0.5 * \max yi(k)} \tag{4}$$

$$\gamma i = \frac{1}{n}\sum_{k=1}^{n} \mathrm{E}i \tag{5}$$

Where $\mathcal{E}i$ is the grey relational coefficient, γi is the grey relational grade and n is the number of the output response. The higher value of grey relational grade indicates better quality. By allocating equal weight to machine outcome a grey relational grade is calculated.

4.0 RESULTS AND DISCUSSIONS

4.1 The Evaluation of Outcomes for Surface Roughness

4.1.1 The Evaluation of Response Table for S/N Ratio

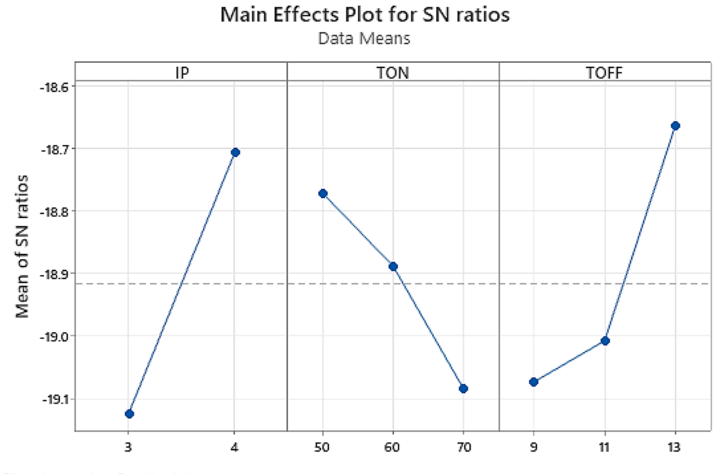
The response table contains rows and each row includes the mean of the S/N ratio for each level of factor followed by two rows named delta and rank. Those factors with the maximum S/N ratio has considered as the best combination for executing results.The analysis for response tables has been carried out by MINITAB-22 software. From Table 6, the best combinations for attaining minimum surface are I_P at level 2, T_{OFF} at level 3 and T_{ON} at level 1. Therefore, I_P is the main affecting factor and the second most affecting factor is T_{OFF}.

Table 6. The response table of S/N ratio for SR

Level	Peak current	Pulse on time	Pulse off time
1	-19.12	-18.77	-19.07
2	-18.71	-18.89	-19.01
3		-19.08	-18.66
Delta	0.42	0.31	0.41
Rank	1	3	2

4.1.2 The Main Effects Plot for S/N Ratios

The main effects plot shows the patterns of the response measures in relation to the machining variables. According to the criteria for machining performance, "smaller is better" for SR has achieved at I_P - 4 A, T_{ON} -50 µs and T_{OFF}-13 µs as depicted in Figure 3. A similar trend has been observed in the case of I_P and T_{OFF}, as I_P (3 to 4 A) and T_{OFF} (9 to 13µs) increases the value of SR increases [11, 31]. However, a different pattern was noticed in the case of pulse on time in which as T_{ON} (50 to 70 µs) increases the value of SR decreases [8, 29]. A rising trend in SR was marked as peak current raises from 3 to 4 A. Because of an increase in peak current results in more electrons smashing the workpiece surface, breaking down more surface material and creating deeper pits and bigger trash. As, T_{ON} increases to its higher values, the surface finish of the machined surface depreciates. It is due to the fact that longer the pulse duration, the longer the duration of the spark will exist.



Signal-to-noise: Smaller is better

Figure 3. Main effects plot for S/N ratios for SR

4.2 The ANOVA

4.2.1 The Analysis of Variance for S/N Ratios of Surface Roughness

The objective of ANOVA is to quantify the effects of different parameters on performance factors. The relative importance of the machining parameters with respect to the SR and MRR has been examined by ANOVA to precisely identify the ideal machining parameter combination. In terms of statistics, the F-test helps determine whether these estimates have significant differences at a certain degree of confidence or not. A higher F-value suggests that there is a significant impact of the process parameter variation on the performance attributes [5, 31].

The results of the ANOVA for surface roughness are presented in Table 7. It was identified that peak current contributes a maximum role towards SR which is 16.25% and its P and F-values are 0.113 and 2.92, respectively. The contributions of pulse on time and pulse off time is 5.54% and 11.34%, respectively.

Table 7. The ANOVA table for SR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
I_P	1	0.8197	16.25%	0.8197	0.8197	2.92	0.113
T_{ON}	2	0.2796	5.54%	0.2796	0.1398	0.50	0.620
T_{OFF}	2	0.5721	11.34%	0.5721	0.2860	1.02	0.391
Error	12	3.3727	66.86%	3.3727	0.2811		
Total	17	5.0440	100.00%				

5.0 THE EVALUATION OF MATERIAL REMOVAL RATE

5.1 The Response Table for S/N Ratios

Table 8 illustrates that the best combinations for attaining maximum MRR is T_{ON} at level 3, T_{OFF} at level 1 and I_P at level 1. Therefore, pulse on time is the main affecting factor and the second most affecting factor is T_{OFF}.

Table 8. The S/N ratio for MRR

Level	Peak current	Pulse on time	Pulse off time
1	21.50	21.45	21.54
2	21.35	21.19	21.32
3		21.63	21.42
Delta	0.16	0.44	0.22
Rank	3	1	2

5.2 The Main Effects Plot for S/N Ratios

According to the machining production conditions ,"larger is better", for MRR has achieved at I_P -3 A, 70 µs T_{ON} -3 A and T_{OFF} - 9 µs as shown in Figure 4. The T_{ON} has the highest influencing factor for MRR as indicated in Table 8. It was noticed that as the value of T_{ON} increased from 60 to 70 µs, the value of MRR is augmented. Because of increasing values of pulse on time, the discharge and spark power is maximum which utilizes to remove the material in the form of debris. As a result, a high material removal rate is attained [13]. Nevertheless, in the case of I_P and T_{OFF}, the value of MRR declined as the parametric values of I_P and T_{OFF} rises [10, 40].

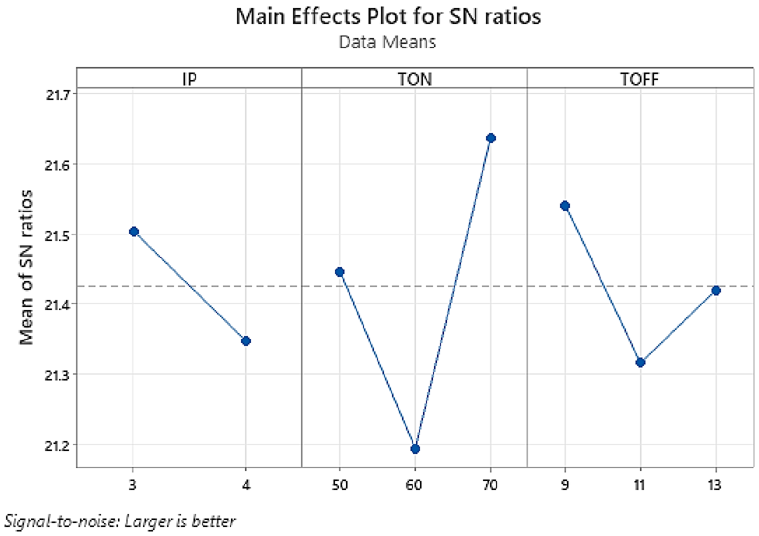


Figure 4. The S/N ratios main effects plot for MRR

5.3 The Analysis of Variance for S/N ratio of MRR

The results of the ANOVA for MRR as illustrated in Table 9. It has been marked that pulse on time contributes a maximum amount towards MRR which is 13.33% and its P and F-values are 0.399 and 0.99, respectively. The contributions of pulse off time and peak current is 3.61% and 2.52%, respectively.

Table 9. The ANOVA table for MRR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
IP	1	0.2120	2.52%	0.2120	0.2120	0.38	0.551
TON	2	1.1193	13.33%	1.1193	0.5596	0.99	0.399
TOFF	2	0.3035	3.61%	0.3035	0.1518	0.27	0.768
Error	12	6.7639	80.53%	6.7639	0.5637		
Total	17	8.3988	100.00%				

5.4 The Results of Grey Relational Analysis

The yield reactions from GRA analysis of the normalized values like GRC, GRG, and Rank obtained by combining with the L18 OA are illustrated in Table 10.

Table 10. The output values from GRA analysis

Exp. No	Input Parameter			Output parameter		Normallized		GRC		GRG	Rank
	I_P (A)	T_{ON} (μs)	T_{OFF} (μs)	SR	MRR	SR	MRR	SR	MRR		
1	3	50	9	9.3060	12.4560	0.23446	0.60056	0.39509	0.55590	0.475494	10
2	3	50	11	9.5340	11.3703	0.10868	0.17434	0.35937	0.37717	0.368271	17
3	3	50	13	8.1716	11.4193	0.86026	0.19358	0.78157	0.38272	0.582148	5
4	3	60	9	8.5713	11.6264	0.63976	0.27488	0.58124	0.40812	0.494679	8
5	3	60	11	8.6290	11.6666	0.60793	0.29066	0.56050	0.41345	0.486972	9
6	3	60	13	9.7310	10.9262	0.00000	0.00000	0.33333	0.33333	0.333333	18
7	3	70	9	9.2220	11.8826	0.28080	0.37546	0.41010	0.44462	0.427364	15
8	3	70	11	9.6200	12.3679	0.06123	0.56597	0.34752	0.53532	0.441418	13
9	3	70	13	8.7153	13.4735	0.56032	1.00000	0.53210	1.00000	0.766049	1
10	4	50	9	9.2960	13.1676	0.23997	0.87991	0.39682	0.80634	0.601577	4
11	4	50	11	7.9183	11.0666	1.00000	0.05512	1.00000	0.34605	0.673024	2
12	4	50	13	8.0276	11.5148	0.93970	0.23107	0.89238	0.39403	0.643208	3
13	4	60	9	8.7060	10.9503	0.56545	0.00946	0.53502	0.33545	0.435234	14
14	4	60	11	8.7066	11.5363	0.56512	0.23951	0.53483	0.39667	0.465750	11
15	4	60	13	8.5096	12.1836	0.67380	0.49362	0.60518	0.49683	0.551006	6
16	4	70	9	8.8606	11.6756	0.48017	0.29419	0.49028	0.41466	0.452469	12
17	4	70	11	9.2380	11.8424	0.27197	0.35967	0.40716	0.43847	0.422814	16
18	4	70	13	8.3963	11.2980	0.73630	0.14596	0.65471	0.36926	0.511988	7

5.5 The Response Table of S/N Ratios for GRG

Table 11 shows the status of parameters such as I_P at level 2,T_{OFF} at level 3 and T_{ON} at level 1. The outcomes reveal that pulse on time is a highly valuable factor followed by pulse off time to obtain the greatest value of GRG.

Table 11. The response table of S/N ratios for GRG

Level	Peak current	Pulse on time	Pulse off time
1	-6.505	-5.253	-6.414
2	-5.656	-6.824	-6.597
3		-6.164	-5.230
Delta	0.848	1.571	1.367
Rank	3	1	2

5.6 The Analysis of Main Effects Plot S/N Ratios for GRG

As per the stated limitations on machining performance, "larger is better" for GRG, who have obtained at I_P-4 A, T_{ON}-50 µs and T_{OFF} -13 µs as depicted in Figure 5. A similar pattern has been marked in the case of peak current and pulse off time. As I_P (3 to 4 A) and T_{OFF} (9 to 13µs) raises the value of GRG increases but a different pattern is noticed in the case of pulse on time in which as T_{ON} (50 to 70 µs) increases the value of GRG first decreases then partially increases.

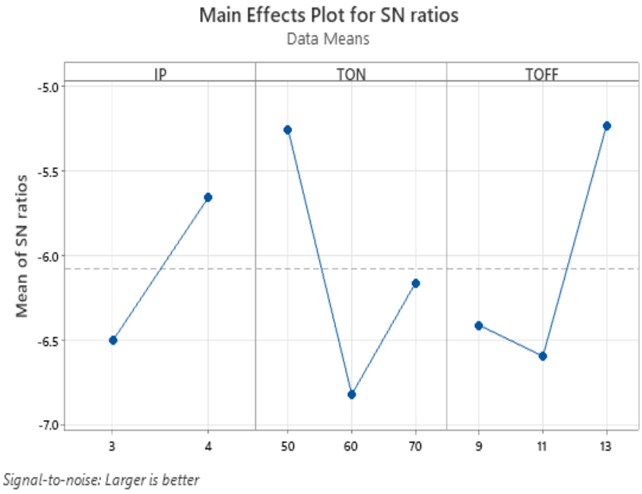


Figure 5. The Main effects plot for S/N ratios

Table 12 shows the optimum level of initial parameters according to Taguchi's method in conjunction with GRA for obtaining the optimized results of the outcomes for the SR and MRR.

Table 12. The optimized values of parameters by adopting Taguchi and GRA techniques

S. No.	Process Parameter	Units	Taguchi Method				GRA	
			SR		MRR		GRG	
			BestLevel	Value	BestLevel	Value	BestLevel	Value
1	Peak current	Amp	2	4	1	3	2	4
2	Pulse on Time	µs	1	50	3	70	1	50
3	Pulse off time	µs	3	13	1	9	3	13

6.0 CONCLUSION

In this experimental analysis, the effectiveness of optimal variables in WEDM machineability for AA6061 has been examined. Three input factors, namely- pulse on time, pulse off time, and peak current are taken into account to evaluate their impact on the output responses of MRR and SR. The Taguchi's L18 OA, S/N ratios, ANOVA, and GRA have been employed along with MINITAB-22 software for optimizing the processes. Based on the findings, the following conclusions are drawn:

- The variations in SR are highly influenced by peak current followed by pulse off time.
- The variations in MRR are highly influenced by pulse on time followed by pulse off time.
- From GRA, it is obtained that the best possible parameter settings are T_{ON}- 50µs, T_{OFF}-13µs , and I_P- 4 amp for MRR and SR.

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