Multi-Objective Optimization of EDM process parameters using Taguchi-Grey Relational Analysis for Aluminium work material with Copper Electrode

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Abstract - *This paper involves the multi objective optimization of EDM process parameters on Aluminium work piece with Copper electrode for obtaining maximum material removal rate (MRR), minimum tool wear rate (TWR) and minimum surface roughness (SR) using Taguchi-Grey Relational Analysis. The machining parameters are selected as Discharge Current, Pulse on Time, Flushing Pressure and Polarity. Experiments were conducted by selecting two operating levels for the said four parameters according to Taguchi's Design of Experiments. Using Grey Relational Analysis (GRA) the multi objective optimization was performed to determine the optimal solution. Analysis of Variance (ANOVA) for Grey relational Grade was carried out to determine the most contributing and significant input parameter/parameters. The optimal level of input parameters are found to be as* $A_2B_2C_1D_1$ *i.e. 16A for discharge current, 1010 µs for pulse on time, 5kgf/cm*^{2} *for flushing pressure and normal polarity. The ranking of the process parameters reveals that current is the most dominant parameter on the output response followed by pulse on time. From the ANOVA for grey relational grade it was also experienced that the current is the only significant factor while machining on Aluminium work piece with Copper electrode.*

***Key Words*: Electro discharge machining, orthogonal array, Material Removal Rate, Tool Wear Rate, Surface Roughness, GRA, and ANOVA.**

1. INTRODUCTION

Electrical Discharge Machining (EDM) is an unconventional machining process which is used for removing material using a series of repeated electrical discharges between a tool called electrode and work piece and the part being machined in the presence of a dielectric fluid [1]. Using thermal energy a high-precision metal removal is possible from an accurately controlled electrical discharge machine. The electrode is moved towards the work piece and a small gap is maintain to ionize the dielectric [2]. EDM process uses for machining hard metals and alloys which would have been difficult to machine by conventional methods, but EDM has made it relatively simple to machine intricate shapes [3]. The process is used for producing dies, moulds, and finishing parts for aerospace, automotive, and surgical components [4].This machining process is continually finding further applications in metal machining industry. The material is removed from electrode and work piece by erosive effect of the electrical discharges. There is no any direct contact between the tool electrode and the work piece material because of that it eliminate mechanical stresses, chatter and vibration problems during machining [1, 5].

2. EXPERIMENTAL DETAILS

2.1 Experimental setup

In this study a series of experiments were conducted using EDM by taking aluminium as work piece and copper as tool electrode and experiments were run to examine the effects of input machining parameters such as Discharge Current, Pulse ON time, Flushing Pressure and Polarity on the material removal rate, tool wear rate and surface roughness. .The experiment has been conducted on EDM model F25 series of Sparkonix India Private Limited, Pune as shown in fig 1. It has the optimum working current of 25A with maximum work-piece weight of 650kg and maximum electrode weight of 35kg. The X-axis and Y-axis movements are given to the work table and Z-axis movement is on the tool holder. A servo mechanism controls the downwards movement of the tool holder during machining. The dielectric tank has a capacity of 400 litres. The flushing pressure can be read on separate gauge fitted on the left side of the working tank. For each of the experiment separate electrode were selected. In this experimentation kerosene was used as dielectric fluid. For each of the experimentation a machining time of 10 minutes was set. Material is removed during machining from both the work piece and the tool and MRR and TWR is determined from their respective weight differences before and after machining divided by machining time. The surface roughness is measured by means of a portable type apparatus (Handy surf surface texture measuring instrument).

Fig -1: EDM machine set-up

2.2 Tool material and work piece material

In this experiments copper electrodes were used which were shown in fig.2. The work-piece material is aluminium as shown in fig.3.The electrode material properties are given in table 1.

Fig -2: Copper tool electrode

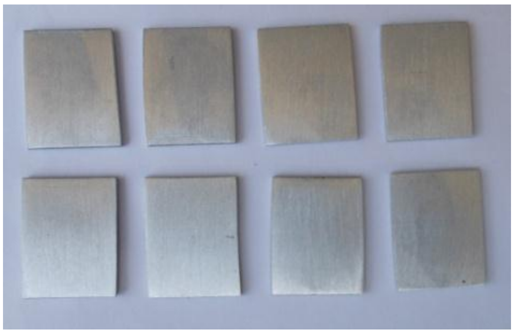

Fig -3 Name of the figure

Table -1: Properties of electrode material

Working conditions	Value
Melting point	1083°C
Elastic modulus (E)	1.23x 10^5N/mm^2
Poisson's ratio	0.26
Density	8.9 gm/cm^3

2.3 Selection of response and control parameters

In this work we are selecting four control parameters and three different response parameters at two different levels for multiple performance optimization as shown in table 2.

Response parameters considered in this study are as follows-

- Material removal rate (mm^3/min)
- Tool wear rate(mm^3/min)
- Surface Roughness (R_a value in μm)

Table -2: Control parameters with their respective levels

	Control parameters	Level 1	Level 2
A	Discharge Current (A)	8	16
B	Pulse on time(μs)	463	1010
C	Flushing pressure (kgf/cm^2)	5	10
D	Polarity	N(Normal)	R (Reverse)

2.4. Design of experiments

In this work based on the calculation done for total degrees of freedom (DOF) in case of four factors for three process parameters at two levels each with no interaction, the best suited orthogonal array L_8 design matrix is used to evaluate the process performance and the layout is shown in table 3. The weight of the tool piece and work pieces were measured before and after machining by using Ishida DX precision electrical balance and were tabulated in table 4. After that material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra) were calculated and were tabulated in table 5. The MRR is expressed as the ratio of the difference of weight of the work piece before and after machining to the machining time and is calculated using given formula [6]. It is expressed in mg/min and denoted by MRR.

$$\text{MRR}=\frac{\text{initial weight}-\text{final weight}}{\text{machining time}}$$

TWR is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time and is calculated using given formula [6]. It is expressed in mg/min and denoted by TWR.

$$\text{TWR}=\frac{\text{Initial weight}-\text{final weight}}{\text{machining time}}$$

Surface Roughness is the size of the surface texture. It is expressed in μm and denoted by Ra. If the value comes higher that means the surface is rough and if lower comes that means that the surface is smooth.

After the experimentation the pictorial view of the copper tool electrode and aluminium work piece has been taken and shown in fig. 4 and fig.5 respectively.

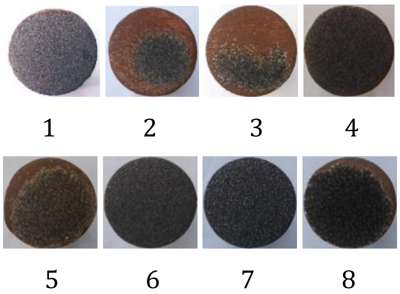

Fig -4 Copper tool pieces after machining

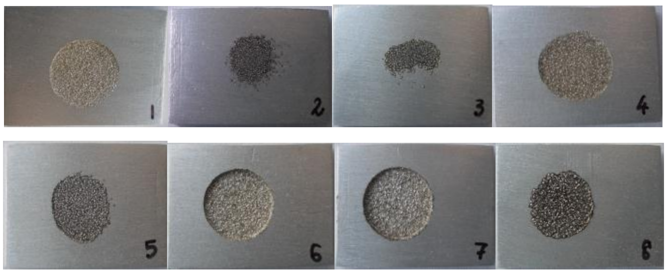

Fig -5 Work pieces after machining

Table -3: Experimental layout using an L_8 orthogonal array

Sl. No.	Current	On time	Flushing pressure	Polarity
1	1	1	1	1
2	1	1	2	2
3	1	2	1	2
4	1	2	2	1
5	2	1	1	2
6	2	1	2	1
7	2	2	1	1
8	2	2	2	2

Table -4: Initial and final weight of tool and work pieces

Sl. No.	Initial Weight Tool (g)	Initial Weight Work piece (g)	Final Weight Tool (g)	Final Weight Work piece (g)
1	52.9017	5.2285	52.9009	5.1631
2	56.8577	5.1310	56.8568	5.1263
3	56.2515	5.1465	56.2503	5.1438
4	55.8003	4.8757	55.8000	4.8139
5	56.7921	5.2668	56.7890	5.2336
6	52.8729	4.5644	52.8725	4.4476
7	55.6733	4.8359	55.6724	4.7148
8	55.6997	5.0570	55.6961	5.0214

Table -5: Calculation of MRR, TWR and SR

Sl. No.	A	B	C	D	MRR	TWR	SR
1	8	463	5	N	6.54	0.08	8.1
2	8	463	10	R	0.47	0.09	5.95
3	8	1010	5	R	0.27	0.12	8.29
4	8	1010	10	N	6.18	0.03	10.2
5	16	463	5	R	3.32	0.31	10.0
6	16	463	10	N	11.68	0.04	12.4
7	16	1010	5	N	12.11	0.09	22.3
8	16	1010	10	R	3.56	0.36	14.55

3. GREY RELATIONAL ANALYSIS

Based on the output responses and using Grey relational analysis the multi-objective optimization is performed for obtaining the optimal set of process parameters. The transformation of S/N Ratio values from the original response values was the initial step. For that the equations of "larger the better" is used for MRR and "smaller the better" is used for TWR and surface roughness values [7, 8]. Subsequent analysis was carried out on the basis of these S/N ratio values.

Type1: $S/N=-10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y^2_{i}}\right]$ Larger the better... (1)

Type2: $S/N=-10\log\left[\frac{1}{n}\sum_{i=1}^{n}Y_i^{2}\right]$ smaller the better... (2)

Where Y_{ij} is the value of the j^{th} response in the i^{th} experiment condition, with i=1, 2, 3…n; j = 1, 2…k

Table -6: Calculation of S/N Ratio for MRR, TWR and SR

Sl. No.	MRR	TWR	SR	S/N Ratio MRR	S/N Ratio TWR	S/N Ratio SR
1	6.54	0.08	8.1	16.312	21.938	-18.169
2	0.47	0.09	5.95	-6.559	20.915	-15.490
3	0.27	0.12	8.29	-11.373	18.416	-18.371
4	6.18	0.03	10.2	15.820	30.458	-20.172
5	3.32	0.31	10.0	10.423	10.173	-20
6	11.68	0.04	12.4	21.389	27.959	-21.868
7	12.11	0.09	22.3	21.663	20.915	-26.966
8	3.56	0.36	14.55	11.029	8.874	-23.257

Using eq. (1) and eq. (2) we evaluate S/N ratio values given in table 6.

The normalized output parameter corresponding to the larger-the-better criterion can be expressed as

$$Z_i = \frac{Y_{ij} - \min\,(Y_{ij}, i=1,2,\ldots,n)}{\max(Y_{ij}, i=1,2,\ldots,n) - \min\,(Y_{ij}, i=1,2,\ldots,n)} \quad (3)$$

Then for the smaller-the-better criterion can be expressed as

$$Z_i = \frac{\max(Y_{ij}, i=1,2,\ldots,n) - Y_{ij}}{\max(Y_{ij}, i=1,2,\ldots,n) - \min\,(Y_{ij}, i=1,2,\ldots,n)} \quad (4)$$

Table -7: Normalized S/N ratio for MRR, TWR and SR

Sl. No.	Normalized S/N ratio MRR	Normalized S/N ratio TWR	Normalized S/N ratio SR
1	0.838	0.395	0.234
2	0.146	0.442	0
3	0	0.558	0.251
4	0.823	0	0.408
5	0.659	0.940	0.393
6	0.991	0.116	0.556
7	1	0.442	1
8	0.678	1	0.677

Using eq. (3) and eq. (4) we normalize the S/N ratio values given in table 7. After that computing grey relational coefficient (GC) for the normalize S/N ratio values. Before that the deviation sequence for the reference and comparability sequence were found out. Grey relational coefficients along with deviation sequence were given in table 8.

Table -8: Calculation of deviation for MRR, TWR and SR

Sl. No.	Normalized S/N ratio MRR	Normalized S/N ratio TWR	Normalized S/N ratio SR	ΔMRR	ΔTWR	ΔSR
1	0.838	0.395	0.234	0.162	0.605	0.767
2	0.146	0.442	0	0.854	0.558	1
3	0	0.558	0.251	1	0.442	0.749
4	0.823	0	0.408	0.177	1	0.592
5	0.659	0.940	0.393	0.340	0.060	0.607
6	0.991	0.116	0.556	0.009	0.884	0.444
7	1	0.442	1	0	0.558	0
8	0.678	1	0.677	0.322	0	0.323

The grey relational coefficient can be expressed as

$$GC_{ij} = \frac{\Delta_{\min} + \lambda\,\Delta_{\max}}{\Delta_{ij} + \lambda\,\Delta_{\max}}$$

Where i=1,2….n experiments and j=1,2….m response
GC_{ij}= grey relational coefficient for the i^{th} experiment/trial and j^{th} dependent variable/response
Δ= absolute difference between Y_{oj} andY_{ij} which is a deviation from target value and can be treated as a quality loss
Y_{oj}= optimum performance value or the ideal normalized value of j^{th} response
Y_{ij}=the i^{th} normalized value of the j^{th} response/dependent variable.
Δ_{min} = minimum value of Δ
Δ_{max} = maximum value of Δ
λ is the distinguishing coefficient which is defined in the range $0 \le \lambda \le 1$ (the value may be adjusted on the practical needs of the system)
After that by averaging the grey relational coefficient corresponding to each performance characteristic grey relational grade was determined which is shown in the table 9. Depending on the calculated grey relational grade the overall performance characteristic of the multiple response process were carried out The grey relational grade can be expressed as $G_i = \frac{1}{m}\sum GC_{ij}$ Where m is the number of responses.

Table -9: Calculation of Grey Relational Grade

Sl. No.	CG_{MRR}	CG_{TWR}	CG_{SR}	G_i	RANK
1	0.861	0.623	0.566	0.683	5
2	0.539	0.642	0.5	0.560	8
3	0.5	0.693	0.572	0.588	7
4	0.849	0.5	0.628	0.659	6
5	0.746	0.943	0.622	0.771	3
6	0.991	0.530	0.692	0.737	4
7	1	0.642	1	0.881	1
8	0.757	1	0.756	0.837	2

Similar to GRC, GRG also gives the degree of closeness of the results to the ideal result that obtained experimentally. Better multiple performance characteristics is obtained when grey relational grade is larger From Table 9, it can be seen that Experiment no. 7 has the best multi-performance characteristic as it has the high GRG value.

Since the motive of this work is to find an optimum level of machining parameters with maximum MRR, minimum TWR and minimum Ra, the multi-objective optimization of machining parameters for EDM process is converted to optimization of GRG. So mean GRG for each level of the input parameters and their total mean are calculated table 10. From this table, the optimal level of input parameters is found to be 16amps for discharge current, 1010 µs for pulse-on time, 5kgf/cm^2 for flushing pressure and normal polarity. The ranking of the process parameter reveals that discharge current is the most dominant parameter on the output response followed by pulse on time. The optimal parameter combination was determined as $\mathbf{A_2B_2C_1D_1}$.

Table -10: Effects of the Factors in Grey Relational Grade

	Factors	Level 1	Level 2	Rank
A	Discharge current (A)	0.6228	**0.8066**	1
B	Pulse on time (μs)	0.6880	**0.7414**	2
C	Flushing pressure (kgf/cm^2)	**0.7307**	0.6987	4
D	Polarity	**0.7403**	0.6892	3

ANOVA for grey relational grade

To obtain the percentage contribution of the factors and their significances Analysis of variance (ANOVA) is performed. For that F-ratio value at 95 % confidence level is used which will decides the significant factors affecting the process. A Larger value of F- ratio indicates a big change on the performance in the variation of process parameters [9, 10]. Usually, when *F* is large the change of the machining parameter has a significant effect on the performance characteristic shown in table11. From this table 11 of ANOVA for GRG, the percentage contribution of factors over the optimum solution of GRG it was observed that the discharge current (77.88%) is the most dominant parameter followed by Pulse on time (6.58%), polarity (5.98%) and flushing pressure (2.43%).

Table -11: ANOVA for GRG

Source	Sum of square	DOF	Mean square	F-Ratio	C (%)	Rank
A	0.0677	1	0.0677	*32.771	77.88	1
B	0.0057	1	0.0057	2.771	6.58	2
C	0.0021	1	0.0021	1.022	2.43	4
D	0.0052	1	0.0052	2.518	5.98	3
Error	0.0062	3	0.0021		7.13	
Total	0.0869	7				

4. RESULTS AND DISCUSSIONS

Polarity and Discharge Current: MRR increases with the increase in current with both positive and negative polarity but it drastically increases with the increase in current with positive polarity as compared to negative polarity. With an increase in current, the available spark energy during discharge increases leading to higher MRR. Positive polarity was found to be optimum for analysis of TWR, because the positive polarity factor decreases TWR rather than negative polarity. This is because relative heat dissipation on the work piece is high at the end of discharge medium [11]. During spark occurs few electrons impinge the tool rather than on the work piece because electrons are normally react with positive polarity which is the work piece. It was experimented that TWR decreases with the decrease in current for both positive and negative polarity but it is decreases more with the decreases in current with positive polarity as compared to negative polarity. With a decrease in current, the available spark energy during discharge decreases leading to lower TWR. Similarly surface roughness also increases with the increase in current with both positive and negative polarity although the SR obtained with negative polarity is relatively lower as compared to SR obtained with positive polarity. Lower current value gives lower SR. Increase in SR with increase in current may be attributed to the increase in energy content of the spark. Generally polarity is to be determined by specific experiments and is a matter of tool material, work material, current density and pulse length combinations [11, 12].

Flushing Pressure: Flushing in the dielectric through the gap of electrode and work piece is necessary to remove the unwanted micro debris produced during the machining, which tends to short circuit the electrodes leading to damage of both tool and work piece. High flushing pressure in the dielectric fluid enhances the MRR, since the tendency of getting short circuit due to the micro debris formed in the machining reduces, thus saving both tool and work piece. Flushing pressure in the dielectric fluid reduce the TWR, since the tendency of getting short circuit due to the micro debris formed in the machining reduces, thus saving both tool and work piece.. As the flushing pressure increases the value of surface roughness considerably reduces since it tries to reduce the irregularities, but very high flushing pressure may again distort the already made surface finish. So, in order to get better surface finish the obtained low level of flushing pressure is justified in compromising with material removal rate [6].

Pulse-on time: The higher pulse on time and pulse current corresponds to higher material removal rate since it is directly proportional. Extended pulse on time gives more heat to work piece, which means the recast layer will be larger and the heat affected zone will be deeper. However too much extended pulse on time may again lead to low MRR. Tool wear rate decrease in increase in pulse on time, because it may be attributed to spark energy and this spark energy is directly proportional to pulse on time. The spark energy increases with increase in pulse on time and higher pulse on time leads to spreading of the spark, due to which heat transfer to the tool reduces and this results in less tool wear rate [13]. The experimental results reveal that for a constant pulse on time, the surface roughness increases with increasing pulse current and it also increases with increasing pulse on time for a constant current [11, 12].

The objective of this multi objective optimization is to obtain a high MRR with low TWR and low Surface Roughness. From the calculation of GRG, it can be concluded that the experiment no. 7 with highest GRG value leads to the best optimal setting. These findings can be verified in the table 5. Also from the study of effects of the factors in Grey Relational Grade, the same optimal setting were obtained as $\mathbf{A_2B_2C_1D_1}$ i.e., 16A for discharge current, 1010μs for pulse on time, 5kgf/cm^2 for flushing pressure and normal polarity. The same conclusion was also drawn from the ANOVA for GRG. The experimental results show that at high level of discharge current with positive polarity, the available spark energy during discharge increases leading to higher MRR. At high level of Pulse on time, the MRR being directly proportional exhibited an increasing trend. High flushing pressure in the dielectric fluid enhances the MRR, since the tendency of getting short circuit due to the micro debris formed in the machining reduces, thus saving both tool and work piece.

In case of TWR, the positive polarity leads to decrease compared to negative polarity, because relative heat dissipation on the work piece is high in the end part of machining process. During spark, few electrons impinge the tool rather than on the work piece, because majority of them are normally attracted towards positive work piece. Tool wear rate decreases in increase in pulse on time, because it may be attributed to spark energy and this spark energy is directly proportional to pulse on time. The spark energy increases with increase in pulse on time and higher pulse on time leads to spreading of the spark, due to which heat transfer to the tool decreases. This results in less TWR. Flushing pressure in the dielectric fluid decreases the TWR, since the tendency of getting short circuit due to the micro debris formed in the machining reduces.

The experimental results reveal that for a constant pulse on time, the surface roughness increases with increasing pulse current and it also increases with increasing pulse on time for a constant current. As the flushing pressure increases the value of surface roughness considerably reduces since it tries to reduce the irregularities, but very high flushing pressure may again distort the already made surface finish. So, in order to get better surface finish the obtained low level of flushing pressure is justified in compromising with MRR.

So, the optimal setting of process parameters i.e. $\mathbf{A_2B_2C_1D_1}$ corresponding to high level of discharge current, high level of pulse on time, low level of flushing pressure with normal polarity has been experienced to be justified with multi objective optimization for responses i.e. MRR, TWR and SR.

5. CONCLUSIONS

In this investigational experiment on EDM to know the effect of machining parameters i.e., ***discharge current, pulse-on time, flushing pressure and polarity*** over responses i.e., ***material removal rate (MRR), tool wear rate (TWR) and surface roughness*** **(Ra)** in the Aluminium work piece using the Copper electrode, it was experienced that the factors affected the responses differently although these responses are important from the industrial point of view. From the above calculation and analysis the following points can be concluded-

- The optimum parameter setting is found to be as $\mathbf{A_2B_2C_1D_1}$ i.e., ***16A for discharge current, 1010 μs for pulse-on time, 5kgf/cm^2 for flushing pressure and normal polarity.*** The experiment no. 7 in table no 5 also reveals this fact.
- MRR increases drastically with increase in current with positive polarity as compared to negative polarity.
- Normal polarity was found to be optimum for analysis of TWR, because the normal polarity leads to decrease in TWR.
- TWR decreases more with the decreases in current with positive polarity as compared to negative polarity.
- Surface roughness also increases with the increase in current with both positive and negative polarity although the SR obtained with negative polarity is relatively lower as compared to SR obtained with positive polarity.
- The higher pulse on time and pulse current leads to higher MRR, however too much extended pulse on time may again leads to low MRR.
- TWR decreases in increase in pulse on time, because it may be attributed to spark energy and this spark energy is directly proportional to pulse on time.
- The experimental results reveal that for a constant pulse on time, the surface roughness increases with increasing pulse current and it also increases with increasing pulse on-time for a constant current
- The study reveals that discharge current is the most dominant parameter on the output response followed by pulse on time.
- From the effects of the factors in the Grey Relational Grade and ANOVA for GRG it is seen that the same ranking order of control parameters were found and it is observed that discharge current is the most significant parameter, while flushing pressure being the least contributing.

ACKNOWLEDGEMENT

The authors express their sincere thanks and gratitude to Department of Mechanical Engineering of Assam Engineering College and NIT Silchar, Assam for providing the facility of tools and equipment for doing the experimental research work. The authors also thank Mr. Maneswar Rahang for the assistance in running the experimental work in the workshop of Mechanical Engineering Department of NIT, Silchar.

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