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Process optimization and comparative analysis of EDM and EDD process in machining Al6063/10% SiC metal matrix composites

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In this work, a comparative investigation of electric discharge machining (EDM) and electric discharge drilling (EDD) has been presented to evaluate the performance measures for machining blind holes in Al6063/10% SiC metal matrix composites (MMCs). The work has been conducted with an aim of optimizing the material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). The input parameters chosen for machining are (i) discharged current, (ii) pulse-on time, and (iii) duty factor. The Taguchi's L_9 orthogonal array has been applied to design the experiments. The grey relational analysis has also been used to determine the optimal level of input parameters to achieve better results. Analysis of variances (ANOVA) has been applied to perform the statistical analysis of the experimental data. The results have shown that discharge current is the most influencing factor that affects the multiple performance characteristics in both EDM and EDD processes.

Keywords: EDM, EDD, MMCs, MRR, TWR, SR

1 Introduction

The present demand of industries for a material which is light-in-weight and possessing good mechanical properties had led to the development of advanced materials known as composite materials. The MMCs are widely used in industries as these materials possess superior mechanical properties like high specific strength and stiffness, high toughness, high-temperature resistance, low-density, etc. as compared to the monolithic metals[1,2]. These superior properties of MMCs make them a viable engineering material for making various components in the aerospace, defense, and automotive industries. The machining of MMCs poses challenges because of their superior mechanical properties and the presence of hard reinforcements. The conventional machining techniques are not economical for processing of MMCs as it causes high tool wear and leads to high energy consumption. Thus, the nonconventional machining techniques have been developed to overcome the challenges associated with the conventional machining of advanced materials[3-5]. The EDD is one of the latest developments in nonconventional machining processes. It is the combination of EDM and traditional drilling process. EDD is used for drilling of burr-free small to large size hole. In EDD, the rotary tool electrode imparts a significant influence on the machining performance of electrically conductive hard-to-machine materials. The centrifugal force induced by the dielectric fluid due to the rotation of the tool electrode causes effective flushing of the debris from the machining zone. This results in improved material removal during EDD when compared one-on-one with EDM of hard-to-machine materials. Sony and Chakraverti[6] experimentally investigated the EDM of titanium with the rotating tool electrode. It was observed that the MRR is higher in making both through and blind holes due to the significant improvement in flushing action. It was also estimated that the MRR was quite high for the rotating tool electrode as compared to the stationary tool electrode. Yan and Wang[7] developed a rotary EDM setup for drilling of Al_2O_3/6063Al composites using a tubular tool electrode. It was found that MRR, TWR, and SR were substantially influenced by the peak current and volume fraction of Al_2O_3 reinforcement. Wang and Yan[8] applied rotary motion to the tool electrode in EDM of blind hole in Al_2O_3/6061Al composites. It was concluded that an eccentric through hole coupled with the rotational motion of the tool electrode resulted in higher MRR. Mohan *et al.*[9] showed that the EDM of Al-SiC MMCs with rotary tube tool electrode resulted in better removal of material

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as compared to that of the rotating solid tool electrode. The hole diameter of the tool electrode tube and rotational speed of the tube tool electrode had a significant effect on the MRR. Singh *et al.*[10] investigated the effect of different tool electrode geometry such as solid cylindrical, chamfer, conical, and helical tool electrode during the EDD of MMCs. It was found that the conical tool electrode has a significant effect on the MRR followed by the chamfered and solid cylindrical tool electrodes. Kumar *et al.*[11] showed that the making of through hole in hybrid MMCs using rotary tool electrode provides the acceptable value of MRR. Zhao *et al.*[12] experimentally concluded that EDM of single-crystal SiC had better MRR and lesser tool wear ratio as compared to that of steel material. Dewangan *et al.*[13] found that the surface roughness obtained with copper and graphite tool electrodes was better than the brass tool electrode during EDM of AISI P20 tool steel. Muthuramalingam and Mohan[14] concluded that the higher electrical conductivity of the tool electrode material resulted in improved MRR. Subsequently, higher melting point coupled with lower electrical conductivity of the tool can produce as mooth surface. Pragadish and Kumar[15] conducted an experimental investigation using a modified tool electrode for making holes in AISI D2 steel by means of dry EDM process. The ANOVA analysis of the experimental results concluded that the current was the most influential parameter followed by the pressure. Khanna *et al.*[16] adopted the Taguchi method to optimize the different input parameters for better MRR and TWR during EDM of Al 7075. The statistical analysis showed that the MRR and TWR were significantly affected by a pulse-on time and pulse-off time. Kao *et al.*[17] conducted an experimental investigation to optimize the multiple performance characteristics in EDM of Ti-6Al-4V alloy. The MRR, electrode wear ratio, and surface roughness are chosen as performance parameters for evaluating the machining behavior. Kumar *et al.*[18] studied the multiple performance optimizations of the abrasive mixed electrical discharge machining (AEDM) of EN-24 tool steel. The experimental results concluded that the machining efficiency and grey relation grade were improved by 10%. Meena and Azad[19] performed micro-EDM of Ti-6Al-V alloy using the tungsten carbide tool electrode for optimizing the input parameters.

From the literature, it can be concluded that the research attempt made majorly focused on the EDM of conventional metals and alloys. The comparative analysis between the EDM and EDD process in the context of machining of MMCs has not been reported. Thus, the present experimental work is aimed to evaluate the performance of EDM and EDD processes in terms of MRR, TWR, and SR in the context of machining of developed MMCs. The influence of different input parameters namely discharge current, duty factor, and pulse-on time has been investigated to study the performance characteristics of the EDM and EDD process.

2 Experimental Details

MMCs were developed using a standard stir, squeeze, and quench casting process. The melting of aluminum alloy (Al6063) and preheating of reinforced particles (SiC) was carried out in the presence of argon gas to develop the MMCs using vertical muffle furnaces. The composition of the developed composites is given in Table 1. The experimental investigation was conducted on the CNC-EDM machine (Electronica, CNCS-50). The modifications were made to the experimental setup of the conventional EDM. A drilling setup was developed and retrofitted with the existing EDM setup. The rotary setup was attached to the servo mechanism of the EDM machine. A special attachment was made to enable rotation of the tool electrode with the help of motor, v-belt, and pulley. The physical setup and schematic diagram of EDD are shown in Fig. 1. The response in both EDM and EDD are influenced by many process parameters. In the present work, discharge current (I), pulse-on time (T_{on}), and duty factor were chosen as the influencing parameters. The fixed parameters chosen were the flushing pressure of 0.75 kg m/sec^2, tool electrode rotational speed of 400 rpm, voltage gap of 60 V, and straight electrode polarity i.e., the work material was connected to positive polarity and tool electrode to negative polarity. Table 2 shows the values of varying input process parameters. The drilling operations were conducted using a copper tool electrode of 7.5 mm in diameter during both EDM

Table 1 — Percentage of various elements in developed MMC.

Al	SiC	Mg	Fe	Mn	Cu	Ti
88.63%	10.44%	0.6%	0.2%	0.07%	0.018%	0.008%

Table 2 — Level of different input parameters and their values.

Symbol	Parameters	Unit	Level-I	Level-II	Level-III
A	Discharge current	A	5	10	15
B	Pulse-on time	μs	50	100	150
C	Duty cycle	--	16	24	32

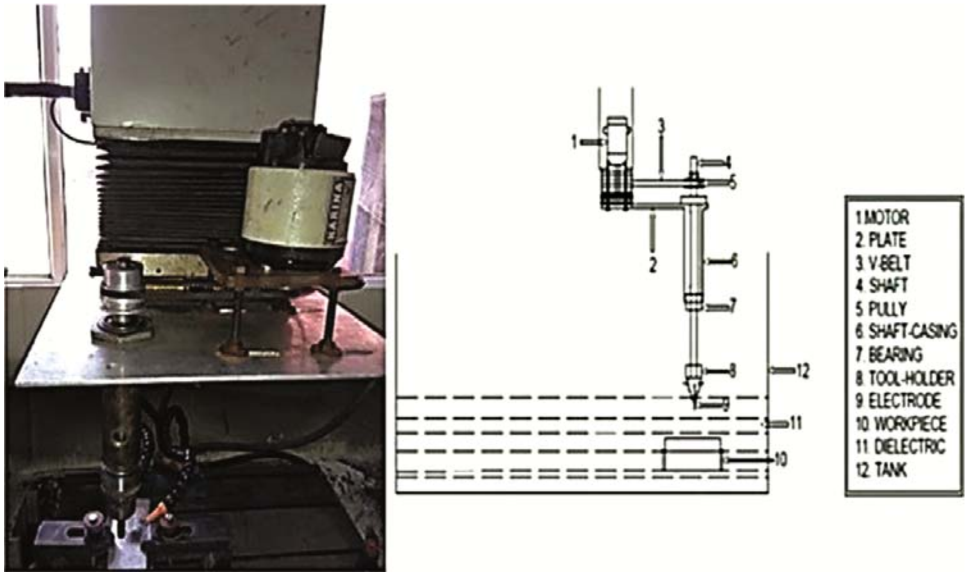

Fig. 1 — Developed rotary setup attached to the EDM servo controller.

and EDD of developed MMCs (test specimen thickness of 6 mm). The volume loss of the machined workpiece and tool electrode was measured after each experiment to calculate the MRR and TWR. The roughness of the hole machined surface was also evaluated using roughness tester. An electronic digital timer was used to note the machining time, whereas an electronic weighing balance was used to measure the weights of the workpiece and tool electrode before and after the removal of materials. The MRR and TWR can be calculated as given by the following equations:

MRR (mm^3/sec) =

$$\frac{W_{iv}-W_{fv}}{T_m \times \delta} \times 1000 \quad \ldots (1)$$

TWR (mm^3/sec) =

$$\frac{T_{iv}-T_{fv}}{T_m \times \delta} \times 1000 \quad \ldots (2)$$

where, W_{iv} and $W_{fv}$is the initial and final weight of the workpiece,

T_{iv} and T_{fv} is the initial and final weight of the tool electrode,

T_m is the machining time, and

$\delta$is the density of the material

3 Experimental Design

Taguchi's orthogonal array was applied to design the set of experiments. Taguchi method investigates the idea of the quadratic quality loss function and utilizes a statistical measure of signal to noise ratio (S/N). The S/N ratio is the ratio of signal (mean) to the standard noise (deviation) quality of the process to be optimized. The experiments were designed Taguchi's L_9 orthogonal array and the ANOVA was done to identify the statistical significance of the different parameters on the output responses such as MRR, TWR, and SR.

The grey relational analysis was also applied for the identification of optimal parameters affecting various responses. The first step in grey relation analysis is the normalization of observed data i.e., conversion of experimental data to normalized data. This normalized data generally varies between the range of 0 and 1. The next step involves the calculation of the grey relation coefficient using the normalized data. The grey relational coefficient generally expresses the relation between experimental and desired data. The average value of the grey relation coefficients (GRC) is then calculated which gives the grey relation grade (GRG). The grey relation analysis was done based on two criteria viz. lower is the better and higher is better. In EDM and EDD, the higher-the-better is preferred for MRR and the lower-the-better is preferred for TWR and SR and given by;

The higher-the-better:

$$y_i(q) = \frac{z_i(q) - \min z_i(q)}{\max z_i(q) - \min z_i(q)} \quad \ldots (3)$$

The lower-the-better:

$$y_i(q) = \frac{\max z_i(q) - z_i(q)}{\max z_i(q) - \min z_i(q)} \quad \ldots (4)$$

where, $y_i(q)$ is the grey relation generation,

$\min z_i(q)$ is the minimum value of the $z_i(q)$,
$\max z_i(q)$ is the maximum value of the $z_i(q)$, and
q stands for the q^{th} response

The very next step is the calculation of grey relation coefficients using the following equation;

$$\xi_i(y_i(q), y_0(q)) = \frac{\Delta\min + \psi\Delta\max}{\Delta_{0i} + \psi\Delta\max} \quad \ldots (5)$$

Here, $\Delta_{0i} = \| y_0(q) - y_i(q) \|$ is the difference between the absolute values of $y_0(q)$ and $y_i(q)$.

The minimum value of $\Delta_{0i}$is $\Delta\min$ and the maximum value of Δ_{0i} is $\Delta\max$. The characteristic coefficient (ψ) lies between 0 and 1 and is usually taken as 0.5. The grey relation grade is calculated by using the grey relation coefficients as given by the following equation.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{1} \xi_i(y_i(q), y_0(q)) \quad \ldots (6)$$

Here, n refers to the number of process responses. The higher the value of the grey relational grade, intense the relation between the given sequence $y_i(q)$ and the reference sequence $y_0(q)$. Only the best possible sequence is taken as the reference sequence. The given set of parameters will be closer to the optimality when the grey relational grade is higher. The assignment of the response weight is the difficult task as it solely depends on the decision-maker perception and this leads to certain uncertainties. Upon identifying the optimal machining parameter levels, the next step is to predict and verify the quality performance characteristics using the optimal level of parameters. The formula used to calculate the estimated grey relational grade is given by;

$$\bar{\eta}_{GRG} = \bar{\eta}_m + \sum_{i=1}^{r_0}(\eta_{GRG_i} - \bar{\eta}_m) \quad \ldots (7)$$

where, $\bar{\eta}_m$ is the overall mean of the grey relational grade,

η_{GRG_i} is the mean of the grey relational grade at the optimal level for the i^{th} factor, and

r_o is the number of the process parameters influencing grey relational grade.

4 Results and Discussion

The effect of different input parameters on the output responses during EDM and EDD of developed MMCs has been investigated. The L9 orthogonal table of the input process parameter along with the experimental results is shown in Table 3 and Table 4, respectively. The MMCs workpiece after machining by EDM and EDD is shown in Fig. 2. Initially, pre-processing of data is done to normalize the experimental data to the range between 0 and 1 which is referred to as grey relation generation. The grey relation coefficient for each response factor and grey relation grade is then calculated for both EDM and EDD, respectively. The grey relation coefficient, grey relation grade, and the ranking for the corresponding experiment of EDM and EDD are shown in Table 5 and Table 6, respectively. From Table 5, it can be noted that the 8^{th} experiment had the highest grade among all the experiments conducted. Thus, the corresponding level of factors for the 8^{th} experiment was considered to be the optimal value for obtaining better multi-response characteristics of high MRR, low TWR, and SR during EDM. In the same manner, it can be noted from Table 6 that the 8^{th} experiment has the relatively highest grade among all the experiments conducted at different sets of input parameters. Thus, the corresponding level of factors of the 8^{th} experiment is considered to be an optimal value for EDD.

Table 7 shows that the average grey relational grade obtained for each level of input parameters for EDM. It can be observed from the table that levels $A_3B_2C_1$ have the highest grey relational grade for the

Table 3 — The experimental results for EDM.

Sl. No.	A	B	C	MRR (mm^3/min)	TWR (mm^3/min)	SR (μm)
1	5	50	16	4.708	0.003	4.087
2	5	100	24	6.042	0.004	5.487
3	5	150	32	7.491	0.004	3.730
4	10	50	24	8.851	0.024	9.820
5	10	100	32	12.966	0.019	12.643
6	10	150	16	13.025	0.011	14.007
7	15	50	32	15.947	0.048	11.527
8	15	100	16	19.989	0.058	11.983
9	15	150	24	12.749	0.018	15.510

Table 4 — The experimental results for EDD.

Sl. No.	A	B	C	MRR (mm^3/min)	TWR (mm^3/min)	SR (μm)
1	5	50	16	7.969	0.018	1.217
2	5	100	24	10.617	0.011	1.147
3	5	150	32	13.463	0.017	1.853
4	10	50	24	21.524	0.036	2.060
5	10	100	32	23.636	0.018	2.463
6	10	150	16	27.607	0.035	2.157
7	15	50	32	18.482	0.049	2.263
8	15	100	16	24.774	0.044	1.970
9	15	150	24	32.322	0.071	2.503

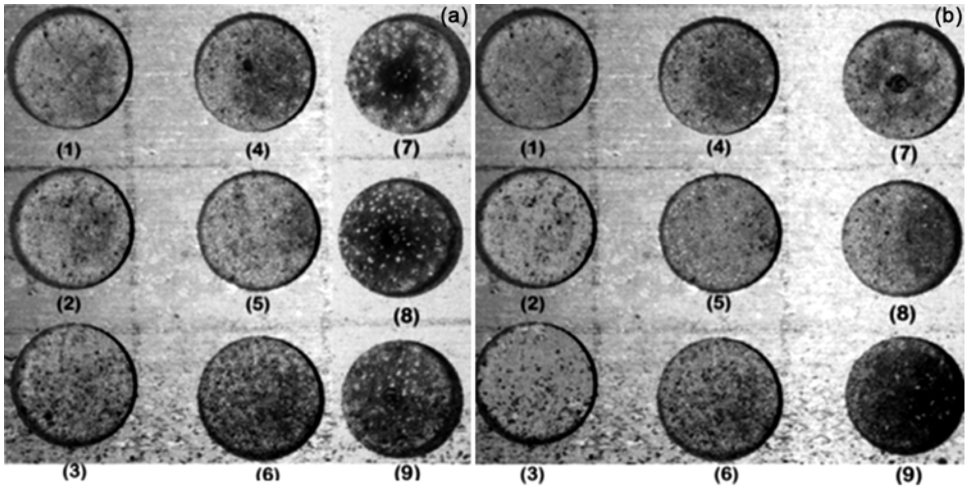

Fig. 2 — Machining of MMCs by means of (a) EDM and (b) EDD.

Table 5 — The grey relation analysis response table for EDM.

Sl.	Normalized			GRC			GRG	Rank
	MRR	TWR	SR	MRR	TWR	SR		
1	0	1	0.969	1	0.333	0.340	0.558	4
2	0.087	0.994	0.851	0.851	0.335	0.370	0.519	8
3	0.182	0.987	1	0.733	0.336	0.333	0.467	9
4	0.271	0.617	0.483	0.648	0.447	0.509	0.535	6
5	0.540	0.710	0.243	0.481	0.413	0.673	0.522	7
6	0.544	0.864	0.128	0.479	0.366	0.797	0.547	5
7	0.735	0.188	0.338	0.405	0.726	0.597	0.576	3
8	1	0	0.299	0.333	1	0.625	0.653	1
9	0.526	0.736	0	0.487	0.404	1	0.631	2

Table 6 — The grey relation analysis response table for EDD.

Sl.	Normalized			GRC			GRG	Rank
	MRR	TWR	SR	MRR	TWR	SR		
1	0	0.983	0.998	1	0.337	0.334	0.557	5
2	0.014	1	1	0.972	0.333	0.333	0.546	6
3	0.226	0.900	0.479	0.689	0.357	0.510	0.519	8
4	0.557	0.583	0.327	0.473	0.461	0.605	0.513	9
5	0.643	0.883	0.029	0.437	0.361	0.944	0.581	4
6	0.683	0.433	0.255	0.423	0.536	0.662	0.540	7
7	0.432	0.367	0.177	0.537	0.577	0.739	0.617	3
8	0.690	0	0.393	0.420	1	0.559	0.660	1
9	1	0.450	0	0.333	0.526	1	0.620	2

input factors. The corresponding values of input factors to the highest grey relation grade are discharged current (A) of 15 A, pulse-on time (B) of 100 μs, and duty factor (C) of 16. From Table 7, it can also be stated that the most influencing input parameter is the discharged current followed by the duty factor and pulse-on time to obtain the best multi-response characteristic for EDM. Table 8 indicates the average grey relational grade for each set of process parameters of EDD. It can be observed from the table that levels $A_3B_2C_1$ have the highest grey relational grade for the input factors and the corresponding values of input factors to the highest grey relation grade are discharge current of 15 A, pulse-on time of

Table 7 — The grey relation grade for EDM.

Source	Level 1	Level 2	Level 3	Max-Min	Rank
A	0.5147	0.5347	0.6198	0.1051	1
B	0.5562	0.5646	0.5485	0.0161	3
C	0.5860	0.5614	0.5218	0.0642	2

Table 8 — The grey relation grade for EDD.

Source	Level 1	Level 2	Level 3	Max-Min	Rank
A	0.5407	0.5448	0.6324	0.0917	1
B	0.5625	0.5958	0.5596	0.0361	2
C	0.5857	0.5598	0.5724	0.0259	3

100 µs, and a duty factor of 16. From Table 8, it is also evident that the most influencing input parameter is the discharge current followed by the pulse-on time and duty factor for obtaining the best multi-response characteristic in EDD.

The interaction plot of the meanvalue of the grey relation grade of EDM and EDD is shown in Fig. 3. The grey relation grade graph presents the influence of each input parameter considered for the purpose of investigation. It was observed from the figure that $A_3B_2C_1$ is the condition for obtaining maximum grey relation grade i.e., the optimal level of the set of input parameters for obtaining maximum MRR and minimum TWR and SR in EDM. Whereas, $A_3B_2C_1$ is the condition for obtaining maximum grey relation grade and thus, the optimal level of the set of input parameters for obtaining maximum MRR and minimum TWR and SR in EDD.

The confirmation test was conducted to verify the influence of different input parameters upon finding the optimum level of process parameters. The corresponding results for EDM and EDD are shown in Table 9 and Table 10, respectively. The responses referring to initial condition parameters and optimal parameters are then compared and presented in Table 9 and Table 10, respectively. From the tables, it is evident that the grey relational grade obtained for optimal parameter condition is larger than that of the initial condition and the grade predicted is very close to the experimental grey relational grade.

The use of the Taguchi experimental analysis method failed to judge the effect of individual parameters over the response. Thus, ANOVA analysis was used to find the contribution of each parameter on the total effect. In the present experimental work, ANOVA analysis was conducted at the confidence level and a significant level of 95 % and 5 %, respectively. From Table 11, it can be noted that the discharge current (71.14 %) is the most influencing factor followed by the duty factor (24.01%) and pulse-on time (1.49%) in EDM. From Table 12, it can also be noted that the discharge current (79.14 %) is the most significant influencing factor followed by the pulse-on time (11.89%) and duty factor (4.94%) in EDD. The discharge current is the most influential parameter because it is directly proportional to the spark energy. The increase in discharge current results in increased heat density within the spark gap (the gap between the tool electrode and workpiece) which helps in achieving higher material removal from the workpiece. The pulse-on time is defined as the duration for which the voltage is applied. The

Table 9 — Results of confirmation test for EDM.

Observed values	Orthogonal array	Predicted	Experimental
Level	$A_1B_1C_1$	$A_3B_2C_1$	$A_3B_2C_1$
MRR	4.7082		19.990
TWR	0.0034		0.058
SR	4.0867		11.983
GRG	0.5578	0.6576	0.6529
Improvement in grey relation grade = 0.0951			

Table 10 — Results of confirmation test for EDD.

Observed values	Orthogonal array	Predicted	Experimental
Level	$A_1B_1C_1$	$A_3B_2C_1$	$A_3B_2C_1$
MRR	7.969		24.774
TWR	0.018		0.041
SR	1.217		1.970
GRG	0.5570	0.6685	0.6600
Improvement in grey relation grade = 0.1030			

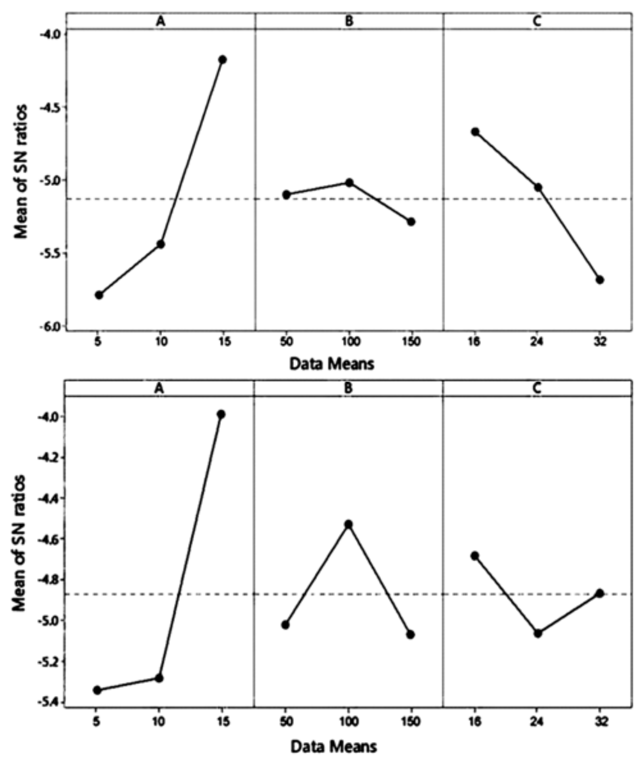

Fig. 3 — Main effect plot for mean grey relation grade (a) EDM and (b) EDD.

Table 11 — ANOVA analysis of grey relation grade for EDM.

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
A	2	0.018668	71.14%	0.018668	0.009334	21.15	0.045
B	2	0.000390	1.49%	0.000390	0.000195	0.44	0.694
C	2	0.006301	24.01%	0.006301	0.003151	7.14	0.123
Error	2	0.000883	3.36%	0.000883	0.000441		
Total	8	0.026242	100%				

Table 12 — ANOVA analysis of grey relation grade for EDD.

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
A	2	0.016109	79.14%	0.016109	0.008054	19.67	0.048
B	2	0.002421	11.89%	0.002421	0.001210	2.96	0.253
C	2	0.001006	4.94%	0.001006	0.000503	1.23	0.449
Error	2	0.000819	4.02%	0.000819	0.000409		
Total	8	0.020354	100%				

maximum energy can be reached depending upon the pulse duration. The maximum spark energy is converted into heat energy which results in the formation of a bigger crater. Thus the lager pulse duration results in higher material removal.

5 Conclusions

In the present experimental work, the cylindrical copper tool electrode and MMCs as workpiece were used. Both EDM and EDD were conducted on the workpiece for drilling of blind holes. The grey relation analysis was applied to obtain the optimum value of process parameters for both EDM and EDD, respectively. From the present experimental and statistical analysis, the following conclusions can be drawn.

(i) The grey relation grade was used to optimize the parameters. The 8thexperimental run ($A_3B_2C_1$ i.e., discharged current of 15 A, pulse-on time of 100 µs, and a duty factor of 16) was found to have the optimal setting for obtaining maximum MRR, minimum TWR and SR in EDM and EDD, respectively.

(ii) The results of optimal parameter conditions were validated by conducting additional confirmation tests. It was found that predicted grey relational grade was near to the grade of the optimal values. It was also noted that there is an improvement in grey relational grade by 0.0951 to 0.1030 for EDM and EDD, respectively.

(iii) The ANOVA results indicated that the discharge current is the most influencing machining parameter in both EDM and EDD processes that affects the multiple performance characteristics.

(iv) It was also found that MRR and SR are better in EDD as compared to EDM. The rotation of the tool electrode applies centrifugal force and whirl which removes the debris from the machining gap and improves the machining performance. However, the TWR is lower in EDM as compared to EDD.

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