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Original Article

An Experimental Analysis of the Effects of Graphite Powder Mixed Dielectric Medium in the Electrical Discharge Machining of Cu-Al Alloy

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Abstract *- Electric Discharge Machining (EDM) is a non-traditional manufacturing method used in a variety of sectors, including automotive, military, aerospace, and microsystems, to produce low-cost products with consistent quality. Powder-Mixed Electric Discharge Machining (PMEDM) is a novel technique that reduces the insulating strength of the fluid and increases the spark gap between the tool and workpiece by combining the electrically conductive powder with the dielectric. This leads to a more consistent process, which enhances the rate of material removal and the quality of the surface. The present study examined the effects of dielectric mixed with micro-sized graphite powder on the material removal rate and surface roughness of the Cu-Al alloy workpiece material. The purpose of using Cu-Al alloy as a work material is to study the process behavior of this material, which has specific applications in nuclear reactors, spacecraft, rocket motors, and gas turbines. We use the Taguchi technique to design the experiments and the ANOVA technique to analyze the results. Using powder-mixed dielectric improves the MRR and SR, with peak current and powder concentration being the most significant factors during the process.*

Keywords *- PMEDM, Cu-Al alloy, Taguchi method, ANOVA, Regression.*

1. Introduction

The need for materials with increased strength, hardness, and toughness has been driven by recent advancements in the industrial sectors like automotive, aerospace, defence, metallic moulds and dies. These materials pose difficulties while being machined using traditional machining. The newly available materials include a combination of lightweight properties together with increased hardness and toughness. At times, these qualities might provide substantial difficulties during the machining process. Therefore, Non-traditional machining techniques such as Electrochemical Machining (ECM), Ultrasonic Machining (USM), Electrical Discharging Machines (EDM), and recently created hybrid machining are used for the purpose of working with challenging materials that are hard to process. An EDM is a non-traditional thermoelectric machining process that is capable of machining metals, alloys, and carbides regardless of their hardness, strength, toughness, and microstructure [1]. A new hybrid material removal process called powder mixed EDM (PMEDM) is being developed to improve surface finish and quality, achieving near mirror-like surfaces at high machining rates. PMEDM also produces surfaces with high resistance to corrosion and abrasion. The process involves mixing a fine powder material into the dielectric fluid of EDM, which improves the breakdown characteristics of the dielectric fluid, increasing the spark gap distance between the electrode and workpiece. This increases the spark gap distance, making the process more stable and improving the machining rate and surface finish [2].

Current research has concentrated on investigating the impacts of using a powder-mixed dielectric medium in electrical discharge machining. Wu et al. [3] conducted a study on the impact of adding the aluminum powder to dielectrics for electrical discharge distribution, revealing that optimal distribution occurs at 0.1 and 0.25 g/L powder and surfactant concentrations, resulting in a 60% improvement in surface roughness. Uno et al. [4] found that EDMed surfaces with metal powder mixed fluid exhibit decreased roughness and greater corrosion resistance. Nickel Powder Mixed Fluid (NPMF) has lower roughness and sand abrasion resistance. Therefore, they presented a powder-mixed fluid surface modification method for high wear resistance.

Paulo Pecas et al. [5] investigated the fact that adding powder particles to EDM dielectric fluid enhances surface quality in large machined areas. They found that increasing the concentration of silicon powder reduces crater dimensions, white-layer thickness, and surface roughness. Kansal et al. [6] conducted a study to improve material removal rate and surface roughness through optimized PMEDM process parameters. They used response surface methodology to analyze experiments. They found that increasing silicon powder concentration in EDM dielectric fluid enhances material removal and surface finish with a higher peak current. Chow et al. [7] investigated the micro-slit EDM method by using SiC powder in a solution of clean water. It was discovered that the addition of SiC powder resulted in an increase in the electrical conductivity of the working fluid and an enlargement of the gaps between the electrode and the workpiece. It facilitated the extrusion of debris, ultimately leading to an enhancement in the material removal rate.

Yan et al. [8] investigated the influence of machining properties on titanium metals by using Electrical Discharge Machining (EDM) with the inclusion of urea in distilled water. Results showed that urea increased material Recovery Rate (MRR) and Electrode Wear Rate (EWR) with peak current but declined with pulse duration. G. Bharath Reddy et al. [9] found that PMEDM simplifies discharge breakdown, increases gaps, widens passage, and forms evenly distributed cavities on workpieces. The addition of metal powders in the dielectric fluid increases the material removal rate. Gangadharudu Talla et al. [10] found that powder properties like density, electrical conductivity, and thermal conductivity significantly influence PMEDM characteristics. A combination of low density and high conductivities leads to better machining rates and superior surface quality. A. Sugunakar et al. [11] found that mixing powders into a dielectric medium improved MRR and slightly increased SR. The maximum MRR was achieved with 9 g/l graphite powder, while the minimum SR was achieved with a 4.5g/l combination of aluminium and graphite powders. Gourab Mohanty et al. [12] investigated the impact of input process parameters on EN19 alloy steel machining using PMEDM. The parameters, such as peak current, gap voltage, pulse on time, and graphite concentration, are varied to study the influence on MRR and SR. The experimental results show an increase in both the MRR and SR with the increase in peak current, gap voltage, and graphite concentration, whereas MRR and SR are seen to decrease with the increase in gap voltage.

A.Y. Joshi et al. [13] found that additive powder mixed dielectric in PMEDM significantly enhances the material removal rate and reduces tool wear compared to conventional EDM. This process results in a mirror-like surface finish, modified surface characteristics, and a burr-free workpiece without stresses. Niwat Mookam et al. [14] investigated the impact of powdered materials on hole dimensions, MRR, EWR, and SR in a dielectric fluid. They found that the addition of Gr and B4C powders significantly enhanced these properties. Jay Vora et al. [15] conducted experiments on the PMEDM of Nitinol SMA using Taguchi's L9 design. The results showed that nano-graphene Polycarbonate at 2 g/L enhanced MRR and decreased SR. J. Shah et al. [16] investigate the effect of Expanded Graphite (EG) nanopowder in the WEDM process of Ti6Al4V. Compared to conventional EDM conditions, using EG nanopowder at 1 g/L significantly improved response values, with MRR of 3.91 g/s and SR of 2.623 µm, resulting in a 45.35% and 36.16% enhancement, respectively.

Recent publications still lack experimental data on Powder Mixed Dielectric medium in Electrical Discharge Machining, and further research is needed to increase our understanding of optimum process parameter settings to improve machining characteristics. The current study examined how Powder Mixed Electrical Discharge Machining (PMEDM) process factors impact the machining characteristics of Electrical Discharge Machining of Cu-Al Alloy. A novel approach using Taguchi design experiment techniques is presented to analyze the machining characteristics of Powder Mixed Electrical Discharge Machining of Cu-Al Alloy. The present study aims to analyze the effects of dielectric fluid mixed with micro-sized graphite powder on the MRR and SR during electric discharge machining of Cu-Al alloy using copper electrodes, along with input factors such as Powder concentration (g/l), Peak current (Amp) and Pulse on time (µs). For optimization, the Taguchi S/N ratio technique was utilized, and experiments were planned using the Taguchi method of the L9 orthogonal array for three factors and three levels each. Machining performance, such as MRR and SR, were analyzed using ANOVA and regression methods.

2. Materials and Methods

2.1. Materials

In the present study, wrought Aluminium alloy grade 2014 (Cu-Al Alloy) was used as work material. The workpiece of Cu-Al alloy is used in a rectangular-shaped plate of dimensions 60mm X 50mm X 12mm, as shown in Figure 1. EDM commonly employs metals with a high melting point and strong electrical conductivity as tool materials. Copper, a red metal with a face-centered cubic crystalline structure, has superior EDM wear and higher conductivity [1, 13]. Copper was used as a tool electrode with a diameter of 10 mm, as shown in Figure 2.

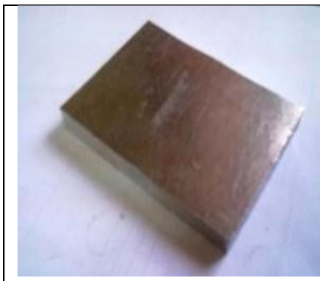


Fig. 1 Workpiece of Cu-Al alloy

Fig. 2 Cu tool electrode

Table 1. Composition of work material (Cu-Al Alloy)

Elements	Composition %
Silicon (Si)	0.50–1.2
Iron (Fe)	0.7
Copper (Cu)	3.9–5.0
Manganese (Mn)	0.40–1.2
Magnesium (Mg)	0.20–0.8
Chromium (Cr)	0.10
Zinc (Zn)	0.25
Titanium (Ti)	0.15
Aluminium (Al)	remainder

Table 2. Properties of work material (Cu-Al Alloy)

Properties	Value
Density	2.80 *10^3 kg/m3
Modulus of elasticity	72 GPa
Thermal expansion (20 ºC)	23*10^{-6} /ºC
Specific heat capacity	880 J/(kg*K)
Thermal conductivity	193 W/(m*K)
Electric resistivity	3.49*10^{-8} Ohm*m
Tensile strength (annealed)	186 MPa
Yield strength (annealed)	97 MPa
Shear strength (annealed)	124 MPa
Fatigue strength (annealed)	90 MPa
Hardness (annealed)	45 HB
Tensile strength (T651)	483 MPa
Hardness (T651)	135 HB
Elongation (annealed)	18 %

2.2. Experimental Method

Experiments were conducted using a die-sinking EDM machine model V6040 manufactured by VM Engineers India Ltd. The workpiece material used is Wrought Aluminium alloy grade 2014 (also known as Cu-Al Alloy). The present study examined how graphite Powder Mixed Electrical Discharge Machining (PMEDM) process factors impact the machining characteristics of Electrical Discharge Machining of Cu-Al Alloy. A novel approach using Taguchi design experiment techniques and ANOVA analysis to analyze machining characteristics of Powder Mixed Electrical Discharge Machining of Cu-Al Alloy. Three levels of process parameters were taken for an experiment, as given in Table 3. The constant process factors for EDM are shown in Table 4. For further expansion of experiment trials, the Taguchi technique was used to develop the experiment design for three factors at three levels. The array chosen was L9, which has 9 rows with 3 columns at three levels, as seen in Table 5. Taguchi's trial design was utilized to optimize process parameters. The responses to be analyzed for the studies are the MRR and SR of Electrical Discharge Machining of Cu-Al Alloy. The current study's output responses are of the "larger the better" for MRR and "lower is better" for SR respectively. The signal-to-noise ratio (S/N) value was estimated using Equations (1) and (2) for the responses respectively [18, 19]. After that, a linear regression method is used to identify the relationship between the responses and the process parameter, i.e. the mathematical model is developed between responses and process parameters with the help of Statistical Software Minitab and within the given range of process parameters [20, 21].

$$S/N = -10\ log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (1)$$

$$S/N = -10\ log_{10}\left(\frac{\sum y^2}{n}\right) \quad (2)$$

Where (S/N) is signal-to-noise, n is the number of repeated experiments, y is the output value.

2.3. EDM Machine Tool

Experiments were conducted on a die-sinking EDM machine model V6040 manufactured by VM Engineers India Ltd. The setup for powder-mixed EDM consists of a transparent bath-like container called a machining tank, where the machining is performed. It contains a fixture assembly for holding the workpiece. The machining tank is filled up with dielectric fluid (kerosene oil), and a stirring system is incorporated. A small dielectric circulation pump is installed there to avoid particle settling and for proper circulation of the powder-mixed dielectric fluid into the discharge gap. The schematic setup for the powder-mixed EDM and experiential setup is shown in Figures 3 and 4 [17].

Table 3. Process parameters and their levels

Symbol	Parameters/ factors	Unit	Level 1	Level 2	Level 3
A	Powder concentration	g/l	0	3	6
B	Peak current	Amp	3	6	9
C	Pulse on time	µs	50	100	200

Table 4. Constant parameters of EDM

Parameters/ factors	Unit	Values/Factor
Gap voltage	Volt	50
Dielectric	---	kerosene
Powder	---	Micro size Graphite powder
Pulse off time	µs	50
Machining Time	Minutes	15

Table 5. Experimental Plan (Taguchi L9)

Experiment no.	Powder concentration (g/l)	Peak current (Amp)	Pulse on time (µs)
1	0	3	50
2	0	6	100
3	0	9	200
4	3	3	100
5	3	6	200
6	3	9	50
7	6	3	200
8	6	6	50
9	6	9	100

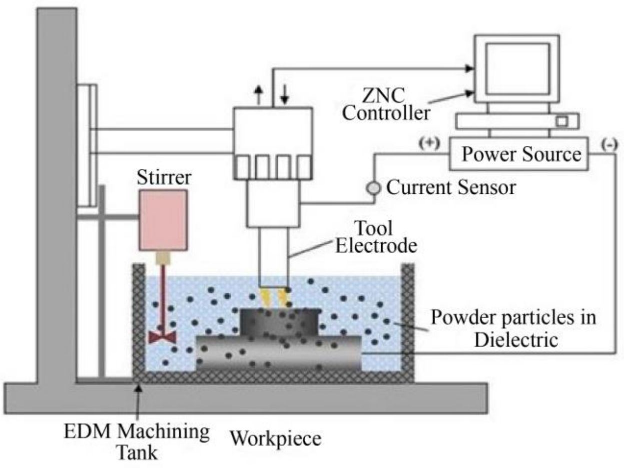


Fig. 3 Schematic of setup for the powder-mixed EDM [17]

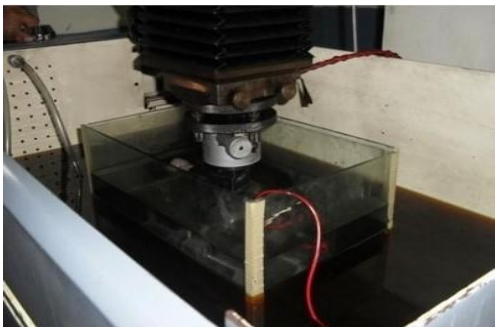


Fig. 4 Experimental setup

Table 6. Specifications of EDM machine tool

Specifications	Units	Machine Tool
Table dimension	mm	600 x 400
Work Tank dimension	mm	900 x 500 x 375
X-travel	mm	400
Y-travel	mm	300
Z-travel	mm	220
Maximum table loading	Kgs	600
Dielectric capacity	liters	400
Normal current	Amps	50/100
Maximum current	Amps	50
Maximum open circuit voltage	volts	75-80
Power consumption	Kw	3

3. Results and Discussion

3.1. Optimization

The experimental results obtained for Electrical Discharge Machining of Cu-Al Alloy 3D as per Taguchi's experimental design are summarised in Tables 7 and 9. Machining responses exhibited a Material Removal Rate (MRR) from a minimum of 2.98 mm^3/min to 10.83 mm^3/min and Surface Roughness (SR) from a minimum of 3.88 µm to 6.45 µm. Taguchi optimization uses the S/N ratio method to determine the best combination of process factors. The primary purpose of the research is to increase machining performance, and the S/N ratio was used to determine whether "larger is better" for MRR and lower is better for SR, respectively. Calculating the mean S/N ratios for each response at each level determines the optimum value; a higher S/N ratio indicates better quality. Table 8 displays the response table for the signal-to-noise ratio of MRR. The result shows the rank of peak current is one (delta = 6.22) and is followed by powder concentration (delta = 4.55) and pulse on time (delta = 1.67). The rank is employed to determine which variable significantly impacts the responses. The optimum machining parameters of EDM for MRR based on S/N ratios were graphite powder concentration of 6 g/l, peak current of 6 Amp and 200 µs pulse on time.

Table 7. Response and S/N ratio for MRR

Exp. No.	Powder concentration (g/l)	Peak current (Amp)	Pulse on time (µs)	Responses			Signal-to-noise (S/N) ratio (in dB)
				Material Removal Rate (MRR) (mm^3/min)		Average MRR (mm^3/min)	MRR
				MRR1	MRR2		
1	0	3	50	3.57	2.38	2.98	9.47
2	0	6	100	5.23	4.76	5.00	13.97
3	0	9	200	6.66	5.95	6.31	15.99
4	3	3	100	4.04	3.95	4.00	12.03
5	3	6	200	9.76	9.04	9.40	19.46
6	3	9	50	6.66	7.14	6.90	16.78
7	6	3	200	5.23	4.76	5.00	13.97
8	6	6	50	10.95	10.71	10.83	20.69
9	6	9	100	8.09	8.57	8.33	18.41

Table 8. Response table for S/N ratios of MRR

Level	Powder concentration	Peak current	Pulse on time
1	13.14	11.82	15.65
2	16.09	18.04	14.80
3	17.69	17.06	16.48
Delta	4.55	6.22	1.67
Rank	2	1	3

Table 10 displays the response table for the signal-to-noise ratio of Surface Roughness (SR). The result shows the rank of peak current is one (delta = 3.20) and is followed by powder concentration (delta = 1.61) and pulse on time (delta = 0.48). The optimum machining parameters of EDM for Surface roughness based on S/N ratios were powder concentration of 6 g/l, peak current of 6 Amp and 100 µs pulse on time.

Table 9. Response and S/N ratio for surface roughness

Exp. No.	Powder concentration (g/l)	Peak current (Amp)	Pulse on time (µs)	Responses			Signal-to-noise (S/N) ratio(in dB)
				Surface Roughness (SR) (µm)		Average Surface Roughness (µm)	Surface Roughness (SR)
				SR1	SR2		
1	0	3	50	4.76	4.87	4.82	-13.65
2	0	6	100	4.10	4.90	4.50	-13.06
3	0	9	200	6.70	6.20	6.45	-16.19
4	3	3	100	4.25	4.41	4.33	-12.73
5	3	6	200	4.10	4.05	4.08	-12.20
6	3	9	50	6.30	6.50	6.40	-16.12
7	6	3	200	4.05	3.90	3.98	-11.99
8	6	6	50	3.96	3.80	3.88	-11.78
9	6	9	100	5.30	5.10	5.20	-14.32

Table 10. Response table for S/N ratios of SR

Level	Powder concentration	Peak current	Pulse on time
1	-14.30	-12.79	-13.85
2	-13.69	-12.35	-13.37
3	-12.69	-15.54	-13.46
Delta	1.61	3.20	0.48
Rank	2	1	3

The main effects graphs for MRR and SR with regard to Powder Mixed Electrical Discharge Machining (PMEDM) process parameters, such as Powder concentration, Peak current and Pulse on time, are shown in Figures 5 and 6, respectively. The greater the S/N ratio corresponds, the smaller the variance of the responses around the desired value.

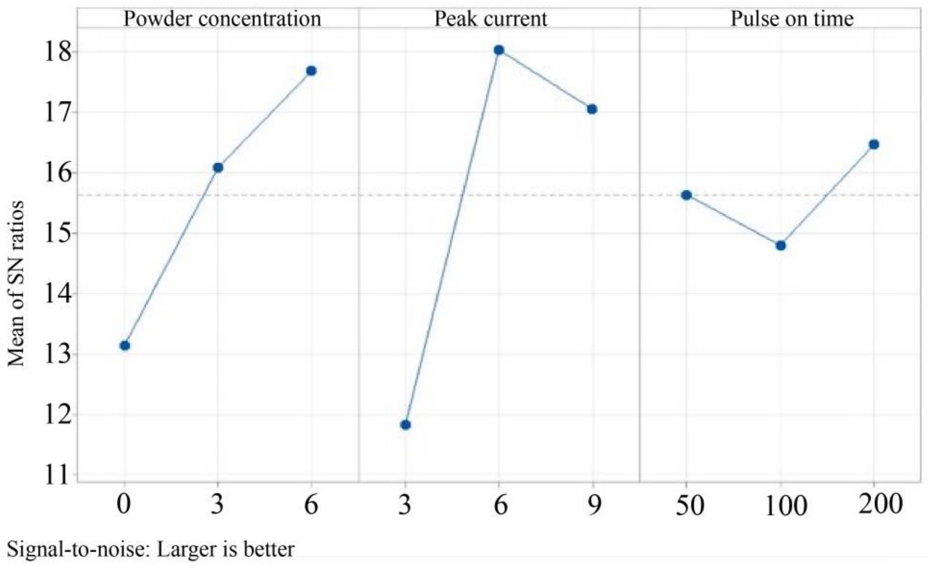


Fig. 5 Main effect plot for S/N ratio of MRR

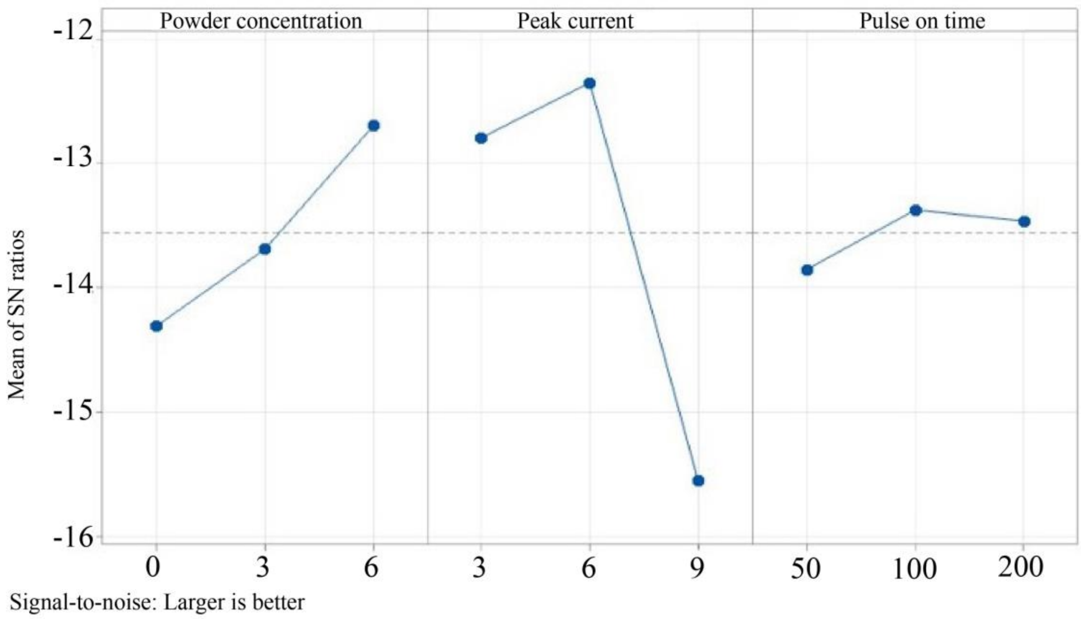


Fig. 6 Main effect plot for S/N ratio of Surface Roughness (SR)

3.2. Effects of Process Parameters on Machining Performance

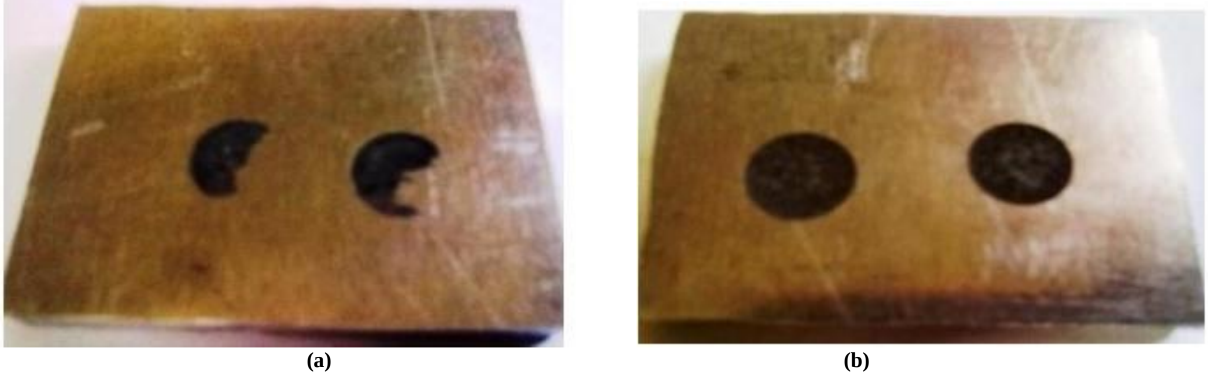
Through the analysis of experimental data and graph plots of the Powder Mixed Electrical Discharge Machining (PMEDM) process, it was seen that an increase in graphite powder concentration leads to an increase in the material removal rate, an improvement in surface quality, and greater stability of the process. The inclusion of graphite powder in the dielectric fluid leads to a reduction in the breakdown strength of the fluid. This provides wider discharge passages, which increase the discharging frequency; as a result, the Material Removal Rate (MRR) is enhanced, and the Surface Roughness (SR) is improved. In the case of peak current increases, it was observed that MRR increases, but at a higher current value, it decreases.

This is due to the fact that the peak current has a large effect on the input energy, which controls the rate of material erosion. As ions and electrons accelerate towards electrodes, they carry more energy and collide with powder particles, increasing the discharging frequency. Higher peak currents directly affect electrode functionality, making the material removal process unstable, resulting in decreased MRR and surface quality. As Pulse on time increases, it was observed that the MRR first decreases and then increases.

This can be due to the fact that at short pulse duration, less vaporization takes place, leading to lower MRR and as the value of pulse on time increases, more vaporization of the material takes place, which increases the MRR. Machining (hole making) performance on the rectangular shaped plate of Cu-Al alloy material comparison by EDM with pure dielectric and with graphite powder mixed dielectric as shown in Figure 7.

3.3. Analysis of EDM Responses

Present research includes interaction graphs depicting how three EDM process factors, graphite powder concentration in a dielectric medium, peak current, and pulse on time, correlate to MRR and surface roughness. Figures 8 and 9 display these graphs. An interaction plot Graphs demonstrate that lines are not parallel to each other, indicating a strong link between the EDM input factors and the values of MRR and surface roughness.



(a) **(b)**

Fig. 7 Machining (hole making) performance comparison by EDM (a) With pure dielectric (b) With graphite powder mixed dielectric

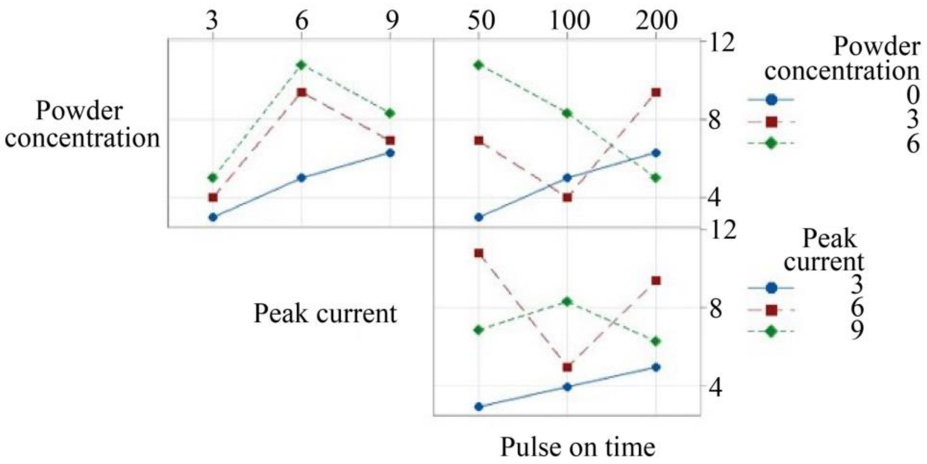


Fig. 8 Interaction plots for MRR

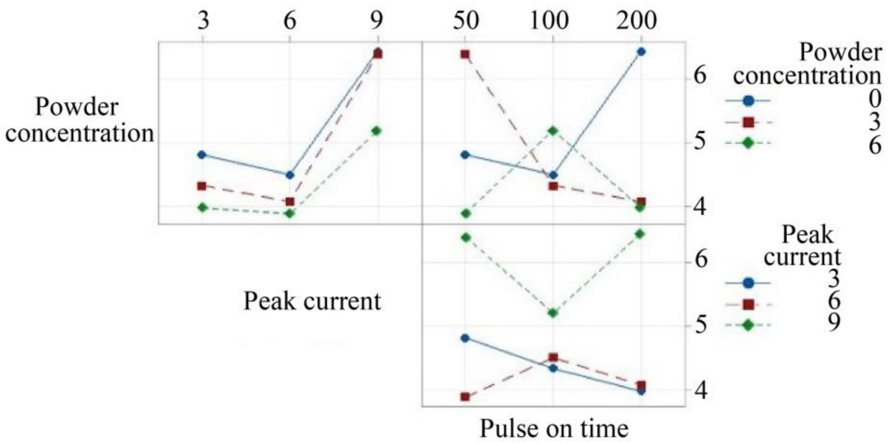


Fig. 9 Interaction plots for surface roughness

An ANOVA analysis was conducted to examine the main impact of EDM process factors on responses with a 95% confidence level. Tables 11 and 12 represent the ANOVA findings for MRR and surface roughness, respectively. In this analysis, it was shown that the graphite Powder concentration in dielectric (30.17%) and peak current (28.30%) had the greatest impact on MRR. On the other hand, the EDM input parameter Pulse on time had the least effect on MRR. Peak current (52.03%) and Powder concentration (15.72%) had the largest impact on surface roughness during electric discharge machining. Another EDM parameter, Pulse on time, had the least effect on surface roughness.

Table 11. ANOVA result for the MRR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	31.6228	58.64%	31.6228	10.5409	2.36	0.188
Powder concentration	1	16.2691	30.17%	16.2691	16.2691	3.65	0.114
Peak current	1	15.2642	28.30%	15.2642	15.2642	3.42	0.124
Pulse on time	1	0.0896	0.17%	0.0896	0.0896	0.02	0.893
Error	5	22.3081	41.36%	22.3081	4.4616		
Total	8	53.9309	100.00%				

Table 12. ANOVA for the surface roughness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5.30379	68.12%	5.30379	1.76793	3.56	0.103
Powder concentration	1	1.22402	15.72%	1.22402	1.22402	2.47	0.177
Peak current	1	4.05082	52.03%	4.05082	4.05082	8.16	0.036
Pulse on time	1	0.02895	0.37%	0.02895	0.02895	0.06	0.819
Error	5	2.48242	31.88%	2.48242	0.49648		
Total	8	7.78621	100.00%				

3.4. Regression Analysis for MRR and Surface Roughness (SR)

The regression equations for Material Removal Rate (MRR) and Surface roughness were obtained by using Statistical Software Minitab-2021 within the given range of EDM process parameters [20, 21].

Regression Equation for MRR

$$MRR = 1.50 + 0.549 * A + 0.532 * B + 0.0016 * C \quad (3)$$

Here A = powder concentration, B= peak current, C= Pulse on time, MRR= Material removal rate

Regression Equation for Surface Roughness (SR)

$$SR = 3.762 - 0.1506 * A + 0.2739 * B - 0.00091 * C \quad (4)$$

Equations (3) and (4) represent a mathematical model between EDM process parameters and the responses to MRR and surface roughness, respectively. These expressions are useful for determining the machining characteristics of the response variable for certain input process parameters of an EDM when producing the hole on the work materials. The deviation between the experimentally observed responses and the predicted outcomes is seen in Figures 10 and 11. It provides a comparison graph illustrating the experiment and mathematical model data for MRR and surface roughness, respectively.

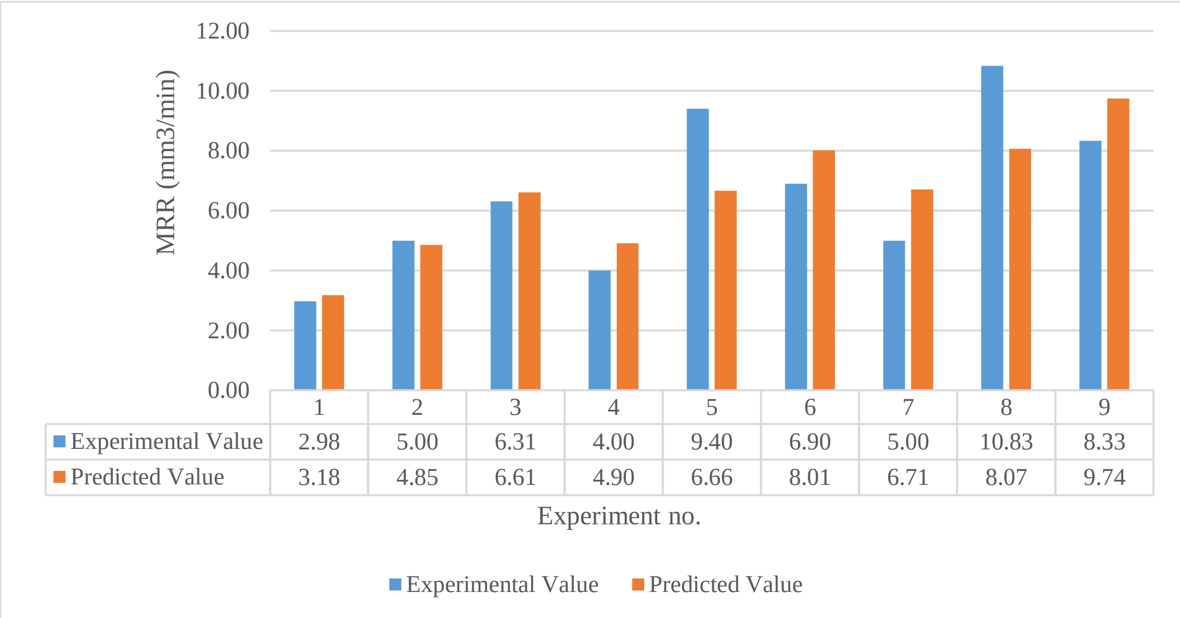


Fig. 10 Regression fit plot of experimental vs. Predicted values for MRR

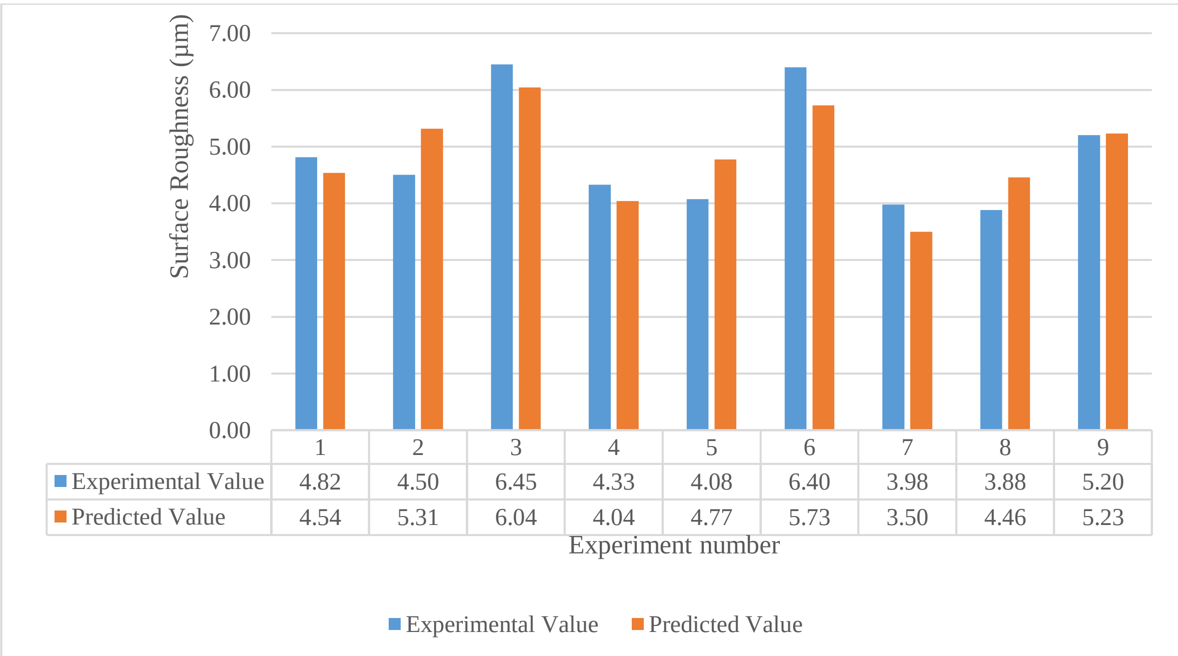


Fig. 11 Regression fit plot of experimental vs. Predicted values for surface roughness

4. Conclusion

The experimental study aimed to examine how graphite powder mixed Electrical Discharge Machining (PMEDM) process factors impact the machining characteristics of Electrical Discharge Machining of Cu-Al Alloy. Various process factors, including Powder concentration (g/l), Peak current (Amp) and Pulse on time (µs), were taken into account throughout the investigation. For optimization, the Taguchi S/N ratio technique was utilized, and experiments were planned using the Taguchi method of the L9 orthogonal array for three factors and three levels each. The obtained findings were then analyzed using ANOVA analysis and a regression model. Machining responses exhibited a Material Removal Rate (MRR) from a minimum of 2.98 mm^3/min to 10.83 mm^3/min and surface roughness from a minimum of 3.88 µm to 6.45 µm. The optimum machining parameters of EDM for MRR based on S/N ratios were graphite powder concentration of 6 g/l, peak current of 6 Amp and 200 µs pulse on time. The optimum machining parameters of EDM for Surface roughness based on S/N ratios were powder concentration of 6 g/l, peak current of 6 Amp and 100 µs pulse on time. The study reveals that increasing graphite powder concentration in the PMEDM process enhances material removal rate, surface quality, and stability. The ANOVA analysis revealed that the graphite Powder concentration in dielectric (30.17%) and peak current (28.30%) had the greatest impact on MRR.

On the other hand, the EDM input parameter Pulse on time had the least effect on MRR. Peak current (52.03%) and Powder concentration (15.72%) had the largest impact on surface roughness during electric discharge machining. Another EDM parameter, Pulse on time, had the least effect on surface roughness. A linear regression model was used to establish mathematical equations between the machining responses and process parameters of graphite powder mixed Electrical Discharge Machining Cu-Al Alloy.

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