EVALUATION OF EDM PROCESS PARAMETERS ON HYBRID ALUMINIUM COMPOSITE REINFORCED WITH SiC AND BN

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Abstract

Using stir casting and electric discharge machining (EDM), a hybrid metal matrix composite was created for this study, consisting of Al7075 reinforced with 8% SiC and 4% BN. Tool wear and material removal behaviour were examined in relation to process variables like current, pulse lengths, and electrode gap. Using a Taguchi L9 orthogonal array, an ANOVA study was conducted. Out of all the responses, punctuality was the most critical factor. This work highlights the potential of EDM for sustainable, complex composite processing, extending beyond machining performance, and recommends future adaptation with treated electrodes and powder-mixed dielectric fluids for increased efficiency.

Keywords

Non-conventional Machining, Boron Nitride (BN), Taguchi Method, Hybrid Aluminium Composites

1. Introduction

Modern sectors, such as the automotive and aerospace industries, are increasingly relying on lightweight materials that offer exceptional strength and durability. Reinforcing aluminium 7075 with ceramic particles can further improve its performance, making it the preferred alloy for such applications. Hybrid metal matrix composites (HMMCs) provide enhanced hardness, wear resistance, and thermal stability by combining reinforcements such as silicon carbide (SiC) and boron nitride (BN). However, the abrasive character of these composites makes them challenging to manufacture using traditional techniques. Hard materials can be handled non-contact with Electric Discharge Machining (EDM) as it has emerged as a preferred non-traditional process for these materials, which removes the material through controlled thermal erosion without direct mechanical contact. Factors such as discharge current, pulse length, and electrode gap have a significant impact on the process's effectiveness. In this work, an Al7075–SiC–BN hybrid composite is examined for EDM machinability. The effects of input parameters on MRR, TWR are investigated using an experimental design based on Taguchi. The work provides insights into performance trends, parameter optimisation, and the feasibility of EDM for precision machining of advanced hybrid materials.

2. Literature Survey

The enhanced mechanical and thermal properties of hybrid metal matrix composites have drawn interest. These materials are challenging for traditional machining due to their low surface quality and excessive tool wear. Numerous studies have been conducted to optimise EDM's characteristics for efficient machining of advanced composites since it presents a viable solution. The effectiveness of cryogenically treated electrodes during EDM of metal matrix composites based on aluminium was examined by N. K. Singh et al. [1]. Their research demonstrated that cryogenic treatment enhanced the electrical conductivity and thermal stability of the tool material, leading to a substantial increase in tool life and surface integrity. A. Kumar et al. [2] used graphene nanoparticle-reinforced aluminium alloy to conduct experimental research on powder-mixed EDM (PMEDM). They found that the dielectric's suspended conductive particles enhanced MRR and decreased surface microcracks, indicating that PMEDM is a successful technique for challenging-to-machine MMCs. The application of dielectrics based on vegetable oil in EDM of aluminium composites has been investigated by R. Sharma et al. [3]. Their research, which emphasised sustainability, demonstrated that, in comparison to conventional EDM oil, bio-dielectrics produced superior surface finishes with less adverse environmental impact. To optimise the machining settings for EDM of SiC-TiC reinforced aluminium composites, J. Patel and K. Bhoi [4] employed the Taguchi-grey relational technique. Their method of multi-response optimisation proved effective in reducing both surface roughness and tool wear simultaneously. Response surface methodology (RSM) was employed by M. Z. Hossain et al. [5] to model and optimise the EDM process of Al7075 composites. The importance of the interaction effects between pulse duration and current on MRR and SR was demonstrated by their regression models. A comparison between dry EDM and conventional EDM for the machining of aluminium hybrid composites was carried out by S. B. Deshmukh et al. [6]. According to the study's findings, dry EDM reduced electrode wear and produced a cleaner surface, although at the expense of poorer MRR. The impact of nanoscale TiO_2 and graphite particles in dielectric fluid for machining Al6061 composites has been studied by T. Nguyen et al. [7]. The results showed that improved dielectric characteristics led to significant improvements in surface shape and spark stability. A numerical simulation of thermal erosion during EDM of hybrid composites was conducted by K. R. Patel et al. [8]. Their FEM-based approach enhanced our understanding of wear mechanisms by illuminating thermal stress distribution and crater formation. K. Shiva Kumar et al. [9] focused on optimising the mechanical and wear characteristics of Nylon-6 composites enhanced with boron nitride using the Taguchi approach. Findings revealed a decline in tensile strength with higher BN content, while wear resistance improved. Some researchers have conducted work in various areas[10-12]. Although most researchers have focused on single-reinforced composites, hybrid composites, such as Al7075-SiC-BN, have been insufficiently studied. This study aims to fill the gap by examining the influence of key EDM parameters on the machinability of an Al7075 hybrid composite reinforced with 8% of SiC and 4% of BN.

3. Methodology

Al7075 was reinforced with 8% SiC and 4% BN using electromagnetic stirring to ensure even dispersion. Using EDM oil as the dielectric fluid and a copper tool, EDM trials were carried out. After an L9 orthogonal array, key machine parameters, such as current, pulse lengths, and electrode gap, were systematically adjusted. To calculate MRR and TWR, the material loss from the workpiece and electrode was measured after machining. For optimal accuracy, all experiments were set up and maintained with the same polarity.

3.1 Selection of Materials

In this investigation, an Al7075 matrix reinforced with 8% silicon carbide (SiC) and 4% boron nitride (BN) by weight was used. The Al7075 alloy was selected for this investigation due to its exceptional mechanical properties, particularly its high strength-to-weight ratio. Silicon Carbide (SiC) powder, approximately 60 µm in size (Fig. 2), and Boron Nitride (BN) micro powder, approximately 5 µm in size (Fig. 1), were selected due to their hardness, resistance to wear, and thermal stability.

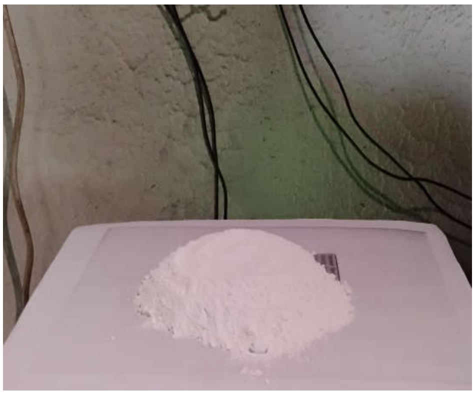

Fig 1: Boron Nitride Micro powder

Fig 2: Silicon Carbon Micro Powder.

The electromagnetic stir casting method, chosen for its excellent process reliability and low cost of producing a homogeneous dispersion of reinforcements, was used to manufacture the hybrid composite. Utilising a graphite crucible (Fig. 3), the Al7075 alloy was melted in an induction furnace at a regulated temperature of 700–710°C. A 600 Hz electromagnetic field was used to agitate the molten metal at 3,000 rpm to ensure homogeneity. This allowed for even particle distribution through motion generated by the Lorentz force. After that, the material was put into a 120 x 120 x 25 mm cast iron mold (Fig. 4) that had been heated and allowed to harden naturally.

Fig 3: Graphite Crucible

Fig 4: Cast Iron Die Mold

3.2 Selection of Parameters and Experimental Set-up

Since output responses directly affect machining performance, four machining settings were considered in this work: current, pulse on time (Ton), pulse off time (Toff), and electrode gap. These settings were chosen because they control discharge duration, spark energy, and flushing efficiency. A structured Taguchi technique was employed, utilising an L9 configuration, to examine their impact systematically. This method optimises machining conditions and reduces experimental effort and cost by allowing for the efficient examination of four control factors at three levels with just nine experimental runs. Table 1 displays the machining conditions and their corresponding levels, while Table 2 provides an overview of the entire trial setup.

Table 1: Machining input parameters and their levels

Machining variables	Level 1	Level 2	Level 3
Current (A)	12	16	20
Pulse on time T_{on} (μs)	100	200	300
Pulse off T_{off} (μs)	50	70	90
Electrode Gap (mm)	0.1	0.2	0.4

Table 2: Experimental runs based on L9 orthogonal array

Trial Number	Current (A)	Pulse on time T_{on} (μs)	Pulse off time T_{off} (μs)	Electrode Gap (mm)
1	12	100	50	0.1
2	12	200	70	0.2
3	12	300	90	0.4
4	16	100	70	0.4
5	16	200	90	0.1
6	16	300	50	0.2
7	20	100	90	0.2
8	20	200	50	0.4
9	20	300	70	0.1

3.3 Experimental Procedure

With the process variables arranged according to a Taguchi design technique, a series of machining operations was carried out using a die-sink electrical discharge machine (Fig. 5). Before machining, the EDM machine was thoroughly cleaned, and all instruments were calibrated. Throughout all experimental runs, a copper electrode with a 12 mm diameter (Fig. 6) served as the cutting tool, while EDM oil served as the dielectric. The tool and target material were attached to the negative and positive terminals, respectively, in a typical polarity arrangement. The control panel's settings were meticulously established for each run. The material was degraded one after the other by a rapid electric discharge between the tool and the sample, while submerged in an insulating liquid. A precise balance was used to weigh the work piece before and after machining (Fig. 7) for each of the nine runs, and it was then cleaned with acetone. Both the TWR and the MRR were recorded. Calculating the difference in specimen weight before and after each test allowed us to calculate the rate at which material separated. The weight loss of the copper electrode during each machining operation was used to calculate the tool's rate.

$$MRR = \frac{Initial\ weight\ of\ work\ piece - Final\ weight\ of\ work\ piece}{Time}\ g/min$$

$$TWR = \frac{Initial\ weight\ of\ tool - Final\ weight\ of\ tool}{Time}\ g/min$$

Fig 5: Die sink EDM machine

Fig 6: 12 mm dia Copper electrode

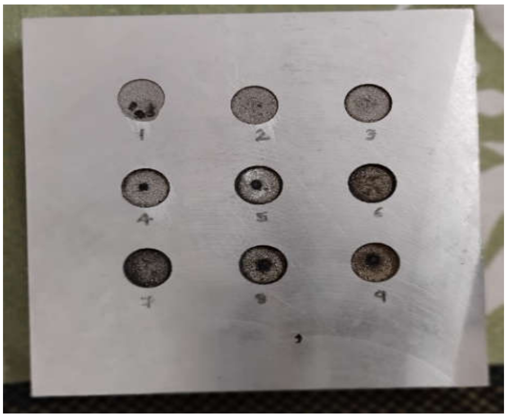

Fig. 7: Machined workpiece

4. Experimental results

Experiments conducted on the Al7075–SiC–BN hybrid composite using the modified Taguchi L9 array revealed significant variation in machining performance based on input parameters. The highest material removal rate (MRR) recorded was 0.0432 g/min, achieved at a discharge current of 20 A and a pulse on time of 300 µs. This increase in MRR is linked to the higher energy input per spark, which intensified the thermal erosion process. The same setting also resulted in the maximum tool wear rate (TWR) of 0.0066 g/min, due to prolonged spark exposure and increased electrode melting. Detailed output responses for all trials are presented in Table 3.

Table 3: Experimental results based on Taguchi L9 design

Experiment number	Current (A)	Pulse on time (µs)	Pulse off time (µs)	Electrode gap (mm)	MRR (g/min)	TWR (g/min)
1	12	100	50	0.1	0.0102	0.0012
2	12	200	70	0.2	0.0145	0.0017
3	12	300	90	0.4	0.0181	0.0021
4	16	100	70	0.4	0.0136	0.0016
5	16	200	90	0.1	0.0229	0.0028
6	16	300	50	0.2	0.0423	0.0062
7	20	100	90	0.2	0.0158	0.0018
8	20	200	50	0.4	0.0402	0.0057
9	20	300	70	0.1	0.0432	0.0066

4.1 ANOVA analysis

Minitab version 19 was used for this analysis to statistically evaluate the significance of each machining variable on performance metrics. For each parameter, the percentage influence, average variation (Mean Square), and total variance (Sum of Squares) were calculated at a 95% level of statistical confidence (α=0.005). Taguchi L9's orthogonal experimental design guaranteed full utilisation of these chosen process inputs in relation to the corresponding degrees of freedom. The percentage contribution was taken into consideration for assessment since residual error was excluded from the analysis, and the related F-values and P-values were not appropriately expressed. With 46.55% of the total variation, pulse on time had the most significant impact on MRR. This demonstrates that longer discharge times permit more energy to be transferred per pulse, resulting in more effective and profound material degradation. With a contribution of 30.81%, Current came in second. Elevated current levels improve eroding capabilities by intensifying sparks. Due to its moderate impact on spark frequency, the pulse off time contributed 20.51%. Reduced cooling time but increased spark rate are the results of shorter off times. With a small contribution (2.11%), the electrode gap has little impact on MRR within the chosen range. These results reveal that MRR is very sensitive to spark energy parameters (current and pulse on time), which must be prioritised for optimising productivity. With a 55.58% contribution, pulse on time was found to be the most significant element for tool wear. Longer pulses accelerate electrode wear by exposing the instrument to continuous heat stresses. The current had a 25.78% influence, suggesting that it plays a role in increasing the spark's strength and, in turn, the electrode's thermal stress. Increased cooling time between pulses helps prevent tool degradation, as evidenced by the 15.59% pulse-off time. In line with the MRR results, electrode gap once more had a negligible effect (2.71%). These findings demonstrate that thermal variables are the primary cause of tool wear and that controlling electrode degradation requires optimising pulse timing and current.

Table 4: ANOVA summary for the influence of EDM parameters on MRR

Source	DF	Seq SS	Adj SS	Adj MS	Contribution
Current	2	64.002	64.002	32.001	30.81%
Pulse on time	2	96.730	96.730	48.365	46.55%
Pulse off time	2	42.621	42.621	21.310	20.51%
Electrode gap	2	4.392	4.392	2.196	2.11%
Total	8	207.745	-	-	-

Table 5: ANOVA table showing the effect of process variables on TWR

Source	DF	Seq SS	Adj SS	Adj MS	Contribution
Current	2	58.870	58.870	29.435	25.78%
Pulse on time	2	126.930	126.930	63.465	55.58%
Pulse off time	2	35.580	35.580	17.790	15.59%
Electrode gap	2	6.180	6.180	3.090	2.71%
Total	8	227.560	-	-	-

4.2 S/N analysis

The hybrid composite's EDM performance was improved by using this analysis related to the Taguchi L9 orthogonal array. Using an orthogonal array and the fewest number of experimental trials possible, the most essential input machining factors were identified.

Equations for the S/N ratio approach

Given that the material removal rate improves machining efficiency, a larger value is preferred.

S/N ratio = -10log10(sum(1/Y^2n)

TWR should be as small as possible, as lower values result in less tool deterioration.

S/N Ratio = -10log10(sum(Y^2n)

With Delta = 8.27, pulse on time is the most significant component, suggesting that longer pulse durations increase MRR by producing deeper craters and more spark energy. With a delta of 7.02, current is the second most important parameter. More energy is given with an increase in current, which promotes faster material degradation. Pulse off time has a moderate impact on MRR. Reduced off-time improves MRR by increasing discharge frequency. Spark spacing had a negligible effect on the overall removal rate within the studied range, as indicated by the minimal impact of electrode gap on MRR (Delta = 0.41). The most significant influence is pulse on Time (Delta = 9.47), indicating that longer discharge times result in higher thermal loads and accelerate electrode deterioration. Second place goes to pulse off time (Delta = 9.31). Wear is increased by shorter off times since they don't give sparks enough time to cool. TWR is moderately impacted by current (Delta = 6.54). Increased currents raise the temperature of the spark, which somewhat accelerates tool deterioration. The electrode gap is small (Delta = 0.83), and its effect on TWR is insignificant. Current = Level 3 (20 A) and pulse on time = Level 3 (300 µs) are optimal for the highest MRR. Pulse on time = Level 1 (100 µs) and pulse off time = Level 3 (90 µs) are the ideal values for the minimal TWR. S/N ratio tables are provided below.

Table 6: S/N based evaluation for Material removal

Level	Current	Pulse on time	Pulse off time	Electrode gap
1	-37.93	-38.45	-31.80	-33.94
2	-33.45	-33.66	-34.05	-34.01
3	-30.95	-30.18	-36.44	-34.35
Delta	7.02	8.27	4.64	0.41
Rank	2	1	3	4

Table 7: Signal-to-Noise ratio analysis of tool wear

Level	Current	Pulse on time	Pulse off time	Electrode gap
1	56.42	58.55	49.20	52.61
2	52.55	51.22	51.14	52.80
3	49.88	49.08	58.51	53.44
Delta	6.54	9.47	9.31	0.83
Rank	3	1	2	4

4.3 Regression models

To assess the impact of machining variables on performance outcomes, a statistical modelling approach was used. Regression techniques were employed to develop second-degree polynomial equations, enabling the investigation of this correlation. The coefficient of determination (R^2) was used to assess the efficacy of each model. For every response, the models displayed a high degree of fit ($R^2 = 1.00$). However, additional validation was necessary because the limited dataset ($n = 9$) revealed potential overfitting. SR was susceptible to interaction effects between the electrode gap and pulse parameters. Below are the output parameters of the predicted regression equations.

MRR = -0.0021 + 0.00182 x current + 0.000104 x pulse on time – 0.00037 x pulse off time – 0.0051 x electrode gap

TWR = -0.00029 + 0.00026 x current + 0.000017 x pulse on time – 0.000054 x pulse off time – 0.00073 x electrode gap

4.4 Main Effect Plot Analysis

The main effect plot, a statistical technique used to demonstrate the distinct influence of each process parameter on the response metrics, is created in Minitab software. These charts aid in visualising how changes in process variables independently impact results in the context of EDM. Unlike interaction or contour plots, which focus on multiple variables simultaneously, main effect plots clearly illustrate the influence of a single factor. These plots can be used in this study to identify the most critical parameters, which help optimise HMMC machining quality and performance.

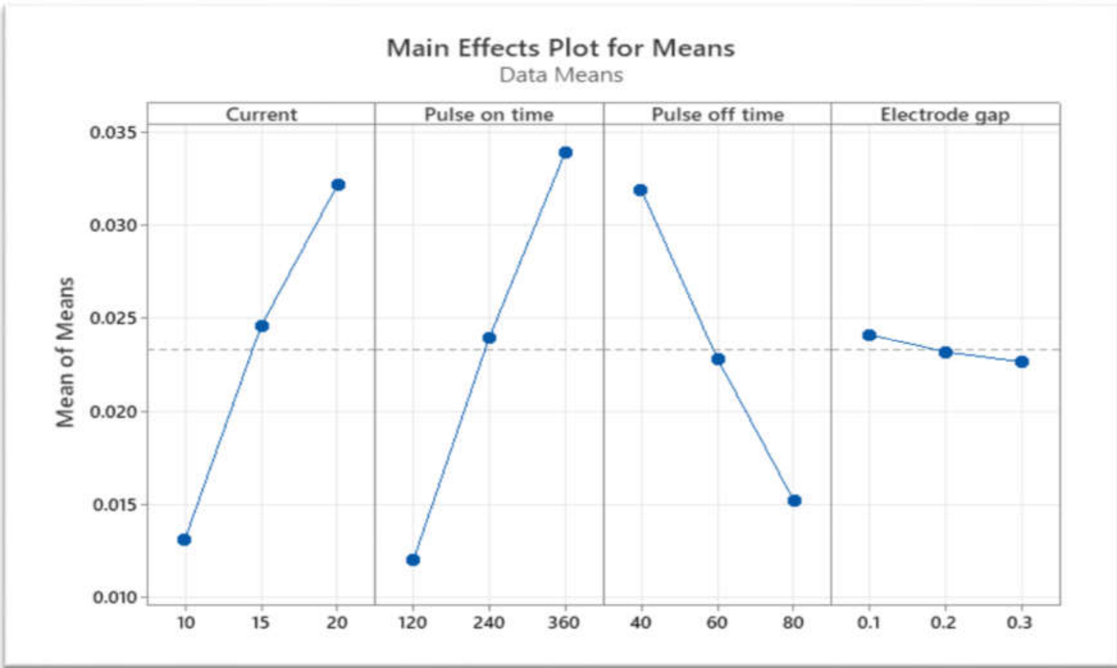

Figure 8: Main effect plots for MRR

The MRR (Fig. 8) exhibits a distinct upward trend as the discharge current increases and the pulse-on time grows. Because larger discharge energy causes more intense erosion, MRR greatly improves when the current rises from 12 A to 20 A. Likewise, there is a noticeable improvement in MRR when the pulse on time is increased from 100 µs to 300 µs, demonstrating the significance of spark length in improving material removal. With longer intervals between discharges, the spark frequency and energy input per unit time decrease, resulting in a modest decline in MRR as the pulse off time increases. Within the tested range (0.10 mm to 0.40 mm), the electrode gap has a marginal influence, resulting in slight changes, which suggests that spark concentration is mainly unaffected by gap distance under the specified conditions.

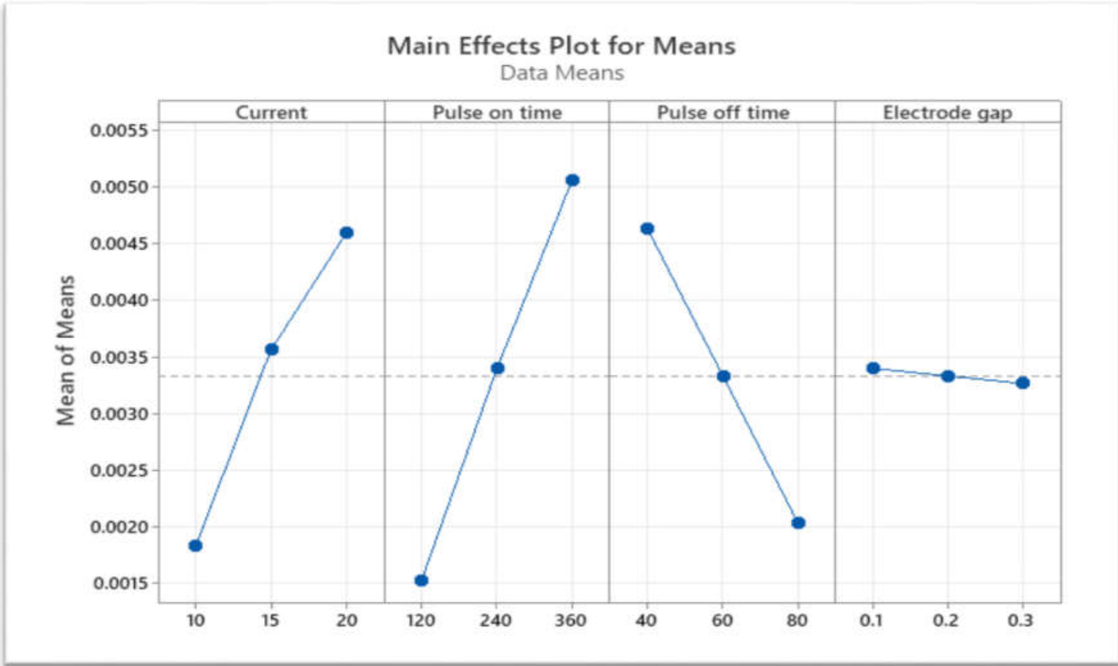

Figure 9: Main effect plots for TWR

Pulse on time again becomes the most critical factor for TWR (Fig. 9). The electrode material softens and degrades with continuous exposure to high heat loads, which is why tool wear increases sharply when the time is increased from 100 µs to 300 µs. Current shows a similar upward pattern, as higher current increases electrode degradation and intensifies the discharge. Pulse off time has an inverse relationship with TWR; larger values encourage better heat dissipation between discharges, which minimises wear and lowers thermal stress on the electrode. As evidenced by TWR's minimal variation among levels and its negligible contribution in ANOVA, the electrode gap's influence remains comparatively small.

5. Conclusion

An Al7075-based hybrid composite reinforced with 8% SiC and 4% BN, created using electromagnetic stirring during the casting process, was the subject of this study's investigation into the performance of Electric Discharge Machining (EDM). To examine the impact of machining parameters, such as current, idle time between pulses, and electrode spacing, on the final performance metrics, this study employed Taguchi and ANOVA approaches. The most significant components were pulse on time and current. Increased TWR and improved MRR were achieved through longer pulses and higher current levels. The regression models demonstrated strong predictive performance, with R^2 values approaching 1.00. With pulse duration accounting for more than 46% of MRR and 55% of TWR, ANOVA and S/N ratio analyses corroborated these results. The highest TWR of 0.0064 g/min and the maximum MRR of 0.0430 g/min were measured at 20 A and 300 µs. Both responses showed little effect from the electrode gap. These results demonstrate that EDM is a successful method for cutting complex hybrid composites and serve as a foundation for upcoming multi-objective optimisation and environmentally friendly machining modifications.

Future Work

Powder-mixed EDM may be used in future research to enhance surface polish and MRR. Cryogenically treated electrodes could improve accuracy and lessen tool wear. After machining, microstructural changes can be seen using SEM and XRD investigation. Investigating environmentally friendly dielectrics is necessary for sustainable EDM. ANNs and other AI-based models can optimise multi-response machining settings.

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