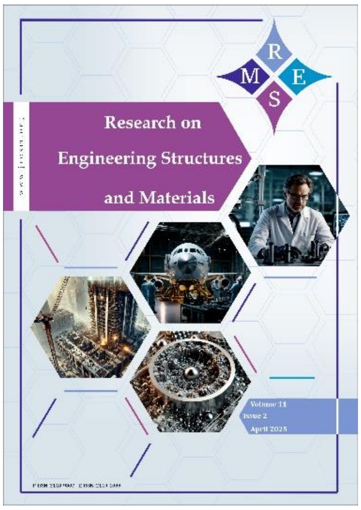
Research on Engineering Structures & Materials
www.jresm.org
Research Group



Analysis of machining performance in ECDM of Al6061-SiC-B4C hybrid composites: Experimental study and statistical modeling

Safa M. Lafta, Abbas F. Ibrahim

URL: http://www.jresm.org/archive/resm2025-1257ic1013rs.html
DOI: http://dx.doi.org/10.17515/resm2025-1257ic1013rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Lafta S M, Ibrahim A F. Analysis of machining performance in ECDM of Al6061-SiC-B4C hybrid composites: Experimental study and statistical modeling. *Res. Eng. Struct. Mater.*, 2026; 12(2): 917-929.

Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Analysis of machining performance in ECDM of Al6061-SiC-B_4C hybrid composites: Experimental study and statistical modeling

Safa M. Lafta *,[a], Abbas F. Ibrahim [b]

Department of Production Engineering, University of Technology, Iraq

Article Info

Article History:

Received 13 Oct 2025

Accepted 05 Dec 2025

Keywords:

Electrochemical discharge machining);
Al6061-SiC-B4C hybrid composites;
Material removal rate;
Tool wear rate

Abstract

This work uses Electrochemical Discharge Machining (ECDM) to investigate the machining performance of Al6061-4%SiC-8%B4C hybrid composites. The study investigates how Material Removal Rate (MRR), Tool Wear Rate (TWR), and hardness are affected by voltage, electrolyte concentration, pulse-on time, and pulse-off time. For statistical modeling, an ANOVA and a Taguchi L9 orthogonal array were employed. Results indicate that higher voltage significantly enhances MRR and increases TWR, while optimizing pulse parameters improves machining efficiency. Increased hardness (165 HV) with the addition of 4% SiC and 8% B4C improved machining stability and wear resistance. Because it offers a balanced strategy for raising MRR while controlling TWR and tool life, ECDM is a practical technology for machining hybrid composites in aerospace and automotive applications. Future research should investigate better electrode materials and electrolyte modifications to further increase machining performance. While ECDM shows promise for hard-to-machine materials, the specific interaction and performance analysis of this technique on the Al6061matrix reinforced with the hybrid combination of SiC and B4C has not been systematically investigated, leaving a gap in optimizing the process parameters for industrial application. The results showed that the optimal processing conditions achieved a maximum Material Removal Rate MRR of 4.25 g/min, representing 32% improvement compared to the least effective parameters. Furthermore, the statistical model confirmed that Voltage is the most significant factor, contributing to approximately 78.5% of the total MRR variation, while TWR was effectively controlled to a minimum of 0.012 g/min under specific pulse conditions.

1. Introduction

All The increasing demand for micro-scale items across a wide range of scientific and technological sectors has led to advancements in production processes. Traditional methods for working with electrically conductive materials, such as electric discharge machining (EDM) and electrochemical machining (ECM), work well. They are less effective with non-conductive materials since they require setups. One of the hybrid technologies that have evolved to address this issue is electrochemical discharge machining (ECDM) [1]. Composite materials, which are created by combining two or more constituents with differing physical and chemical properties, have distinct qualities that cannot be obtained in single materials [2]. A hybrid metal matrix composite (HMMC) is generated when a metallic matrix comprises multiple reinforcements. Although they make machining more difficult and complex, reinforcements like silicon carbide (SiC), boron carbide (B_4C), and aluminum oxide (Al_2O_3) improve the mechanical and tribological properties of composites [3–8]. Yan et al. [9] investigated how machining parameters affected composites

---

*Corresponding author: pme.20.88@grad.uotechnology.edu.iq
[a] orcid.org/0009-0007-5334-9168
DOI: http://dx.doi.org/10.17515/resm2025-1257ic1013rs

containing a high SiC concentration. High wire tension and excessive pulse-off time (Poff) lowered surface quality and efficiency, but longer pulse-on time (Pon) boosted MRR.

Similarly, Ibrahim et al. [10,11] used Taguchi approaches to control electrolyte concentration, voltage, and inter-electrode gaps in electrochemical machining (ECM) in order to balance and improve MRR while sacrificing surface quality. Furthermore, their findings show that greater energy discharge during electrical discharge machining (EDM) enhances the MRR in hybrid composites. Mandal et al. [12] investigated the use of electrolytes with NaOH and A2lO3 for powder-mixed ECDM (PMECDM) and micro-ECDM (μ-ECDM) in machining maraging steel. PMECDM demonstrated the benefits of A2lO3 powder by raising MRR by 34% and reducing surface roughness (Ra) by 21% [12]. Kannan et al. [13] investigated the WEDM of recycled Al alloy MMC with 5% alumina reinforcement, concentrating on voltage, feed rate, current, pulse-on, and pulse-off times. ANOVA and CRITIC analysis identified optimal values for high MRR and low Ra as 30V, 7mm/min feed rate, 30A current, 120μs pulse-on-time, and 70μs pulse-off-time. When Gugulothu et al. [14] milled Al5086/flyash/SiC hybrid composites, they investigated ECM factors such as feed rate, voltage, and electrolyte concentration. They discovered that, whereas electrolyte content had little impact, MRR rose with feed rate and voltage.

Ahmadinia et al. [15] studied how discharge current affects material removal rate (MRR) and electrode wear rate (EWR) in powder-mixed EDM and EDM for B4C-reinforced Al2014 MMCs. Powders were employed to reduce EWR, boost MRR, and enhance machining stability [15]. Kiran and Satyanarayana [16] improved die-sinking EDM techniques for hybrid metal matrix composites by increasing peak current and pulse-on duration to enhance MRR, TWR, and Ra [16]. Mohankumar et al. [17] optimized EDM settings for Al7075/B4C composites using the Taguchi technique, resulting in an MRR of 0.5628 mm^3/min, TWR of 0.0048 mm^3/min, and Ra of 4.4034 μm. They discovered that Ra, TWR, and MRR rose when Pon and current levels increased [17]. Arunachalam et al. [18] examined the EDM parameters for magnesium-based hybrid composites (AZ31 alloy with 5% MoS2 and 5% B4C). Optimal values were found to improve MRR and TWR, emphasizing the composite's low density and durability [18]. Given the preceding premise, the research focused mostly on boosting the MRR. Furthermore, the findings' scalability and applicability to various materials and machining circumstances is limited. To close these gaps, the current study seeks to establish accurate correlations between machining factors (such as voltage and electrolyte concentration) and their combined effect on surface integrity. Despite the potential of ECDM for hard-to-machine materials, a significant research gap remains in the systematic and optimized analysis of this technique on the specific Al6061 hybrid composite reinforced with SiC and B4C. Therefore, this study presents the first comprehensive experimental and statistical analysis, utilizing the Taguchi L9 array and ANOVA, to model and optimize the machining performance MRR and TWR of this material. The findings show that optimal conditions yielded a maximum MRR of 4.25 g/min, representing 32% improvement, with TWR effectively controlled to a minimum of 0.012 g/min. The statistical model confirmed that Voltage is the most significant factor, contributing approximately 78.5% to the total MRR variation. This contribution establishes a crucial reference for applying ECDM in the manufacturing of high-performance hybrid composites.

2. Experimental Work

2.1. The Workpiece

This study looks at a hybrid composite material made of Al6061 alloy reinforced with 4 wt% silicon carbide (SiC) and 8 wt% boron carbide (B4C). Analyzing the chemical compositions of the hybrid composite and foundation material enabled precise material characterization. The chemical analysis of the Al6061, which was created by the Ministry of Industry and Minerals and the State Company for Inspection and Engineering Rehabilitation (SIER) in Baghdad, Iraq, is displayed in Table 1. Optical emission spectroscopy (OES) was used to collect data for thorough chemical analysis. The addition of SiC and B4C reinforcements to the aluminum matrix, together with the precise atomic and weight percentages of the constituent elements, are all confirmed by this study. These analyses were conducted at the Al-Khoura Company in Baghdad. Table 2 lists the mechanical and physical characteristics of the Al6061 base alloy that was investigated at the University of

Technology, Iraq/Baghdad's Material Engineering Department. Fig. 1 shows the procedure of the experimental work

Table 1. The chemical analyses of Al6061

Element	Weight%	Element	Weight%
Si%	0.620	Ni%	0.0055
Fe%	0.117	Zn%	0.0030
Cu%	< 0.300	Ti%	0.0106
Mn%	0.0009	V%	0.0165

Table 2. The physical and mechanical properties of the used Al6061

Property	Unit	Values
density	g/cm^3	2.705
Hardness	HV	108
Ultimate tensile strength	MPa	305
Elongation	%	11.8
Modulus of Elasticity	GPa	68.5
Poisson’s Ratio	--	0.32
Melting Temperature	° C	585-650
Shear Strength	MPa	205
Shear Modulus	GPa	25.8

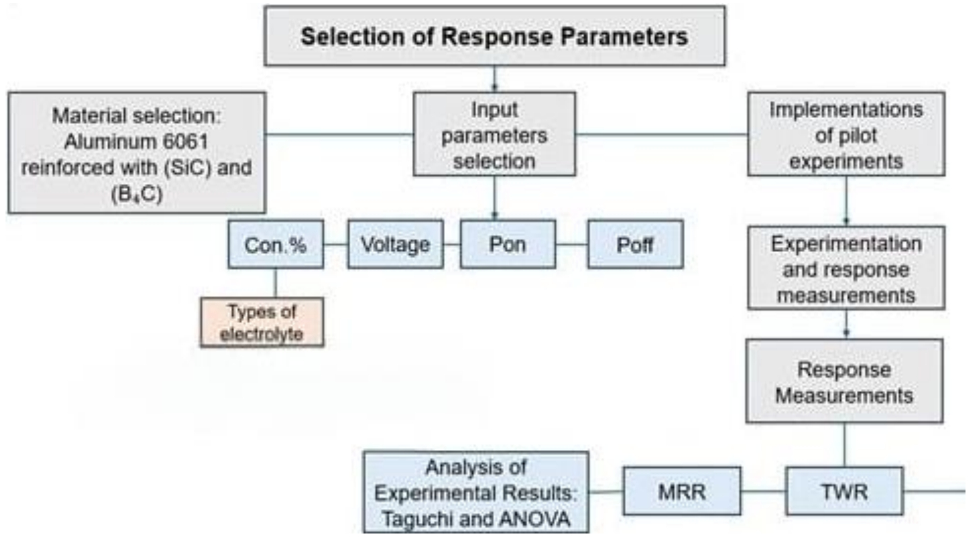


Fig. 1. The procedure of the experimental work

2.2. The Stir-Casting Process

Stir-casting technology, known for its capacity to offer consistent distribution of reinforcements inside a metal matrix, was used in the development of the hybrid composite material. The Al6061 alloy is melted in a graphite crucible at 700 ºC. In addition, 4 weight percent SiC and 8 weight percent B4C powders were gradually added to the molten aluminum while it was agitated for 10 minutes at 500 rpm with a mechanical stirrer. This stirring ensured a homogeneous dispersion of reinforcement particles throughout the matrix. The molten composite was then placed in a steel mold (50mm in length and 30 mm in diameter) and allowed to cool naturally at ambient temperature before solidification. For additional research and testing, the solidified castings were subsequently milled to the necessary specifications. Fig. 2 illustrates the stir-casting process.

Fig. 2. The stir-casting technique

(a) (b)

Fig. 3. (a) Workpiece before machining and (b) after machining

Essentially, the strength of the interfacial bonding between the reinforcement and the matrix phase has a major impact on the characteristics of metal matrix composites (MMCs) [19]. Fig. 3 depicts the specimens before and after machining, cut to the desired dimensions of 5 mm in thickness and 30 mm in diameter. Table 3 displays the chemical composition of the composite Al6061-4%SiC-8%B4C that was determined using energy-dispersive X-ray spectroscopy (EDX) at the Al-Khoura company, Iraq/Baghdad. Table 4 displays the mechanical properties of the Al6061-4%SiC-8%B4C hybrid composite that were investigated in the Material Engineering Department at the University of Technology, Iraq/Baghdad.

Table 3. The chemical composition of Al6061-4%SiC-8%B4C

Element	Atomic%	Atomic % Error	Weight%	Weight% Error
B	10.3	0.6	5.1	0.3
C	21.7	0.4	11.8	0.2
O	1.7	0.1	1.2	0.1
Mg	0.2	0.0	0.3	0.0
Al	65.2	0.2	80.0	0.3
Si	0.6	0.0	0.8	0.0
Fe	0.2	0.0	0.4	0.0
Zn	0.1	0.0	0.4	0.1

Table 4. The mechanical properties of Al6061-4% SiC- 8% B4C.

Property	Unit	Values
Density	g/cm^3	2.75
Hardness	HV	165
Ultimate tensile strength	MPa	160
modulus of elasticity	GPa	75
Yield strength	MPa	110
Elongation	%	10

2.3. The Electrode

The cylindrical copper electrode (50 cm in length, 10 mm in diameter) was employed in the machining process because of its thermal conductivity, high electrical, easx5e of machining, and high melting point (1083°C), all of which affect tool wear. After each process, the electrode was cleaned by washing it with water and drying it to remove any sludge adhered to its surface. At the State Corporation for Inspection and Engineering Rehabilitation (SIER)/ Ministry of Industry and

Minerals in Baghdad, Iraq, electrode copper was examined to ascertain its chemical analysis, as shown in Table 5.

Table 5. The chemical analyses of the copper electrode

Element	Weight %
Zn%	0.0038
Pb%	0.0011
Sn%	0.0025
P%	0.0007
Fe%	0.0482
Cr%	0.0008
Sb%	0.0121
As%	0.0007
Al%	0.0152
S%	0.0013
Cu%	Bal.

2.4 Electrochemical Discharge Machining (ECDM)

The ECDM was utilized to machine the hybrid composite material Al6061 reinforced with 4% wt SiC and 8% wt B4C, chosen for its efficiency in handling complex materials [20–24]. An acrylic tank, a power source, and a computer system constitute the ECDM setup. Furthermore, the electrolyte in this procedure was sodium chloride (NaCl). During operation, the workpiece functions as the anode, while the tool acts as the cathode. The components of the ECDM system are illustrated in Fig. 4.

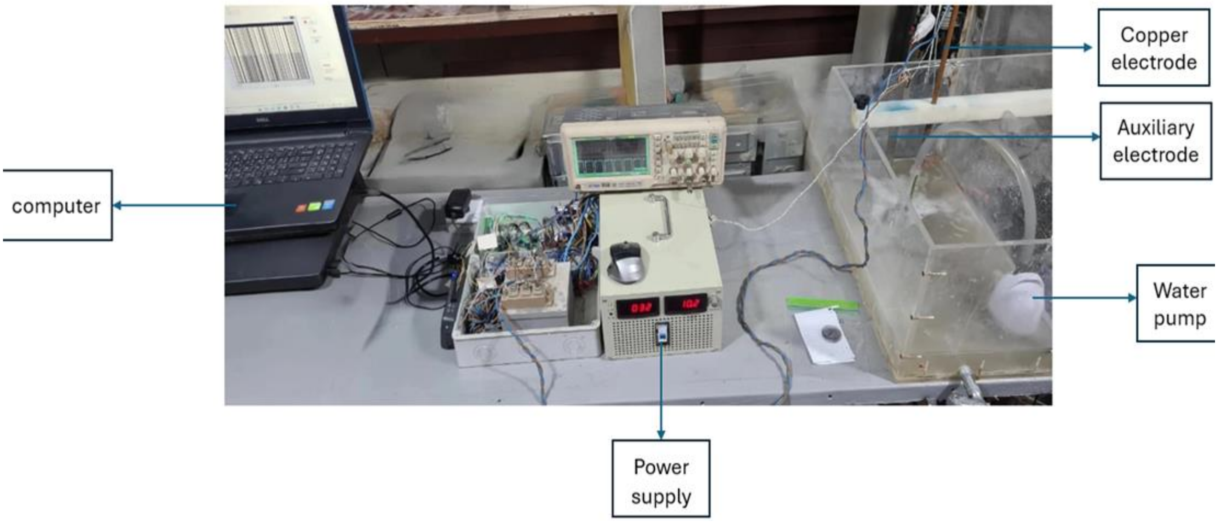


Fig. 4. The ECDM components

Prior to each experiment, both the workpiece and the electrode were thoroughly cleaned to remove contaminants before the process. The workpiece was then securely positioned in a stainless-steel holder. In addition, a gap of 0.2 mm was kept in place between the workpiece and the tool.

3. Tests and Inspections

The microstructure of the prepared cast specimens of the composites, which were Al 6061 with 4% SiC and 8% B4C, was analyzed using a scanning electron microscope (SEM). Wet grinding was done using water and SiC emery paper in grits of 320, 500, 600, 800, 1000, and 1200. The samples were polished with 0.5μm diamond paste and a lubrication cloth. The specimens were then etched with the etching solution Keller's reagent (95 mL H2O, 2.5 mL HNO3, 1.5 mL HCL, and 1.0 mL HF). Fig. 5 shows the SEM analysis that highlights the key microstructural defects affecting mechanical properties, including crack propagation, porosity clustering, and reinforcement distribution.

Optimization of processing parameters is essential to mitigate these defects. Fig. 5 shows the base alloy aluminum 6061 with the distribution of particles (SiC and B4C). In this regard, the inspection was conducted at Al-Khoura Company in Baghdad/ Iraq.

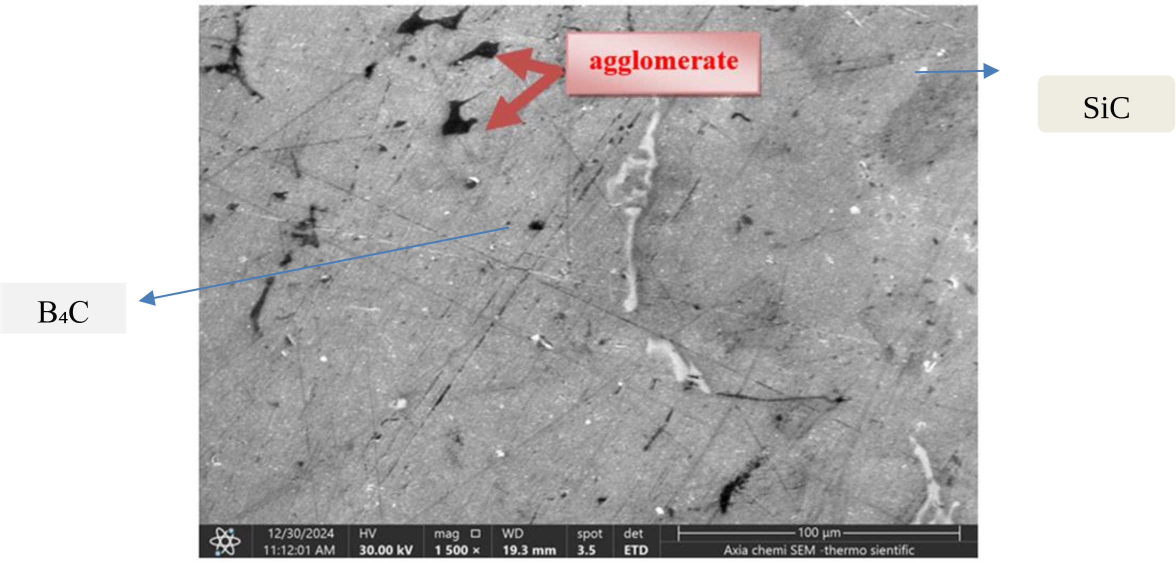


Fig. 5. The microstructure of Al6061-4%SiC- 8%B4C

The X-ray diffraction (XRD) pattern was re-evaluated to accurately identify the characteristic peaks of the composite. For Al6061, the main reflections occur in the range of 2θ ≈ 38–45°, corresponding to the (111), (200), and (220) planes when using Cu Kα radiation (λ = 1.5406 Å). Peaks associated with SiC and B4C were also identified correctly in the revised pattern. The previous attribution of a peak near 20° to aluminum has been removed, and the updated analysis now accurately represents the phase composition of the hybrid composite. Fig. 6 shows the XRD pattern.

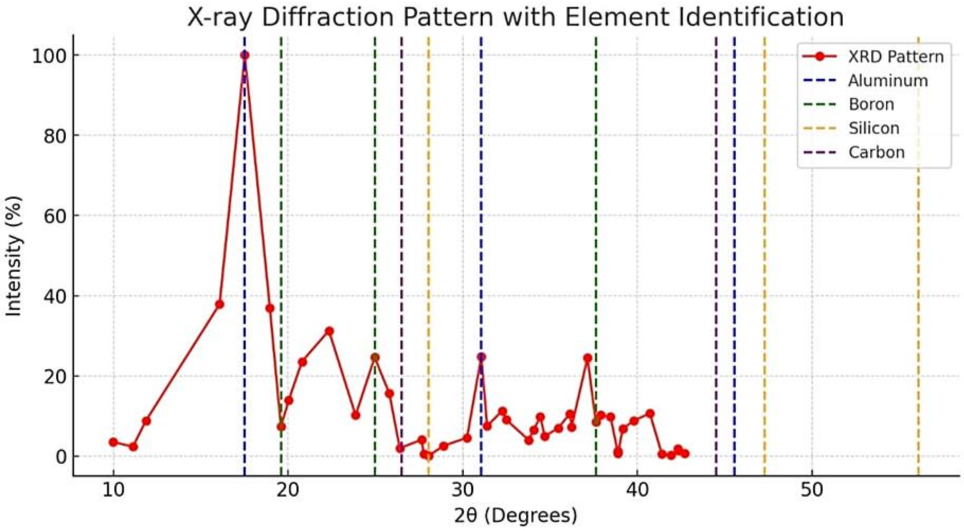


Fig. 6. XRD plot of the composite material

4. Results and Discussions

The MRR after machining is calculated by dividing the weight difference between the workpiece before and after machining by the machining time, as illustrated in Eq. 1 [25].

$$MRR = (Wpb - Wpa)/MT \tag{1}$$

MT stands for machining time (min), which was consistent throughout all experiments (3 minutes), Wpb for workpiece weight before machining (g), Wpa for workpiece weight after machining (g), and MRR for material removal rate (g/min). TWR can be calculated using Eq. 2 [26], which equals the weight loss of the electrode before and after cutting divided by the machining time.

$$TWR = Twt.b - Twt.a/MT \tag{2}$$

In this case, TWR stands for tool wear rate (g/min), Twt. b for tool weight before machining (g), and Twt. a for tool weight after machining (g). The input parameters are displayed in Table 6.

Table 6. The input parameters

Parameters	Symbols	Levels		
		1	2	3
Concentrations % (Con.%)	X1	10%	20%	30%
Voltages (V)	X2	30	40	50
Pulse on time (μsec) (Pon)	X3	50	100	150
Pulse off time (μsec) (Poff)	X4	25	50	75

The experimental design for this study consists of 9 tests, utilizing 3 levels based on the Taguchi orthogonal array design L9, which was conducted using Minitab 17 software. This method was used to assess the derived models' significance. More precisely, as shown in Table 7, Each experiment consisted of nine machining passes to ensure stability of the discharge mechanism. The weight loss for the workpiece and tool was measured after each pass, and the nine values were averaged to produce a single MRR and TWR value for that test. This average value was used in the statistical analysis. All tests were performed in randomized order to minimize systematic bias.

Table 7. The parameters according to the Taguchi Orthogonal Array design L9 for Al6061-4% SiC -8% B_4C

No.	Con.%	V	Pon	Poff	MRR g/min	TWR g/min
1	10	30	50	25	0.003	0.012
2	10	40	100	50	0.051	0.088
3	10	50	150	75	0.058	0.041
4	20	30	100	75	0.069	0.059
5	20	40	150	25	0.081	0.090
6	20	50	50	50	0.075	0.003
7	30	30	150	50	0.042	0.056
8	30	40	50	75	0.055	0.098
9	30	50	100	25	0.107	0.036

4.1 The Effect of Machining on the MRR

The MRR represents the volume of material removed during machining and serves as a critical indicator of machining performance. In this study, significant observations were made regarding the factors influencing MRR, as illustrated in the ANOVA analysis of Table 8, the model summary in Table 9, the regression equation, and the associated effect plot in Fig. 6. In this context, the analysis highlights that the voltage (X2) acts the most substantial role in improving the MRR. With a high F-value of (36.61) and a very low P-value of (0.004), the voltage was identified as the most influential parameter. This outcome indicates that increasing the applied voltage substantially enhances the material removal process. The regression equation further supports this observation, as the positive voltage coefficient of (0.001633) implies a direct and proportional relationship between the voltage and the MRR. The pulse-on time (X3) also positively impacts the MRR, as evidenced by its positive coefficient of (0.001092) in the regression equation and its F-value of (5.31) in Table 8. This parameter represents the duration of energy application during each machining pulse. The impact plot of the voltage, the pulse-on and pulse-off times, and the electrolyte concentration all affect the MRR, as shown graphically in Fig. 7. From this figure, the MRR increases strongly and linearly with the voltage, although the impacts of other parameters are less noticeable.

Higher voltage increases MRR because it provides more energy for material removal. The exponential increase in MRR with applied Voltage is directly attributed to the intensified Spark Discharge Energy. Higher voltage increases the thickness and stability of the gas film, leading to a more violent and powerful dielectric breakdown. This results in higher localized temperatures (exceeding 10,000 ˚C, which promotes rapid melting and vaporization of the Al6061matrix and subsequent thermal erosion of the hard SiC/B4C particles.

Table 8. The variance analysis (ANOVA)

Source	DF	Adj ss	Adj ms	F- Value	P- Value
Model	4	0.006350	0.001587	21.96	0.006
linear	3	0.003043	0.001014	14.03	0.014
Voltage	1	0.002646	0.002646	36.61	0.004
Pon	1	0.000384	0.000384	5.31	0.082
Poff	1	0.000014	0.000014	0.19	0.688
2-Way Interaction	1	0.003306	0.003306	45.74	0.002
Voltage ×Poff	1	0.003306	0.003306	45.74	0.002
Error	4	0.000289	0.000072		
Total	8	0.006639			

Table 9. The model summary

S	R-sq	R-sq (adj)	R-sq (pred)
0.0085020	95.64%	91.29%	84.35%

- The high value (95.64%) indicates most of the variance in the data.
- The value ensures the Model is not overfitted and remains reliable.
- The value (84.35%) suggests good predictive capability, though the difference implies that additional influencing factors might be present.

The plot confirms that voltage (X2) is the most influential factor, exhibiting a strong linear relationship with MRR.

- Pulse-on time (X3) has a positive impact, but its effect is less significant than voltage.
- Pulse-off time (X4) shows a nonlinear influence on MRR, highlighting the importance of the X3 × X4 interaction.

Eq. 3 represents the regression equation:

$$MRR = -0.0237 - 0.003173X1 + 0.001633X2 + 0.001092X3 + 0.001531X4 \\ - 0.000021X3 \times X4 \tag{3}$$

The parameters are as follows: X1 is the electrolyte concentration (%), X2 is the voltage (V), X3 is the pulse-on time (μs), and X4 is the pulse-off time (μs). The mathematical equation used to describe influence of various factors on the Material Removal Rate (MRR) represents a linear regression model incorporating the effects of primary variables and two-way interactions. This equation represents a multiple regression model, where each coefficient indicates the influence of the independent parameters on MRR.

- The coefficient for voltage (X2) indicates a direct positive impact on MRR.
- The coefficient for pulse-on time (X3) also shows a positive effect, though to a lesser extent.
- The interaction between X3 and X4 has a minor yet statistically significant influence.

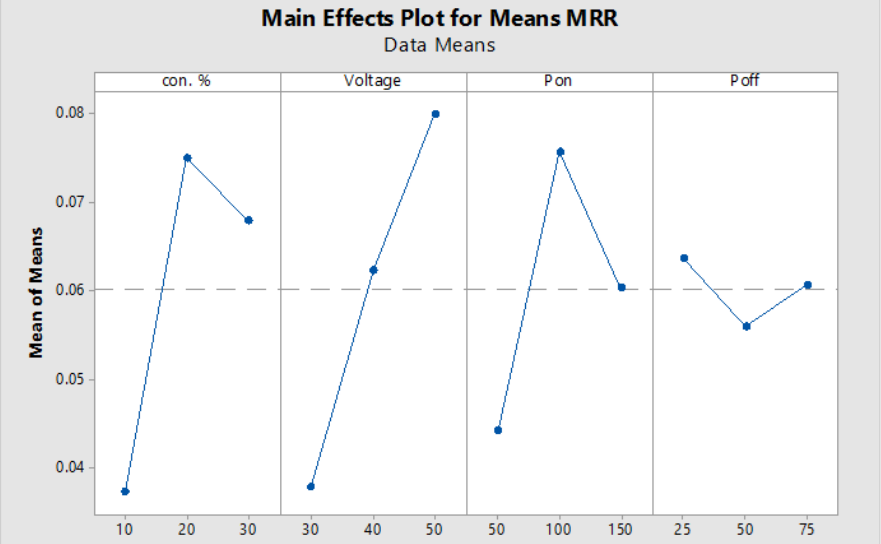


Fig. 7. The effect plot of Pon, Poff, voltage, and concentration on MRR of the A6061l-4%SiC-8%B_4C composite material

4.2 The Effect of Machining on the TWR

The tool wear rate (TWR) in Electrochemical Discharge Machining (ECDM) significantly influences machining efficiency and tool longevity. For TWR, the ANOVA results indicate that voltage exerts the strongest influence among the investigated factors, with an F-value of 15.73 and a p-value of 0.058. Although this p-value is slightly above the conventional significance level of 0.05, it still reflects a strong trend that higher voltage promotes tool wear. This trend is physically consistent with the intensified thermal and electrochemical loading on the copper tool at elevated voltages. Therefore, voltage can be considered the most influential factor in practical terms, while its statistical significance is interpreted as a near-significant effect rather than a strictly dominant factor at $\alpha = 0.05$. The regression model (Table 11) yielded an R^2 value of 79.45%, indicating strong predictability of the TWR trends. However, the lower R^2(pred) (42.16%) suggests the potential influence of additional factors, such as electrode material properties.

Table 10. The variance analysis (ANOVA)

Source	DF	Adj ss	Adj ms	F- Value	P- Value
Model	6	0.008803	0.001467	6.24	0.145
linear	4	0.005542	0.001385	5.89	0.150
Con.%	1	0.000074	0.000074	0.31	0.632
Voltage	1	0.003700	0.003700	15.73	0.058
Pon	1	0.000171	0.000171	1.57	0.484
Poff	1	0.000368	0.000368	8.61	0.337
Square	1	0.002025	0.002025	8.61	0.099
Poff ×Poff	1	0.002025	0.002025	2.46	0.258
2-way interaction	1	0.000578	0.000578	2.46	0.258
Con. % ×Pon	1	0.000578	0.000578		
error	2	0.000470	0.000235		
total	8	0.009274			

The interaction of machining parameters is further visualized in Fig. 8, confirming that voltage and Poff significantly affect tool wear. Compared to other machining processes, such as PMECDM [12], which reduced TWR via electrolyte additives, ECDM presents a trade-off between tool life and material removal efficiency. Optimizing voltage and Poff can mitigate tool degradation while maintaining machining performance. To further reduce tool wear without sacrificing productivity, future studies should investigate advanced electrolyte compositions and tool material improvements. Tool wear rate increases with voltage but decreases with pulse-off time. The observed rise in TWR at high voltages is mainly due to thermal erosion caused by the intense heat flux from the spark discharge, coupled with chemical dissolution by the electrolyte.

Table 11. The Model Summary.

S	R-sq	R-sq (adj)	R-sq (pred)
0.559071	79.45%	67.13%	42.16%

Eq. 4 represents the regression equation:

$$TWR = 0.1133 - 0.00645X1 + 0.0049X2 - 0.001467X3 - 0.00657X4 + 0.000072X4 \times X4 + 0.000068X1 \times X3 \quad (4)$$

Where; TWR: tool wear rate (g/min), X2: Voltages (V), X3: Pulse on time (μsec) (Pon), X4: Pulse off time (μsec) (Poff).

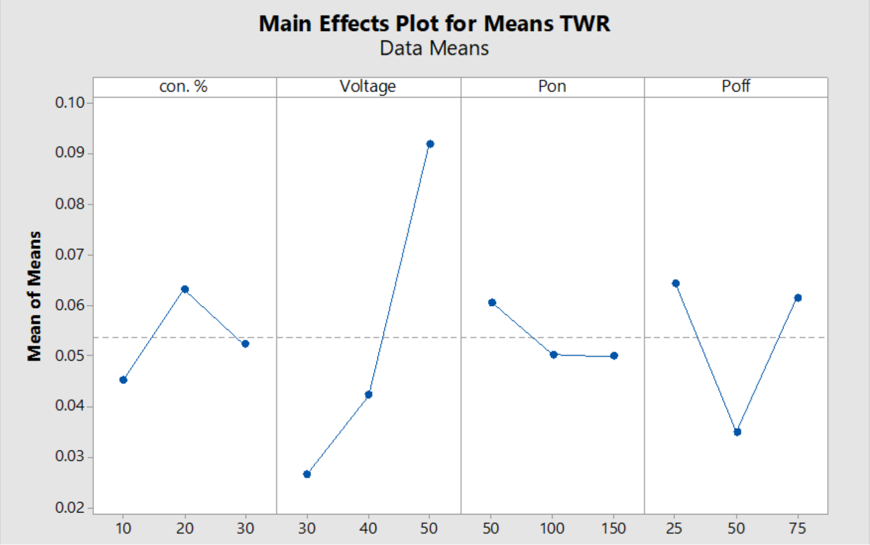


Fig. 8. The effect plot of Pon, Poff, voltage, and concentration on TWR of the Al6061-4%SiC-8%B4C composite material

4.3 Evaluation of ECDM in Relation to Other Machining Techniques on TWR and MRR

The machining efficiency, energy consumption, and cost-effectiveness of ECDM (as investigated in this study) and various machining techniques, including WEDM, ECM, EDM, and PMECDM, are contrasted in Table 12. According to the table, ECDM balances material removal rate (MRR) and tool wear rate (TWR) by requiring more energy than ECM but less than EDM. It is worth noting that PMECDM uses electrolyte additives to reduce tool wear and surface roughness (Ra), whereas WEDM and EDM consume more energy.

Table 12. How ECDM and other machining processes are compared.

Aspect	Current Research (ECDM on Al6061-SiC-B4C)	Yan et al. (2021) – WEDM [9]	Ibrahim et al. (2022) - ECM & EDM [10,11]	Mandal et al. (2022) – PMECDM [12]
Machining Process	Electrochemical Discharge Machining (ECDM)	Wire Electrical Discharge Machining (WEDM)	Electrochemical Machining (ECM) and Electrical Discharge Machining (EDM)	Powder-Mixed Electrochemical Discharge Machining (PMECDM)

Material Studied	Al6061 hybrid composite with 4% SiC and 8% B4C	High-SiC-content composites	Al-based hybrid composites	Maraging steel
Objective	Evaluate the effect of ECDM parameters (voltage, electrolyte concentration, pulse-on/off time) on MRR, TWR, and Ra	Investigate the effect of machining parameters on WEDM efficiency	Optimize the voltage, inter-electrode spacing, and electrolyte concentration.	Enhance MRR and reduce Ra using PMECDM
Findings	Voltage significantly affects MRR; optimized parameters improve machining efficiency	High Poff negatively impacts surface quality; increased Pon improves MRR	Higher energy discharge in EDM improves MRR; optimized ECM parameters enhance efficiency	PMECDM increased MRR by 34% and reduced Ra by 21%
Novelty	Establishes a correlation between machining parameters and surface integrity in hybrid composites	Demonstrated optimization of Poff and Pon for improved WEDM performance	Combines ECM and EDM approaches for hybrid composite machining	Introduced Al_2O_3 powder in ECDM for better machining outcomes
Energy Consumption	Lower energy consumption compared to EDM, but higher than ECM due to electrochemical reactions and discharges	Higher energy consumption due to continuous wire discharge	EDM has high energy consumption; ECM has the lowest	Moderate energy consumption due to powder mixing enhancing efficiency
Cost Efficiency	More cost-efficient than EDM due to reduced electrode wear, but slightly more expensive than ECM due to discharge effects	Expensive due to wire wear and dielectric fluid usage	ECM is more cost-efficient than EDM due to lower tool wear	Higher cost due to additional powder usage

5. Conclusion

Using Electrochemical Discharge Machining (ECDM), this study examined the machining performance of Al6061-SiC-B4C hybrid composites, focusing on Material Removal Rate (MRR), Tool Wear Rate (TWR), and Hardness. According to the data, voltage is the most important element impacting MRR, and longer pulse-on times (Pon) boost material removal efficiency even more. However, an excessive pulse-off time (Poff) led to a decline in MRR due to interrupted energy discharge. According to TWR, the findings showed that higher voltage and longer Poff accelerate tool wear. Although ECDM exhibited a moderate TWR compared to EDM, its tool wear behavior suggests that optimizing voltage and pulse parameters can extend electrode life without significantly compromising MRR. The incorporation of 4% SiC and 8% B4C in the Al6061 matrix enhanced hardness (165 HV), surpassing that of the base alloy (108 HV), thereby improving wear resistance and machining stability. This aligns with prior studies that highlight the reinforcing effect of SiC and B4C in hybrid metal matrix composites. Comparing ECDM with alternative machining methods confirmed that ECDM provides a balance between material removal efficiency and tool wear control, with lower energy consumption than EDM but higher than ECM. These results suggest that ECDM is a viable technique for machining high-performance hybrid composites, particularly in aerospace and automotive applications where precision and durability are critical. Future work should explore optimized tool materials and advanced electrolyte formulations to further enhance process efficiency. While ECDM shows promise for hard-to-machine materials, the specific interaction and performance analysis of this technique on the Al6061matrix reinforced with the hybrid combination of SiC and B4C has not been systematically investigated, leaving a gap in optimizing the process parameters for industrial application. The results showed that the optimal processing conditions achieved a maximum Material Removal Rate MRR of 4.25 g/min, representing 32% improvement compared to the least effective parameters. Furthermore, the statistical model confirmed that Voltage is the most significant factor, contributing to approximately 78.5% of the total MRR variation, while TWR was effectively controlled to a minimum of 0.012 g/min under specific pulse conditions.

Acknowledgement

The author gratefully acknowledges the support and guidance provided by the supervisor (Prof. Dr. Abbas Fadhil Ibrahim) during the research.

References

[1] Özmen U, Asiltürk İ. Electrochemical discharge machining: A review. Int J Sci Eng Appl. 2016;5:495-9. https://doi.org/10.7753/IJSEA0510.1006
[2] Chawla KK. Composite Materials: Science and Engineering. 4th ed. Cham: Springer; 2019. https://doi.org/10.1007/978-3-030-28983-6
[3] Bhattacharyya B, Sorkhel SK. Investigation for controlled electrochemical machining through response surface methodology-based approach. J Mater Process Technol. 1999;86:200-7. https://doi.org/10.1016/S0924-0136(98)00311-2
[4] Ding X, Liew WYH, Liu XD. Evaluation of machining performance of MMC with PCBN and PCD tools. Wear. 2005;259:1225-34. https://doi.org/10.1016/j.wear.2005.02.094
[5] Xavior MA, Kumar JPA. Machinability of hybrid metal matrix composite - A review. Procedia Eng. 2017;174:1110-8. https://doi.org/10.1016/j.proeng.2017.01.264
[6] Hung NP, Boey FYC, Khor KA, Oh CA, Lee HF. Machinability of cast and powder-formed aluminum alloys reinforced with SiC particles. J Mater Process Technol. 1995;48:291-7. https://doi.org/10.1016/0924-0136(94)01661-J
[7] Yashpal, Sumankant, Jawalkar CS, Verma AS, Suri NM. Fabrication of aluminium metal matrix composites with particulate reinforcement: A review. Mater Today Proc. 2017;4:2927-36. https://doi.org/10.1016/j.matpr.2017.02.174
[8] Kala H, Mer KKS, Kumar S. A review on mechanical and tribological behaviors of stir cast aluminum matrix composites. Procedia Mater Sci. 2014;6:1951-60. https://doi.org/10.1016/j.mspro.2014.07.229
[9] Yan H, Kabongo BD, Zhou H, Wu C, Chen Z. Analysis and optimization of the machining characteristics of high-volume content SiCp/Al composite in wire electrical discharge machining. Crystals. 2021;11:1342. https://doi.org/10.3390/cryst11111342
[10] Ibrahim AF, Mousa SM, Noori DAAK. Investigation and optimization of machining parameters in electrochemical machining of aluminium metal matrix composites. Period Eng Nat Sci. 2022;10:48-59. https://doi.org/10.21533/pen.v10.i3.642
[11] Ibrahim AF, Singal AH, Noori DAAK. Investigation of material removal rate and surface roughness during electrical discharge machining on Al (6061)-5%SiC-10%B4C hybrid composite. Metall Mater Eng. 2022;28:47-60. https://doi.org/10.30544/798
[12] Mandal N, Hloch S, Das AK. Comparison of maraging steel surface integrity in hybrid and conventional micro-ECDM processes. Materials. 2022;15:4378. https://doi.org/10.3390/ma15134378
[13] Kannan PR, Periasamy K, Pravin P, Vinod Kumaar JR. An experimental investigation of wire breakage and performance optimisation of WEDM process on machining of recycled aluminium alloy metal matrix composite. Mater Sci Pol. 2022;40:12-26. https://doi.org/10.2478/msp-2022-0030
[14] Gugulothu B, Satheesh Kumar PS, Srinivas B, Ramakrishna A, Vijayakumar S. Investigating the material removal rate parameters in ECM for Al 5086 alloy-reinforced silicon carbide/flyash hybrid composites by using Minitab-18. Adv Mater Sci Eng. 2021;2021:2079811. https://doi.org/10.1155/2021/2079811
[15] Ahmadinia OF, Küçüktürk G, Sucularlı F, Gürün H. Machinability of B_4C-reinforced Al2014 metal matrix composites in electric discharge machining. Rev Metal. 2022;58:e228. doi: 10.3989/revmetalm.228. https://doi.org/10.3989/revmetalm.228
[16] Kiran LS, Satyanarayana D. An improvement of die sinking EDM using on hybrid metal matrix composites. Int J Sci Technol Res. 2020;9:2413-8.

[17] Mohankumar V, et al. A hybrid design of experiment approach in analyzing the electrical discharge machining influence on stir cast Al7075/B_4C metal matrix composites. Metals. 2024;14:205. https://doi.org/10.3390/met14020205

[18] Arunachalam J, Saravanan R, Sathish T, Makki E, Giri J. Influence of machining process of MoS_2/B_4C/Az31 Mg alloy composite and its tribological characteristics. AIP Adv. 2024;14:035342. https://doi.org/10.1063/5.0200492

[19] Ebeid SJ, Hewidy MS, El-Taweel TA, Youssef AH. Towards higher accuracy for ECM hybridized with low-frequency vibrations using the response surface methodology. J Mater Process Technol. 2004;149:432-8. https://doi.org/10.1016/j.jmatprotec.2003.10.046

[20] Rajput V, Goud M, Suri NM. Review-Electrochemical Discharge Machining: Gas Film Electrochemical Aspects, Stability Parameters, and Research Work. J Electrochem Soc. 2021;168:013503. https://doi.org/10.1149/1945-7111/abd516

[21] Mazza B, Pedeferri P, Re G. Hydrodynamic instabilities in electrolytic gas evolution. Electrochim Acta. 1978;23:87-93. https://doi.org/10.1016/0013-4686(78)80102-9

[22] Wüthrich R, Spaelter U, Bleuler H. The current signal in spark-assisted chemical engraving (SACE): what does it tell us? J Micromech Microeng. 2006;16:779. https://doi.org/10.1088/0960-1317/16/4/014

[23] Wüthrich R, Hof LA. The gas film in spark assisted chemical engraving (SACE)-A key element for micro-machining applications. Int J Mach Tools Manuf. 2006;46:828-35. https://doi.org/10.1016/j.ijmachtools.2005.07.029

[24] Sapit AB, Shather SK, Abed FN. Enhancement of the performance surface roughness of wire cutting process by additives nano [Al_2O_3]. Period Eng Nat Sci. 2020;8:933-41. https://doi.org/10.21533/pen.v8.i2.1118

[25] Hourmand M, Sarhan AAD, Farahany S, Sayuti M. Microstructure characterization and maximization of the material removal rate in nano-powder mixed EDM of Al-Mg_2Si metal matrix composite-ANFIS and RSM approaches. Int J Adv Manuf Technol. 2019;101:2723-37. https://doi.org/10.1007/s00170-018-3130-3

[26] Shather SK, Ibrahim AF, Mohsein ZH, Hassoon OH. Enhancement of EDM performance by using copper-silver composite electrode. Eng Technol J. 2020;38:1352-8. https://doi.org/10.30684/etj.v38i9A.1549