

Original Article

Influence of Al₂O₃ and B₄C Hybrid Reinforcements on the Mechanical Properties and WEDM Machinability of Aluminum Matrix Composites

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Received: 15 November 2025

Revised: 16 December 2025

Accepted: 17 January 2026

Published: 20 February 2026

Abstract - The Mechanical Properties and WEDM performance of AMCs containing Al₂O₃ and B₄C are investigated in this study. A total of nine composite specimens were prepared by the stir-casting method with different weight percentages of Al₂O₃ and B₄C reinforcements. The Microstructural, Tensile Strength, Hardness, Wear Behavior, and WEDM responses, such as MRR, Surface Roughness (SR), and kerf width of the prepared composites, were investigated. Of all combinations investigated, the hybrid composition with 5% Al₂O₃ and 3% B₄C displayed indeed maximum mechanical properties along with better machinability (higher MRR as well as lower Ra). Microstructural studies through X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) indicated a homogeneous distribution of reinforcing particles with few pores, resulting in better performance. The synergistic effect of the reinforcement exhibited a synergetic interaction -that is, Al₂O₃ provided improved hardness and heat stability, whereas B₄C enhanced the lubrication property and wear resistance. The optimization process using Taguchi's L27 orthogonal array and ANOVA analysis also indicates the important parameters and potential influence of reinforcement composition and WEDM on the response. The results in general suggest that Al-Al₂O₃/B₄C hybrid composites have a good potential for the aerospace and automotive industry, requiring high strength along with efficient EDM machinability.

Keywords - Aluminum Matrix Composites, Wire Electrical Discharge Machining, Hybrid Reinforcement, Stir Casting Process.

1. Introduction

The ever-increasing requirement of lightweight-to-strength materials with improved mechanical properties, wear behavior, and thermal stability has spurred strong research focus on Aluminum Matrix Composites (AMCs) for advanced engineering applications such as aerospace, automotive, and defense industries [1-4]. As one of the commercially applicable aluminum alloys, 6061-T6 has been commonly used because it possesses an excellent ratio of strength to weight and good resistance against corrosion, as well as formability; its low hardness level and inferior wear resistance ability still limit its overall performance in heavy mechanical loading and high temperature working environments [8, 9]. These restrictions have led to the development of ceramic-reinforced AMCs as an efficient

method to upgrade mechanical strength and reliability in service.

Aluminium Oxide (Al₂O₃) and Boron Carbide (B₄C) are among the most studied ceramic reinforcements due to their complementary material properties. The Al₂O₃ has high hardness, chemical stability, and good thermal stability, which will improve the load-carrying capacity and limit plastic deformation of the aluminum matrix [9, 10, 26]. In contrast, B₄C is known to have an extremely high hardness and low density and exhibits excellent wear resistance, thus it has good application prospects with respect to the tribological applications or under high-temperature conditions; also in wear-resistant fields with consideration for weight reduction [21, 25, 27]. It has been widely shown



that both Al_2O_3 and B_4C are effective for reinforcing an aluminum matrix to enhance hardness, tensile strength, and wear resistance; however, these single-reinforcement systems tend to have a restricted tunability in the quest for an ideal combination of mechanical performance and machinability [3, 10, 28].

To defeat these limitations, numerous studies have focused on hybrid Aluminum Matrix Composites reinforced with multi-ceramic particles. Hybrid Reinforcement systems combine the synergistic effects of diverse reinforcement types, leading to better load transfer and thermal stability, and superior wear resistance than mono-reinforced composites [17, 22, 29]. More recently, beneficial mechanical and tribological properties of Al6061-based hybrid composites containing $\text{Al}_2\text{O}_3/\text{B}_4\text{C}$ have been reported as a result of uniform dispersion of particles, enabling minimization in matrix deformation and increasing resistance to crack propagation [9, 25, 30]. However, the machinability of hybrid AMCs is considerably affected by the presence of hard ceramic particles, which remains to be one of the critical issues for successful implementation on a large-scale industrial scale.

Processing of AMCs with traditional cutting tools is frequently connected with high rates of tool wear and a low-quality surface finish, due to the abrasive nature of reinforcement particles and non-homogeneous stress distribution [5, 6]. As a result, non-conventional methods, which include Wire Electrical Discharge Machines (WEDM), have become the best alternatives in manufacturing complex and composite materials.

Material is removed during WEDM by controlled electrical discharges and not through mechanical contact, thus it is apt for electrically conductive hard-to-cut materials [4, 11, 31]. Nevertheless, in the case of WEDM, machining is strongly affected by process parameters including pulse current, pulse-on time, and wire feed rate, which directly affect Material Removal Rate (MRR), Surface Roughness (SR), and Kerf Width (KW) [11, 14, 32].

There have been several studies on the WEDM performance of aluminum alloys and single-reinforced AMCs, and it has been found that a higher discharge energy enhances MRR. However, poor job accuracy causes surface integrity degradation [12-14, 33]. Recent publications have also revealed that the hybrid AMC has excellent spark erosion because of the reinforcement-induced hindrance (reduction) in thermal conductivity and electric discharge intensity [7, 17, 33].

For hybrid systems, namely Al-SiC- B_4C and Al-SiC-Gr composites, it has been reported that the reinforcement combination can contribute to improved stability of machining and a reduction in excessive lateral erosion

during WEDM [17, 19, 34]. However, to the best of the authors' knowledge, systematic studies devoted to mechanical properties and WEDM machinability under identical processing conditions of Al6061 reinforced simultaneously with Al_2O_3 and B_4C , as well as analyzing the combined effects of reinforcing phases, are still scarce [17, 19, 35].

Moreover, the majority of existing studies deal with mechanical characterization and machining optimization as two independent research problems without establishing any relationship among microstructural features, reinforcement content, and WEDM response. Although statistical optimization tools such as the Taguchi method, grey relational analysis, and hybrid multi-objective methods were successfully utilized in WEDM investigations [2, 11, 23, 24, 34], their combined application for Al6061- Al_2O_3 - B_4C hybrid composites to achieve simultaneous optimizations of MRR, SR, and KW is insufficient. As a consequence, the synergistic effect of Hybrid Reinforcement compositions and WEDM-process parameters on machining performance has not been well-explained so far.

In such a scenario, Hybrid Reinforcement-based composites like Al_2O_3 and B_4C are being explored, and hence in the current work, a solid particulate reinforced Al6061 metal matrix-based composite is developed with microstructural, mechanical behaviour, and WEDM machinability. The composites were prepared by a Stir Casting Process at different weight fractions of reinforcement and characterized microstructurally in conjunction with mechanical testing.

The performance of WEDM was systematically investigated via a Taguchi-based experimental design, and multi-response optimization was conducted using the grey relational analysis simultaneously to maximize MRR while minimizing surface roughness and kerf width. Such a coupling approach sheds an insight into the cutting behavior of the advanced machinable Al6061- Al_2O_3 - B_4C hybrid composites vs. their tapped performance for high-precision engineering applications.

2. Methodology

2.1. Materials and Reinforcements

The matrix material used in the present study is an Aluminum alloy AA6061, a popular and well-recognized Al-alloy with good mechanical properties, high strength-to-weight ratio, corrosion resistance, and processability suitable for composite processing.

The nominal chemical composition, in weight percent, of AA6061 is Si (0.4-0.8), Fe (≤ 0.7), Cu (0.15-0.40), Mn (≤ 0.15); Mg (0.8-1.2); Cr (0.04-0.35); Zn (≤ 0.25); Ti (≤ 0.15) with the balance being aluminum [21]. The detailed chemical compositions of the alloy are listed in Table 1.

Table 1. The content of the elements in the sample

Element	Composition (%)
Mn	0.10
Fe	0.70
Mg	0.80
Si	0.60
Cu	0.40
Zn	0.10
Ti	0.05
Cr	0.05
Al	Balance

Ceramic reinforcement, such as Aluminum Oxide (Al_2O_3) and Boron Carbide (B_4C), due to their exceptional hardness, thermal stability, and wear resistance, was employed. Al_2O_3 powder having an average particle diameter of about 45 μm and a purity exceeding 99%, which is used for increasing hardness, thermal resistance, or the like, was added.

In order to improve the wear resistance and tribological performance, the B_4C powder with a particle size smaller than 50 μm and purity higher than 98% was adopted. The main physical and mechanical properties of the matrix material and reinforcement are tabulated in Table 2.

Table 2. Characteristics of the materials

Properties	Matrix	Reinforcement	
	Al alloy (6061)	Alumina (Al_2O_3)	Boron Carbide(B_4C)
Tensile Strength (Min MPa)	260	-----	-----
Young’s Modulus (GPa)	70	-----	-----
Melting Temp. (oC)	650	2,072	2763
Density (g/cm ³)	2.70	3.95	2.52
Thermal Conductivity (W/m-K)	166	29	31 – 90
Thermal Expansion (/K)	23.4 * 10 ⁻⁶	7.4 * 10 ⁻⁶	3.2 * 10 ⁻⁶

Before the preparation of composites, the Al_2O_3 and B_4C powders were oven-dried and preheated at 250 °C for 2 hours to remove adsorbed water and to enhance wettability with molten aluminum during casting.

2.2. Fabrication of Hybrid Aluminum Matrix Composites

The stir-casting method was chosen considering its simplicity, cost-effective platform, and ability to develop particulate reinforced composites.

The AA6061 alloy ingots were melted in a graphite crucible by an electric resistance furnace at about 650 °C. The melt temperature was stabilized after complete melting to achieve uniform fluidity.

Preheated Al_2O_3 and B_4C powders were added incrementally to the molten aluminum in weight ratios that had been established beforehand.

Mechanical stirring was performed with a stainless-steel impeller at a speed of 250–300 rpm for about 10 minutes in order to achieve homogeneous distribution of the reinforcing particles and reduce agglomeration.

The molten composite slurry was then cast into preheated steel molds and cooled to ambient temperature. A schematic illustration of the stir-casting process is shown in Figure 1. Nine composite mixtures with different weights of Al_2O_3 (1–5 wt%) and B_4C (1–3 wt%) are synthesized, as shown in Table 3.



Fig. 1 Stir casting image

Table 3. Weight percentage of Al_2O_3 and B_4C reinforced with aluminum 6061 composites

Sample	Aluminum 6061	Alumina (Al_2O_3)	Boron Carbide (B_4C)
1(A)	98	1	1
2 (B)	97	1	2
3 (C)	96	1	3
4 (D)	96	3	1
5 (E)	95	3	2
6 (F)	94	3	3
7 (G)	94	5	1
8 (H)	93	5	2
9 (I)	92	5	3

2.3. Mechanical Characterization

2.3.1. Hardness Testing

Standard microhardness tests were performed at a load of 500 g and dwell time of 15 s using a standard microhardness tester, indenting with a square-based pyramidal indenter for each composite sample at five different areas to cover the variations in the microstructure, and the mean value was reported as the representative hardness.

2.3.2. Tensile Testing

The tensile tests were carried out on a universal testing machine in accordance with ASTM E8/E8M. Dog-bone-shaped specimens with a gauge length of 25 mm were cut from the cast samples. All tests were conducted at a fixed crosshead speed of 1 mm/min, and the ultimate tensile strength was measured.

2.3.3. Wear Testing

The behavior under dry sliding wear test was carried out on a pin-on-disc tribometer, according to the ASTM G99. From the composite samples, cylindrical pins (10 mm diameter and 30 mm length) were prepared and tested against an EN31 steel disk. The tests were conducted under a normal load of 20 N, sliding speed of 1 m/s, and sliding distance of 1000 m. The wear loss was quantified based on the weight difference before and after testing using an analytical balance.

2.4. WEDM Machining Setup

Wire EDM experiments were conducted using an Electronica WEDM machine. The cutting tool was a high-purity copper wire electrode, and the dielectric medium used was deionised water. Composite machetes with the dimensions of 25 mm × 25 mm × 10 mm were fabricated for machining.

Three input factors were considered for the machining parameters, namely pulse current (6, 9, and 12 A), pulse-on time (50, 100, and 150 μ s), and pulse-off time (25, 50, and 75 μ s). These parameters were selected since they control the discharge energy as well as the spark stability and material erosion mechanisms. A Taguchi L27 orthogonal array was used to plan the experiments and systematically analyze the effects of machining parameters with few experimental runs.

2.5. Measurement of Machining Responses

Machining performance was assessed by Material Removal Rate (MRR), Surface Roughness (Ra), and Kerf Width (KW). Machining Rate Ratio (MRR) was determined according to the volume of material removed per unit machining time.

The surface roughness is measured by the surface profilometer with a cut-off length of 0.8 mm, and the average Ra value is taken away. The width of the kerf was checked in

an optical microscope, and the average of readings was taken along the machined slot to avoid uncertainty.

2.6. Statistical Analysis and Optimization

The significance of the WEDM process parameters was investigated using Analysis of Variance (ANOVA). S/N ratios were obtained in a Taguchi manner with 'larger-the-better' for MRR and the 'smaller-the-better' for surface roughness and kerf-width. Multi-objective optimization of machining process parameters was then performed using Grey Relational Analysis (GRA), which enabled the determination of the best set of process variables to maximize MRR while minimizing surface roughness and kerf width simultaneously.

2.7. Microstructural and Phase Analysis

Optical Microscopy, Scanning Electron Microscopy (SEM), and Energy-Dispersive X-Ray Spectroscopy (EDS) were used for microstructural analysis. The specimens were ground successively with SiC abrasive papers, polished with alumina suspension, and etched by Keller's reagent. Reinforcement distribution and grain structure were studied by means of optical microscopy, while details such as particle dispersion, porosity, and fracture characteristics were obtained using SEM. EDS testing was used to verify elemental composition. Phases were identified by X-Ray Diffraction (XRD) with Cu K α radiation ($\lambda = 1.54 \text{ \AA}$). XRD spectrum was utilized to determine the phase composition and confirm the soundness of the structure of the 6 prepared hybrid composites.

3. Results

3.1. Phase Analysis (XRD)

X-ray Diffraction (XRD): The as-synthesised composites displayed a multi-phase crystalline structure, which was confirmed by the XRD pattern. The magenta diffraction peaks are consistent with the Alumina, which can be indexed to reflections (102), (112), (113), (213), (225), (226), (400), (211), (401), and (523) based on JCPDS 00-001-1303; see Figure 2.

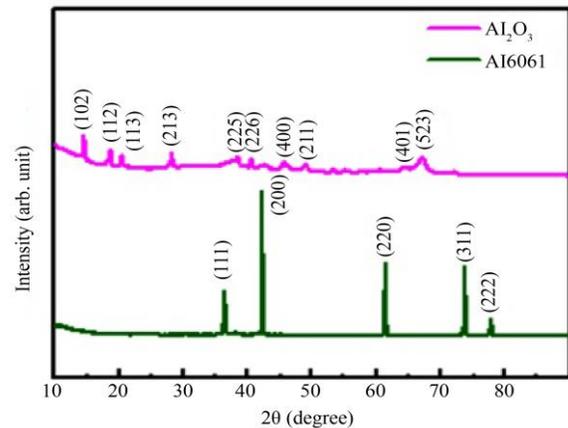


Fig. 2 XRD analysis of the fabricated sample

The green peaks are associated with the Al6061 matrix and can be indexed to planes (111), (200), (220), (311), and (222), which is consistent with Reference PDF No. 04-012-3461. The sharp, well-defined peaks are due to the composite's high crystallinity. The marked back-fast Al6061 reflections indicate that it is the dominant phase, and the Alumina peaks indicate successful reinforcement incorporation. It can be seen that the peak shifts compared with standard patterns are not substantial, indicating there is little remaining stress in the composite. Moreover, the narrow FWHM of the peaks denotes restricted lattice defects and low-angle scattering. In general, the XRD results support that stable aluminum matrix composites with homogeneous and structurally uniform dispersed reinforcement phases were synthesized.

3.2. Thermal Analysis (TGA/DTA)

As shown in Figure 3, the TGA/DTA profiles of Alumina indicate its high thermal stability and transitions during phase change. The weight loss of less than 400 °C is the evaporation of physically adsorbed and chemically combined water. The enhanced weight loss from 400 °C to 1000 °C may be attributed to the oxidation of some residual organic pollutants and the γ -Al₂O₃ structural transformation into the more stable α -Al₂O₃ phase. This evolution is evidenced by distinct DTA Endothermic Peaks at around 522–523 °C and a corresponding DTG response at 523 °C. The mass loss remains constant beyond 1000 °C with approximately 92% of the initial weight as observed, which attests to the completion of phase change and makes thermally stable α -alumina. The above inference indicates this material is applicable in high-temperature ceramic, thermal, and structural treatment.

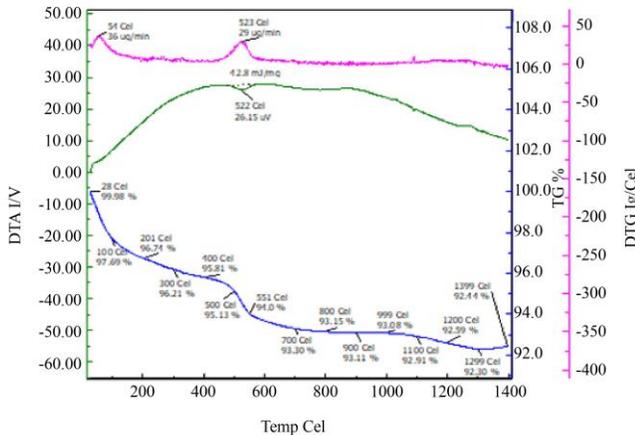


Fig. 3 TGA/DTG/DTA analysis of alumina (Al₂O₃)

3.3. Microstructural Analysis

The Microstructure features of Al6061 with 3 wt% Al₂O₃ and 3 wt% B₄C are shown in Figure 4. The distribution of the reinforcement particles within the matrix is uniform and well defined. In contrast, the micrograph of

unreinforced Al6061 alloy reveals a homogeneous structure ascribed to the metallic phase without the presence of secondary phases. The composites exhibit uniformly distributed reinforcing particles, little aggregation, and improved hardness, wear resistance, and load-carrying properties. The uniform distribution of the reinforcements additionally leads to enhanced thermal stability and minimizes risk for local distortion or premature material failure. Taken together, these observations reveal the favorable nature of the stir-casting method for a fractionalized microstructure and for fine control of particle incorporation.

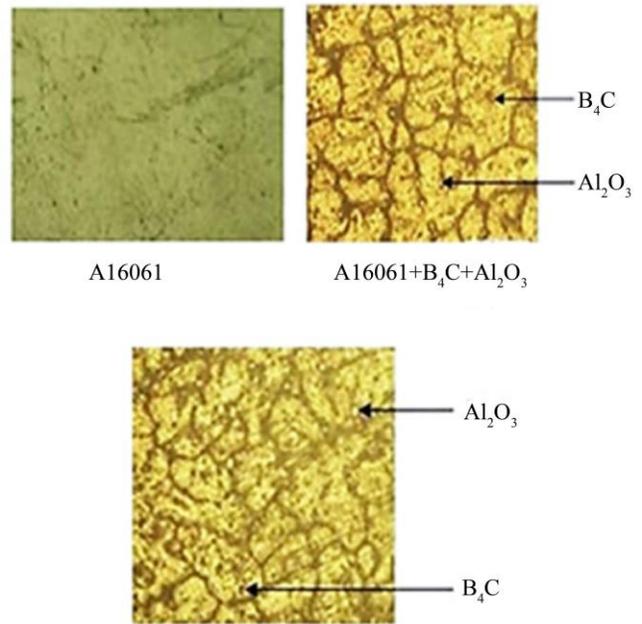


Fig. 4 Microstructural images of Al6061 with reinforcement of 3% B₄C and 3% Al₂O₃

3.4. SEM and EDS Characterization after WEDM

The Morphology of the surfaces machined by WEDM (Figure 5) displayed clear features, such as craters, ridges, micro-voids, recast layers, and some microcracks.

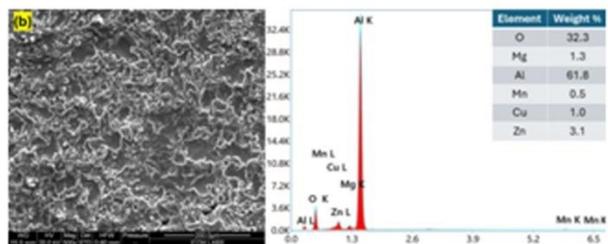


Fig. 5 Micrographs of the hybrid MMC machined surface, (a) B₄C 1% Al₂O₃ 1%, and (b) B₄C 5% Al₂O₃ 3%.

The surface effects are ascribed to spot melting, vaporization, and gas entrapment during spark-erosion, adequate and higher crater formation in terms of the high thermal conductivity of Al6061. Microcracks have been

found mainly at the reinforcement/matrix interfaces, indicating debonding induced by thermal stress concentration. The black areas of the surface correspond to reconsolidated melted material that was formed in the rapid chill. Energy-Dispersive X-Ray Spectroscopy (EDS) was used to verify the chemical composition of the alloy and reinforcements, which showed prominent peaks for Aluminum and Oxygen, followed by minor signals for Magnesium, Manganese, Copper, Silicon, and Zinc. In general, the analysis shows that the surface morphology is strongly dependent on WEDM parameters, and it represents a compromise between machining productivity and surface quality.

3.5. Hardness

The hardness test of the prepared composite (Figure 6) indicated that there is a significant enhancement with an increasing content of reinforcement. The unreinforced Al6061 Metal Matrix (Sample A) had the lowest hardness of 51 Kgf, and it increased in successive samples (B – H). Sample I obtained the highest hardness of 64 Kgf, which is in good agreement with the above result that Al₂O₃ was beneficial to increase the hardness and thermal stability. At the same time, B₄C could enhance wear resistance and self-lubricating property. The findings validate that combining these ceramic reinforcements is an efficient means of reinforcing the aluminum matrix.

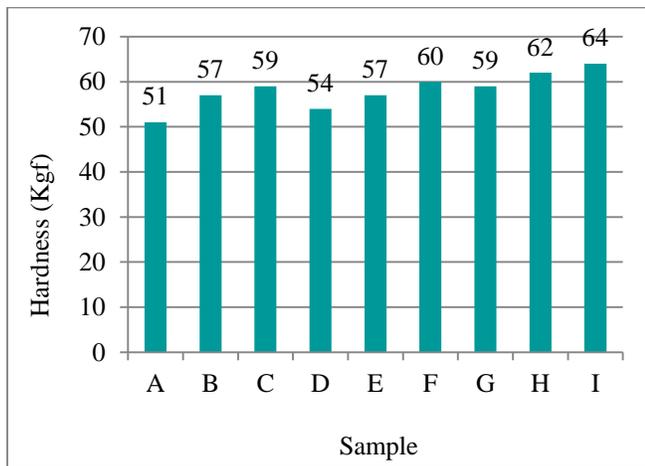


Fig. 6 Hardness of the samples A to I

3.6. WEDM Machinability

3.6.1. Kerf Width

As presented in Figures 7(a)–(c), the kerf's width of machined specimens is increased by increasing pulse current, the power-on time, and wire feeding speed. This has been attributed to the larger discharge energy in the machining zone, which consequently increases the material erosion. Nevertheless, the hybrid Al6061–Al₂O₃/B₄C composites caused a smaller kerf width compared with the unreinforced Al6061 alloy, showing improved thermal resistance as well as structural stability during WEDM.

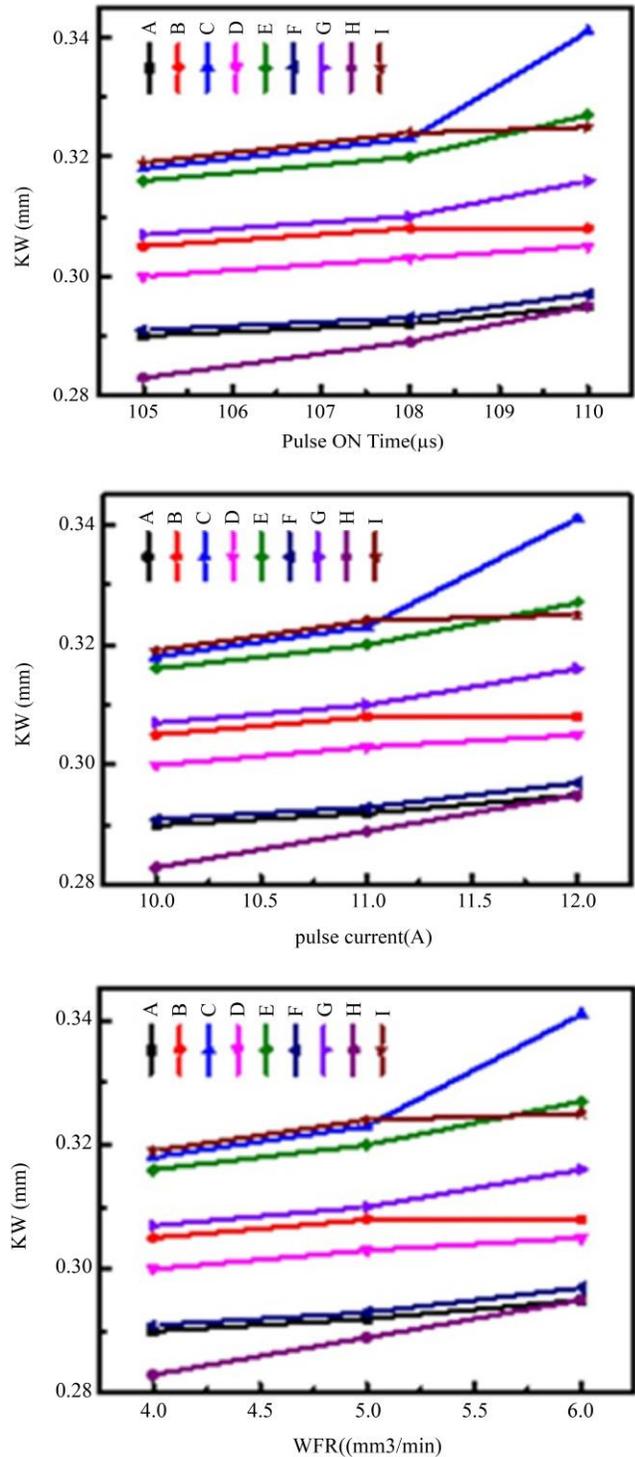


Fig. 7 (a) Effect of pulse on time (µs), (b) Effect of pulse current (A), and (c) Effect of wire feed rate (mm³/min) on KW for AA6061 and composite materials.

3.6.2. Surface Roughness

As shown in Figures 8(a)–(c), the surface roughness increased with an increasing pulse current and a longer pulse-on time, because the stronger spark energy induced more

severe material removal. However, several hybrid Al6061–Al₂O₃/B₄C composites exhibited relatively smooth surfaces as compared with those of the Al6061 base alloy. The improvement in the thermal shock resistance is attributed to advanced thermal stability and controlled erosion mechanism enabled by the synergistic action of Al₂O₃ with B₄C reinforcements.

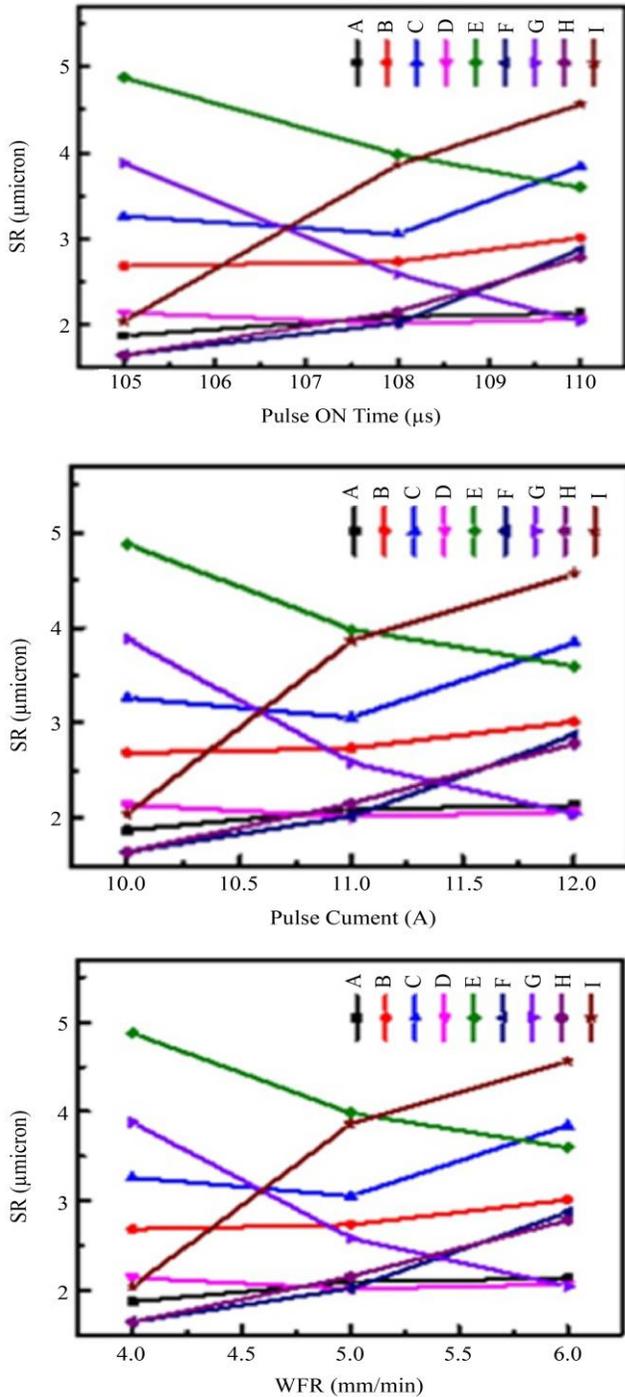


Fig. 8 (a) Effect of pulse on time (µs), (b) Effect of pulse current (A), and (c) Effect of wire feed rate (mm³/min) on Surface Roughness (SR) for AA6061 and composite materials.

3.6.3. Material Removal Rate (MRR)

As shown in Figure 9 (a)–(c), the MRR increased with increasing pulse current, pulse-on duration, and wire feed speed. This is attributed to the higher discharge energy, resulting in greater material-removal efficiency. Hybrid composites (Samples E-G) had higher MRR than the unreinforced Al6061 alloy, suggesting that the dual reinforcements retained morphology and improved machinability. The higher MRR with acceptable surface finish indicates that the Al–Al₂O₃–B₄C hybrid composites have good industrial applicability for WEDM performance.

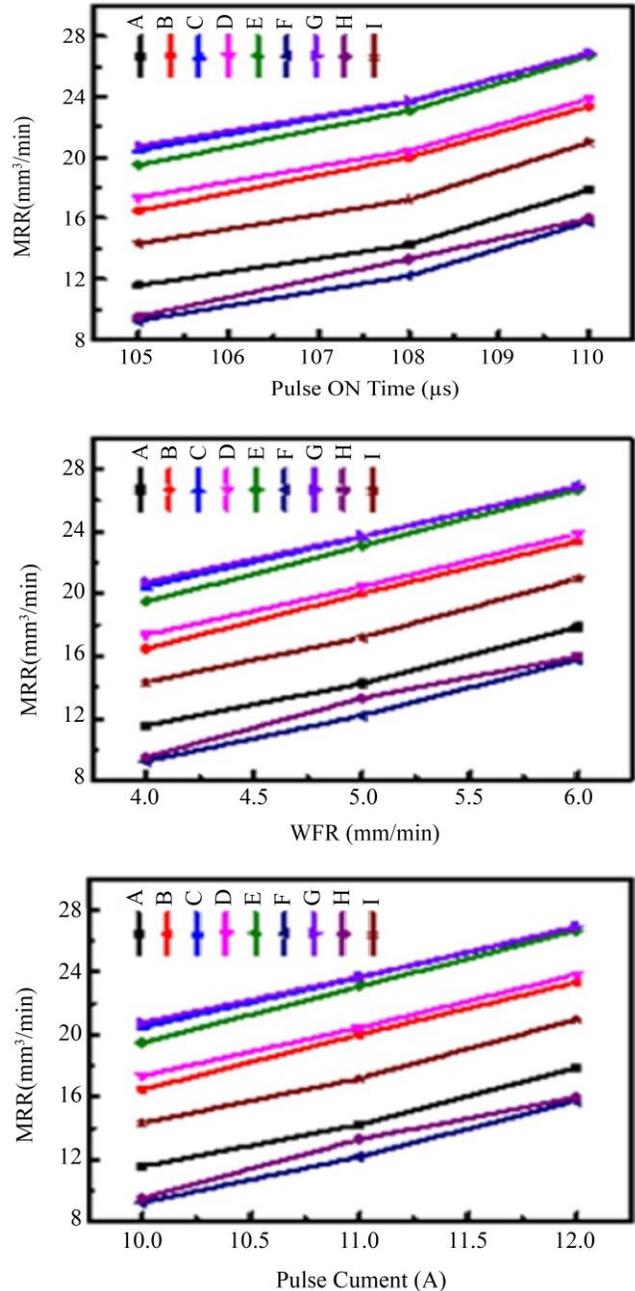


Fig. 9 (a) Effect of pulse on time (µs), (b) Effect of pulse current (A), and (c) Effect of wire feed rate (mm³/min) on Material Removal Rate (MRR) for AA6061 and composite materials.

4. Discussion

The current study has revealed that properties and machinability of Al6061-based Hybrid Metal Matrix Composites are strongly affected by reinforcement addition as well as WEDM parameters. The findings of hardness, MRR, Ra, and the Kerf Width during WEDM are in accordance with combined mechanisms caused by reinforcement strengthening phenomena and the PCD discharge-energy-regulated materials removal.

The increase in hardness with increasing Al₂O₃ and B₄C content, however, can be ascribed to the existence of challenging ceramic phases hindering the movement of dislocations in the Aluminium Matrix. Al6061 composites reinforced with Al₂O₃ and B₄C individually have also shown similar strengthening behaviour where load transfer from the ductile matrix to the hard particles, as well as dislocation pinning at the matrix–reinforcement interface, is responsible for increased hardness and strength [9, 10, 25].

For the hybrid composite, due to the simultaneous presence of Al₂O₃ and B₄C, there is a synergic effect. That is, Al₂O₃ contributes to better thermal stability and a more complex structure, while B₄C increases wear resistance and restricts localized plastic flow. This dual mechanism rationalizes the increase in hardness for the 5 wt% Al₂O₃ and 3 wt% B₄C composition compared with mono-reinforced systems from previous works [21, 30].

Microstructural observations also revealed that the stir-casting technique was able to achieve a relatively homogeneous distribution of reinforcement with minimum agglomeration. This homogeneity is crucial for uniform mechanical properties and a consistent machining response. It has been reported in the literature [17, 34] that hybrid AMCs with non-uniform particle distribution will result in Local Overheating (localized) and Poor Stability of Spark Erosion during WEDM. Thus, the relatively uniform distribution and well-dispersed particulate reinforcement in the present composites directly lead to the improvements of machinability, stability, and surface quality.

The WEDM results also show that the MRR increases as an increasing function of the pulse current and pulse-on time, resulting from higher discharge energy and deeper crater formation. This behavior agrees with observations made for aluminum alloys and particle-reinforced composites machined by WEDM [11-14]. Nevertheless, the performance of hybrids in terms of MRR is higher at similar machining parameters compared with Al6061 and other mono-reinforced systems found in the literature [12, 33]. This enhanced performance is attributable to the superior thermal stability of hybrid composites, which makes for more efficient material removal with fewer problems in terms of melting and re-solidification of the matrix aluminum.

The Surface Roughness and Kerf Width increased as discharge energy increased, and these results are consistent with typical WEDM erosion mechanisms, as violent material breakthrough accompanied by recast layer growth [31-33]. However, the hybrid Al6061–Al₂O₃–B₄C composites always had less Kerf Width and a nearly smoother surface compared to the base alloy in similar machining conditions. This is in contradistinction to some observations made with single-reinforced AMCs, which showed that a high amount of ceramic resulted in rough surface irregularities because of unstable discharge conditions [14, 34]. In this work, the presence of both Al₂O₃ and B₄C seems to be effective in stabilizing a spark erosion process by suppressing thermal gradients in the contact region as well as excessive lateral material removal.

The decreased Kerf Width in hybrid composites is attributed to the hardness and thermal stability of B₄C, which restrains lateral erosion and limits the extension of the discharge channel. Equivalent Kerf Size reduction has been seen in the case of B₄C-reinforced Hybrid Composites with Optimal Machining Parameters [17, 35]. Besides, Al₂O₃ particles help maintain the structural strength at high temperatures to reduce the deformation of the matrix in the cutting process. This coupled effect can account for the better dimensional accuracy in our present work than in the above references [19, 25].

ANOVA-based statistical analysis reveals that pulse-on-time is the most significant factor for all machining performance, followed by discharge current and wire feed. This result is in agreement with previous WEDM works that the pulse width is the most significant factor for discharge energy and crater formation [11, 23, 24]. Grey relational analysis was used to optimise the competing characteristics in a single process, i.e., Maximising MRR and Minimising Surface Roughness and Kerf Width. There are also some parallel multi-objective optimization methods successfully used for the multi-objective WEDM of Hybrid Composites. However, they put much emphasis on several selected reinforcement combinations or one desired performance target only [2, 17, 23]. The existing acceptance of the findings is further expanded in this research, showing a successful multi-response optimization for Al6061–Al₂O₃–B₄C hybrid composites.

The better machining behavior of the hybrid composite (5 wt% Al₂O₃ and 3 wt% B₄C) emphasizes the role of reinforcement proportion rather than maximum reinforcement content. An oversupply of ceramic might enhance the electrical instability and surface damage, as verified in previous reports [34, 37]. By contrast, the optimal composition found in this work offers a good balance of hardness, thermal stability, and machinability, which was believed to benefit the WEDM performance of the micro-tool but not surface integrity.

In general, the Mechanical, Microstructural, and Machining results indicate that the dual reinforcement of Al_2O_3 and B_4C has advantages over mono-reinforced and non-reinforced aluminum alloys. Combining reinforcement-induced microstructures with the WEDM response to statistically optimized machining parameters, this work suggests a fundamental research for hybrid composite machinability other than the previous reported studies. These results confirm the possibility of using Al6061– Al_2O_3 – B_4C hybrid composites as precision-engineered components where high strength, wear resistance, and dimensional accuracy are demanded at the same time.

5. Conclusion

The purpose of this work is to study the synergistic effect of Al_2O_3 - B_4C Hybrid Reinforcement on the mechanical properties and WEDM machinability characteristics of AMCs, to find an optimal composition combination for reinforcement as well as machining parameters for achieving a delicate balance between strength, surface integrity, and MRE. The data clearly indicate that Hybrid Reinforcement significantly influences mechanical properties and EDM performance. Al_2O_3 and B_4C additions resulted in a significant increase in the hardness, tensile strength, and wear resistance as compared to unreinforced Al6061. The composition of the hybrid composites containing 5 wt% Al_2O_3 and 3 wt% B_4C showed the best compromise in mechanical properties. The microscopic observation also demonstrated the homogeneous distribution of the reinforcement and low porosity that resulted in improved load transfer and thermal stability of the matrix. The WEDM machinability has been observed to be highly influenced by pulse-on time, discharge current, and wire feed rate. Statistical analysis showed that pulse-on time was the most significant factor for MRR, Roughness, and Kerf Width. Hybrid composites presented higher MRRs and lower Kerf Widths with acceptable SR, compared to the base alloy, reflecting enhanced turning stability. It was possible to optimize two conflicting machining responses simultaneously using Taguchi-based experimental design and grey relational analysis, which identified machining conditions instead of a trade-off between productivity and the surface finish. However, this study has certain limitations.

References

- [1] Srijan Prabhakar, Ravi Kumar Digavalli, and Sivanandam Aravindan, "Microstructural Evolution during Multi-axial Forging of AA6082/B4C Nanocomposites," *Journal of Materials Science*, vol. 60, pp. 3751-3767, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] Kishore Debnath et al., "Gray Relational Analysis for Parametric Optimization of Micro-EDM of Thermo-mechanically Processed AA7075 and AA7075/SiC/Gr Composite," *Journal of Micromanufacturing*, vol. 7, no. 2, pp. 164-180, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Vibhu Singh, Soni Kesarwani, and Mahendra Singh Niranjana, "Synergistic Effects of Boron Carbide and Eggshell Particles on Mechanical and Tribological Properties of Ultrasonic-assisted Stir cast Aluminium Alloy based Composites," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

The research was carried out within a narrow range of reinforcing particle sizes and weight percentages, and such experiments were performed using a single WEDM Wire Material and Dielectric Liquid. Moreover, rough-cut WEDM conditions were considered in this work, and no effects of trim cutting, multi-pass machining, or long-term tool wear were taken into account. Moreover, thermal effects such as the recast layer thickness and residual stress distribution were not evaluated.

It is thus advisable to aim at a larger range in reinforcement composition, the effect of particle size and morphology, as well as novel WEDM strategies, e.g., trim cutting or pulse waveform control, in future work.

There is a scope to explore more with fatigue, corrosion, and residual stress analysis for long-term performance of such materials in practical engineering applications. The incorporation of ML-based optimization methods might also improve the predictability of complex machining responses.

In summary, the results of this study highlight the relation between Hybrid Reinforcement composition and microstructure characteristics with WEDM performance, suggesting that Al6061– Al_2O_3 – B_4C hybrid composites have the potential to be used as high-precision components requiring a balance among mechanical strength, wear resistance, and machining efficiency.

Acknowledgments

The authors acknowledge the assistance of colleagues who contributed to material characterization and data analysis.

Credit - Author's Contribution Statement

All authors contributed to the study design, experiments, analysis, and manuscript preparation.

Lead Roles: Ashwin (concept & drafting), Sable/Pachpute (supervision), Patel/Hemanth/Thakur (testing & analysis), Balaji/Rahul (statistics & WEDM optimization).

- [4] Md. Nadeem Alam et al., “A Comprehensive Review on Wire EDM Performance Evaluation,” *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 236, no. 4, pp. 1724-1746, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] D. Vijay Praveen, D. Ranga Raju, and M.V. Jagannadha Raju, “Optimization of Machining Parameters of Wire-cut EDM on Ceramic Particles Reinforced Al-metal Matrix Composites – A Review,” *Materials Today: Proceedings*, vol. 23, pp. 495-498, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] S. Vijayabhaskar et al., “Review of WEDM Studies on Metal Matrix Composites,” *The 3rd International Conference on Materials and Manufacturing Engineering*, Tamilnadu, India, vol. 390, pp. 1-6, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Sneha H. Dhoria, K. Venkata Subbaiah, and V. Durga Prasada Rao, “Multi-Objective Parametric Optimization on WEDM of Hybrid Al6351/SiC/Gr Composites Using NSGA-II,” *Journal of The Institution of Engineers (India): Series D*, vol. 106, pp. 277-290, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] CH. Maheswara Rao, “Experimental Investigation on Improvements in Mechanical Properties of AA2024/Al₂O₃/B₄C Hybrid Composite,” Andhra University, India, pp. 1-81, 2024. [[Publisher Link](#)]
- [9] Şener Karabulut et al., “A Comparative Study on Mechanical and Ballistic Performance of Functionally Graded Al6061 Composites Reinforced with B₄C, SiC, and Al₂O₃,” *Journal of Materials Research and Technology*, vol. 23, pp. 5050-5065, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] Xiaoxuan Pang et al., “Tensile Properties and Strengthening Effects of 6061Al/12 wt%B₄C Composites Reinforced with Nano-Al₂O₃ Particles,” *Journal of Alloys and Compounds*, vol. 768, pp. 476-484, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] S.A. Sonawane, and M. Kulkarni, “Optimization of Machining Parameters of WEDM for Nimonic-75 Alloy using Principal Component Analysis Integrated with Taguchi Method,” *Journal of King Saud University – Engineering Sciences*, vol. 30, no. 3, pp. 250-258, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [12] M. Arunadevi, and C.P.S. Prakash, “Predictive Analysis and Multi-objective Optimization of Wire-EDM Process using ANN,” *Materials Today: Proceedings*, vol. 46, pp. 6012-6016, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] A. Dey, and K. M. Pandey, “Selection of Optimal Processing Condition during WEDM of Compcasted AA6061/Cenosphere AMCs Based on Grey-based Hybrid Approach,” *Materials and Manufacturing Processes*, vol. 33, no. 14, pp. 1549-1558, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Ram Singh et al., “Modelling and Optimizing Performance Parameters in the Wire-electro Discharge Machining of Al5083/B₄C Composite by Multi-objective Response Surface Methodology,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, pp. 1-32, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] A. Arunnath, S. Madhu, and Mebratu Tufa, “Experimental Investigation and Optimization of Material Removal Rate and Tool Wear in the Machining of Aluminum-Boron Carbide (Al-B₄C) Nanocomposite Using EDM Process,” *Advances in Materials Science and Engineering*, vol. 2022, pp. 1-11, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Md Nadeem Alam et al., “A Comparative Investigation on Powder Mixed EDM Machining of Steel Alloys with Multi-Objective Optimization Using Fuzzy-TOPSIS Method,” *Diyala Journal of Engineering Sciences*, vol. 17, no. 4, pp. 18-37, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Sree Ram Hariharan et al., “Optimization of AA6351–SiC–B₄C hybrid Composites in Wire EDM using Grey Relation Technique,” *Mechanics of Advanced Composite Structures*, vol. 11, no. 2, pp. 385-400, 2024. [[Google Scholar](#)]
- [18] R. Amuthakkannan et al., “Optimization of Multi Parameters of WEDM using ANN based on Principal Component Analysis for AA6063/B₄C Metal Matrix Composites,” *Materials Today: Proceedings*, pp. 1-8, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Nilesh Kumar, and Jatinder Kumar, “An Experimental Investigation on Surface Integrity and Wire Wear in Rough and Trim Cut Modes of WEDM for Hybrid Composite,” *Aircraft Engineering and Aerospace Technology: An International Journal*, vol. 96, no. 9, pp. 1234-1246, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] TS. Senthilkumar et al., “Studies of Kerf width and Surface Roughness using the Response Surface Methodology in AA 4032–TiC Composites,” *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 235, no. 6, pp. 2240-2253, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] Daulat Kumar Sharma, Mileend Sharma, and Gautam Upadhyay, “Boron Carbide (B₄C) Reinforced Aluminum Matrix Composites(AMCs),” *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 1, pp. 2094-2203, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Dilşad Akgümüş Gök, Ceren Bayraktar, and Merve Hoşkun, “A Review on Processing, Mechanical and Wear Properties of Al Matrix Composites Reinforced with Al₂O₃, SiC, B₄C and MgO by Powder Metallurgy Method,” *Journal of Materials Research and Technology*, vol. 31, pp. 1132-1150, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] Mangesh R. Phate, Shraddha B. Tone, and Vikas R. Phate, “Multi-Response Optimization and Analysis of Al/B₄Cp EDM using Grey Relational Analysis,” *Journal of Mechanical Engineering*, vol. 19, no. 1, pp. 39-56, 2022. [[Google Scholar](#)] [[Publisher Link](#)]

- [24] Ahmet Tolunay Işık, Ramazan Çakıroğlu, and Mustafa Günay, “Multiresponse Optimization of Performance Indicators through Taguchi-grey Relational analysis in EDM of Cemented Carbide,” *CIRP Journal of Manufacturing Science and Technology*, vol. 41, pp. 490-500, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [25] P. Bharathiraja, and M. Anthony Xavier, “Effect of B₄C and Graphene on the Microstructural and Mechanical Properties of Al6061 Matrix Composites,” *Journal of Materials Research and Technology*, vol. 31, pp. 496-505, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [26] M.K. Surappa, “Aluminium Matrix Composites: Challenges and Opportunities,” *Sādhanā*, vol. 28, pp. 319-334, 2003. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [27] D.B. Miracle, “Metal Matrix Composites – From Science to Technological Significance,” *Composites Science and Technology*, vol. 65, no. 15-16, pp. 2526-2540, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [28] J. Hashim, L. Looney, and M.S.J Hashmi, “Metal Matrix Composites: Production by the Stir Casting Method,” *Journal of Materials Processing Technology*, vol. 92-93, pp. 1-7, 1999. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [29] M. Kok, “Production and Mechanical Properties of Al₂O₃ Particle-Reinforced 2024 Aluminium Alloy Composites,” *Journal of Materials Processing Technology*, vol. 161, no. 3, pp. 381-387, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [30] Michael Oluwatosin Bodunrin, Kenneth Kanayo Alaneme, and Lesley Heath Chown, “Aluminium Matrix Hybrid Composites: A Review of Reinforcement Philosophies; Mechanical, Corrosion and Tribological Characteristics,” *Journal of Materials Research and Technology*, vol. 4, no. 4, pp. 434-445, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [31] K.H Ho, and S.T Newman, “State of the Art Electrical Discharge Machining (EDM),” *International Journal of Machine Tools and Manufacture*, vol. 43, no. 13, pp. 1287-1300, 2003. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [32] M. Kunieda et al., “Advancing EDM through Fundamental Insight into the Process,” *CIRP Annals*, vol. 54, no. 2, pp. 64-87, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [33] Nihat Tosun, Can Cogun, and Gul Tosun, “A Study on Kerf and Material Removal Rate in Wire Electrical Discharge Machining based on Taguchi Method,” *Journal of Materials Processing Technology*, vol. 152, no. 3, pp. 316-322, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [34] Ajay R. Bhardwaj, AM. Vaidya, and SP. Shekhawaj, “Machining of Aluminium Metal Matrix Composite: A Review,” *Materials Today: Proceedings*, vol. 21, pp. 1396-1402, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [35] P. Narender Singh, K. Raghukandan, and B.C. Pai, “Optimization by Grey Relational Analysis of EDM Parameters on Al–10%SiCp Composites,” *Journal of Materials Processing Technology*, vol. 155-156, pp. 1658-1661, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [36] Vagheesan Senthilkumar, Anbazhagan Nagadeepan, and K. K. Ilavenil, “Investigating and Multi-Objective Optimizing WEDM Parameters for Al6061/Mg/MoS₂ Composites Using BBD and NSGA-II,” *Materials*, vol. 17, no. 23, pp. 1-13, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [37] Douglas C. Montgomery, *Design and Analysis of Experiments*, 9th ed., John Wiley & Sons, Incorporated, pp. 1-734, 2017. [[Google Scholar](#)] [[Publisher Link](#)]
- [38] Gaurav Anand et al., “Multi-objective Optimization to Enhance Surface Integrity in WEDM for Al-matrix Composite: A Comparative Assessment of Self-weight Adjusting MCDMs and Objective Weight Integrated Hybrid TOPSIS Methods,” *Results in Surfaces and Interfaces*, vol. 18, pp. 1-28, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [39] C. Prakash et al., “Machinability Analysis of LM26 Aluminium Metal Matrix Composites Reinforced with Graphite and Fly Ash using the AWJM Process,” *Scientific Reports*, vol. 15, pp. 1-16, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [40] K. Kalaiselvan, N. Murugan, and Siva Parameswaran, “Production and Characterization of AA6061–B₄C Stir Cast Composites,” *Materials & Design*, vol. 32, no. 7, pp. 4004-4009, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]