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Mechanical Characterization of Al6061 Hybrid Composites Reinforced with Boron Carbide and Fly Ash via Stir Casting

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Abstract

The growing demand for lightweight, cost-effective, and high-performance materials in structural and automotive sectors has accelerated the development of hybrid metal matrix composites (HMMCs). This study investigates Al6061 alloy as the matrix material, reinforced with varying weight fractions of boron carbide (B_4C), a high-hardness ceramic, and fly ash, an economical industrial byproduct, to assess their synergistic effects on mechanical properties. Hybrid composites were synthesized using the stir casting technique to ensure uniform dispersion of reinforcements. Five compositions were evaluated: the base alloy, 5 wt.% B_4C + 5 wt.% fly ash, 7.5 wt.% B_4C + 7.5 wt.% fly ash, 10 wt.% B_4C + 10 wt.% fly ash, and 12.5 wt.% B_4C + 12.5 wt.% fly ash. Mechanical performance was assessed through hardness testing, tensile strength analysis, and compressive strength evaluation. Results revealed that B_4C significantly improved hardness and strength due to its intrinsic properties and strong interfacial bonding, while fly ash contributed to weight reduction and cost efficiency. Among the tested compositions, the hybrid with 7.5 wt.% B_4C and 7.5 wt.% fly ash demonstrated superior tensile and compressive strength, indicating an optimal balance between mechanical enhancement and material sustainability. This study underscores the potential of B_4C and fly ash as effective hybrid reinforcements in Al6061 composites and promotes the sustainable integration of industrial waste in advanced engineering materials

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Keywords: Al6061, fly ash, B_4C, stir casting, tensile

INTRODUCTION

The demand for advanced engineering materials with superior mechanical properties and reduced weight has intensified in recent years, especially in sectors, such as aerospace, automotive, defense, and structural engineering [1–5]. Traditional monolithic materials often fail to meet the multifaceted requirements of these industries, which has led to increased research into composite materials.

Among these, metal matrix composites (MMCs) have gained significant attention due to their enhanced strength-to-weight ratio, wear resistance, and thermal stability [6]. These composites consist of a metal or alloy matrix reinforced with ceramic, metallic, or organic materials, which together improve the performance of the base metal.

Aluminum and its alloys, particularly Al6061, are widely used as matrix materials in MMCs due to their excellent combination of low density, corrosion resistance, good machinability, and moderate strength [7]. Al6061 is a precipitation-hardened alloy containing magnesium and silicon as its major alloying elements, which offers good mechanical properties and weldability, making it a preferred material for structural and transportation applications [8]. However, in its monolithic form, Al6061 does not possess the required wear resistance and strength for more demanding applications, necessitating the incorporation of reinforcements to improve its overall performance.

While the addition of a single reinforcement, such as silicon carbide (SiC), alumina (Al_2O_3), or boron carbide (B_4C) can significantly improve the mechanical properties of aluminum alloys, these improvements often come at the cost of reduced ductility or increased brittleness. To overcome such limitations, researchers have introduced the concept of hybrid metal matrix composites (HMMCs), where two or more types of reinforcements are combined to exploit the strengths of each. This approach enables tailored material behavior, allowing a balance between strength, ductility, and toughness depending on the application.

Boron carbide (B_4C) offers high hardness, low density, and a high elastic modulus, making it ideal for strengthening aluminum composites. However, its high cost and brittleness can limit its use. Fly ash, an inexpensive by-product of coal combustion, contains silica and alumina and serves as a cost-effective secondary reinforcement. It enhances compressive strength and damping while promoting sustainability by recycling industrial waste.

Over the last few years, increased demands for high-strength and wear-resistant lightweight materials have fueled extensive research into aluminum matrix composites (AMCs). Among them, Al6061 has also become one of the base metals of preference because of its optimum strength-to-weight ratio, corrosion resistance, and ease of machining. To further improve its tribological and mechanical properties, researchers have added ceramic reinforcements like silicon carbide (SiC), boron carbide (B_4C), and aluminum oxide (Al_2O_3) to the matrix. several studies have proven that these reinforcements greatly enhance tensile strength, hardness, and wear resistance. Didwania et al. [9] have reported that hybrid composites reinforced with combinations, such as SiC, fly ash, graphite, and mica resulted in better dispersion and mechanical performance, evidencing a synergistic strengthening effect when more than one reinforcement is utilized. Anand et al. [10] highlighted the functions of Al_2O_3 particles, micro- and nanosized, in improving interfacial bonding and mechanical properties of aluminum composites, with nanoreinforcements demonstrating even more significant advantages because of their higher surface area.

Besides reinforcement type, the fabrication and process routes are also important in controlling composite performance. Keskin et al. [11] optimized the powder-mixed electrical discharge machining (PMEDM) parameters for composites based on AA7075 reinforced with B_4C and SiC, which resulted in improved machining performance and surface quality. Mehta et al. [12] investigated CNC turning and friction stir processing (FSP) as postprocessing techniques to enhance the machinability and wear resistance of aluminum composites and found that fine-grain structures and homogeneous reinforcement distribution played a critical role in the improvement of the properties. Maniraj et al. [13] employed recent processing methods like extrusion and directed energy deposition to produce Al6061 composites with CNTs and B_4C, which resulted in uniform dispersion of reinforcements and a substantial increase in strength and resistance to wear.

In addition, research by Agrawal et al. [14] attested that optimized incorporation of SiC in hybrid metal matrix composites results in enhanced tensile strength and erosion resistance. These observations together emphasize that both reinforcement selection and processing method are crucial toward optimizing the properties of AMCs. These observations are the foundation for the current study, which deals with the influence of hybrid reinforcements—, i.e., B_4C and fly ash—on the mechanical performance of Al6061 composites.

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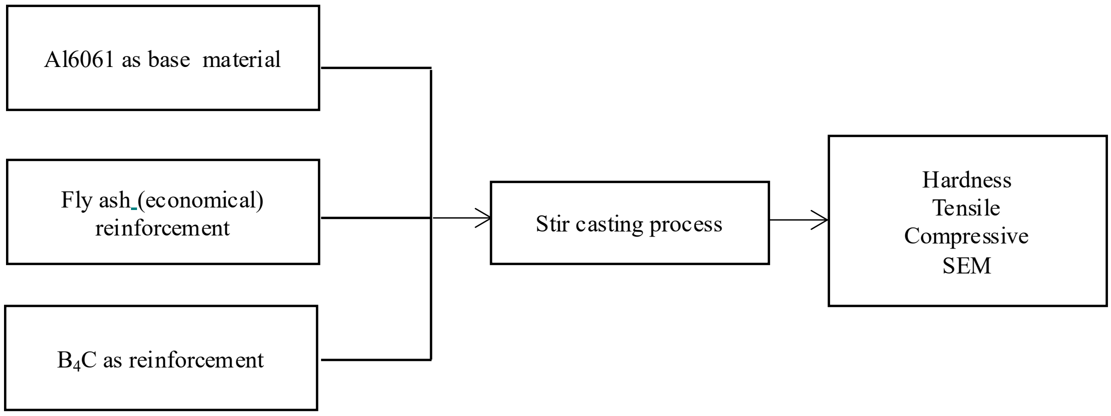

Figure 1. Workflow diagram.

Although Al6061 composites with B_4C or fly ash have been studied individually, limited work exists on their combined effect. B_4C improves hardness and wear resistance, while fly ash reduces cost and enhances sustainability. No prior study has examined Al6061 composites reinforced only with B_4C and fly ash in matched proportions. For example, one researcher studied a different Al alloy with 3% B_4C + 7% fly ash, and another researcher has reinforced Al6061 with B_4C, MgO, and fly ash, but these include additional reinforcements or different matrices. The present work is novel in systematically investigating Al6061 with equal-weight B_4C–fly ash hybrids, identifying the optimal blend for strength and sustainability. This study investigates Al6061-based hybrid composites with varying B_4C and fly ash ratios, focusing on hardness, tensile, and compressive strength. The goal is to identify an optimal, cost-effective reinforcement blend for structural applications.

MATERIALS AND METHODS

In this study, Al6061 alloy was selected as the base metal for fabricating hybrid metal matrix composites (HMMCs) due to its excellent mechanical properties, corrosion resistance, and widespread industrial usage. The reinforcements employed were boron carbide (B_4C) and fly ash. The B_4C powder used had an average particle size of about 63 µm, and the fly ash particles were roughly 12 µm in diameter. The fly ash was a low-calcium Class F ash ($SiO_2 + Al_2O_3 \geq 70\%$ by weight, ASTM C618). These size and composition details are included for completeness and to aid reproducibility. B_4C was chosen for its high hardness, wear resistance, and low density, while fly ash—a cost-effective, eco-friendly by-product of coal combustion—was incorporated to reduce the overall density and manufacturing cost of the composites while contributing to mechanical performance.

The hybrid composites were fabricated using the stir casting technique, a widely adopted method for producing metal matrix composites owing to its simplicity, scalability, and ability to accommodate diverse reinforcements [15–18]. Al6061 alloy was melted in a resistance furnace at approximately 750 °C. Once the alloy reached a fully molten state, preheated B_4C and fly ash particles were introduced in varying proportions, as detailed in Table 1. The overall workflow diagram is as shown in Figure 1.

To ensure uniform dispersion of the reinforcements, the molten mixture was stirred continuously at 500 rpm for 15 minutes using a mechanical stirrer. The reinforcement particles were preheated to 200 °C prior to addition to minimize moisture content and improve wettability within the molten aluminum matrix. After stirring, the composite melt was poured into preheated steel molds and allowed to solidify under ambient conditions. The resulting cylindrical castings measured 20 mm in diameter and 100 mm in length.

Each mechanical test (hardness, tensile, and compressive) was conducted on three specimens for each composite composition. The reported values represent the mean of three measurements. Error bars shown in the graphs correspond to ± one standard deviation, ensuring statistical reliability and repeatability of the experimental results.

Table 1. Composition of composites.

Composite	Notation	Al6061 (%)	B_4C (%)	Fly Ash (%)
Composite 1	A1	100	0	0
Composite 2	A2	90	5	5
Composite 3	A3	85	7.5	7.5
Composite 4	A4	80	10	10
Composite 5	A5	75	12.5	12.5

Testing of Mechanical Properties

Microstructural Analysis

Microstructural characterization was conducted using scanning electron microscopy (SEM) to evaluate the dispersion, bonding, and interfacial integrity of boron carbide (B_4C) and fly ash particles within the Al6061 matrix. Specimens were polished and etched to reveal the microstructure. SEM images demonstrated a relatively uniform distribution of reinforcements with minimal clustering or porosity across all composite formulations. The homogeneous dispersion of B_4C and fly ash suggests effective stirring and wetting during the casting process, contributing to improved mechanical performance.

Hardness Testing

Hardness measurements were performed using the Rockwell B (HRB) scale in accordance with ASTM E18 standards. Cylindrical castings (20 mm diameter × 100 mm length) were sectioned into disc-shaped samples approximately 10 mm thick. These samples were polished to achieve a smooth surface finish and tested using a 1/16-inch steel ball indenter under a 100 kgf major load. Multiple readings were taken and averaged to ensure accuracy and repeatability. The results indicated a progressive increase in hardness with higher reinforcement content, attributed to the intrinsic hardness of B_4C and the particulate strengthening effect of fly ash. The synergistic interaction between the ceramic reinforcements and the aluminum matrix contributed to enhanced resistance against localized deformation [19].

Tensile Testing

Tensile properties were evaluated using a universal testing machine (UTM) following ASTM E8 standards. Specimens were machined from the castings into sub-size dog-bone shapes with a gauge diameter of 6 mm and a gauge length of 25 mm. Tests were conducted at ambient temperature with a constant crosshead speed of 1 mm/min. Load-displacement data were recorded to determine ultimate tensile strength (UTS), yield strength, and percentage elongation. The results revealed that increasing the content of B_4C and fly ash led to a notable improvement in tensile strength, primarily due to enhanced load transfer and matrix reinforcement. However, a slight reduction in ductility was observed, attributed to the brittle nature of the ceramic particles and their tendency to restrict plastic deformation [20].

Compressive Testing

Compressive strength testing was carried out on cylindrical specimens (20 mm diameter × 20 mm height), extracted from the original castings. The tests adhered to ASTM E9 standards using a UTM equipped with compression platens. Specimen ends were ground flat to ensure parallelism and uniform stress distribution during loading. Axial compressive load was applied at a constant rate until visible deformation or fracture occurred. Compressive strength was calculated based on the maximum load sustained. The incorporation of B_4C and fly ash significantly enhanced compressive strength, particularly at higher reinforcement ratios, due to improved load-bearing capacity and the stiffening effect of the ceramic phases [21,22].

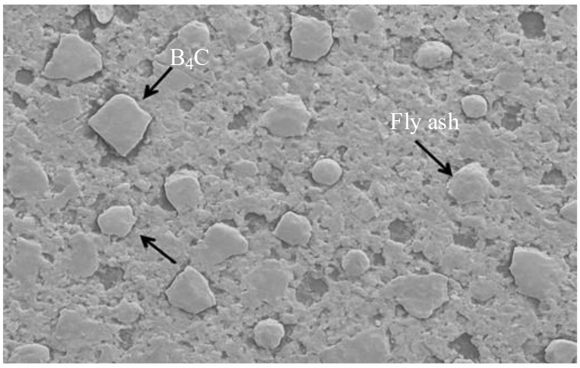

Figure 2. SEM image of Al6061 + 7.5% B_4C + 7.5% fly ash hybrid composite.

RESULTS AND DISCUSSION

Microstructural Studies

Figure 2 presents the SEM micrograph of composite A2 (Al6061 + 7.5 wt.% B_4C + 7.5 wt.% fly ash), which exhibited the best mechanical performance among all tested samples. The image reveals a uniform distribution of angular B_4C particles and spherical fly ash particles within the aluminum matrix. The absence of significant agglomeration and interfacial debonding indicates successful dispersion achieved through the stir casting process. Minimal porosity and strong particle-matrix bonding are evident, contributing to the enhanced mechanical properties observed in this composition. The microstructural integrity of composite A2 confirms the effectiveness of the selected processing parameters and reinforcement ratios.

Hardness

Vickers hardness testing revealed a clear trend of increasing hardness with the addition of ceramic reinforcements. The base alloy (A0) recorded the lowest hardness value of 58.2 HV, while composite A2 achieved the highest hardness of 79.4 HV, as shown in Figure 3. This improvement is attributed to the intrinsic hardness of B_4C and its strong interfacial bonding with the aluminum matrix. Composites A1 and A4 showed moderate hardness values, whereas A3, with a higher proportion of fly ash, exhibited reduced hardness. This suggests that while fly ash contributes to weight and cost reduction, its lower hardness compared to B_4C limits its effectiveness in enhancing surface resistance.

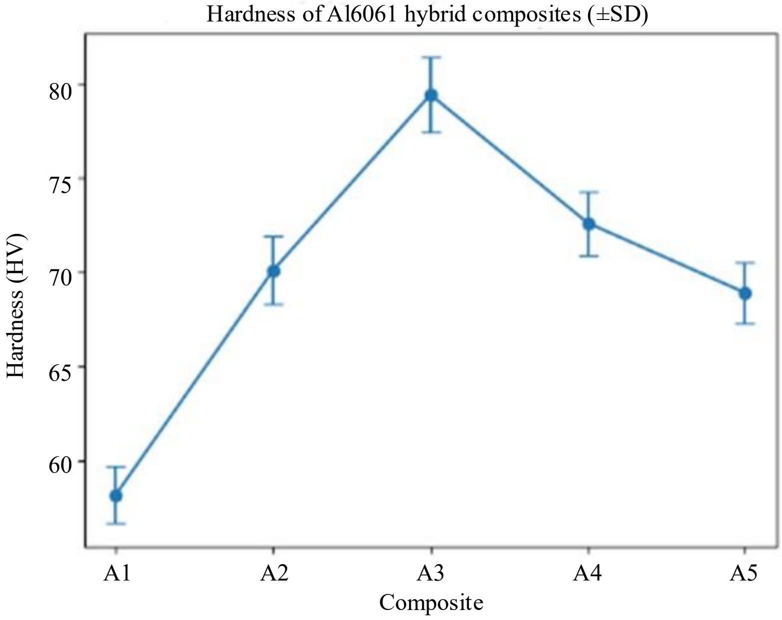

Figure 3. Graph of hardness with error bars.

Tensile Test

Tensile testing, conducted in accordance with ASTM E8 standards, demonstrated a consistent increase in ultimate tensile strength (UTS) and yield strength (YS) with increasing reinforcement content. The base alloy (A0) exhibited the lowest UTS (145.2 MPa) and highest ductility (12.4%), as shown in Figure 4. Composite A4, with the highest reinforcement content (12.5% B_4C + 12.5% fly ash), recorded the highest UTS (176.8 MPa) and YS (128.2 MPa). However, this came at the cost of reduced ductility, with elongation dropping to 6.5%. The stiff and brittle nature of ceramic reinforcements restricts plastic deformation, leading to this trade-off. These results confirm that hybrid reinforcement effectively enhances tensile strength, though careful optimization is required to balance strength and ductility.

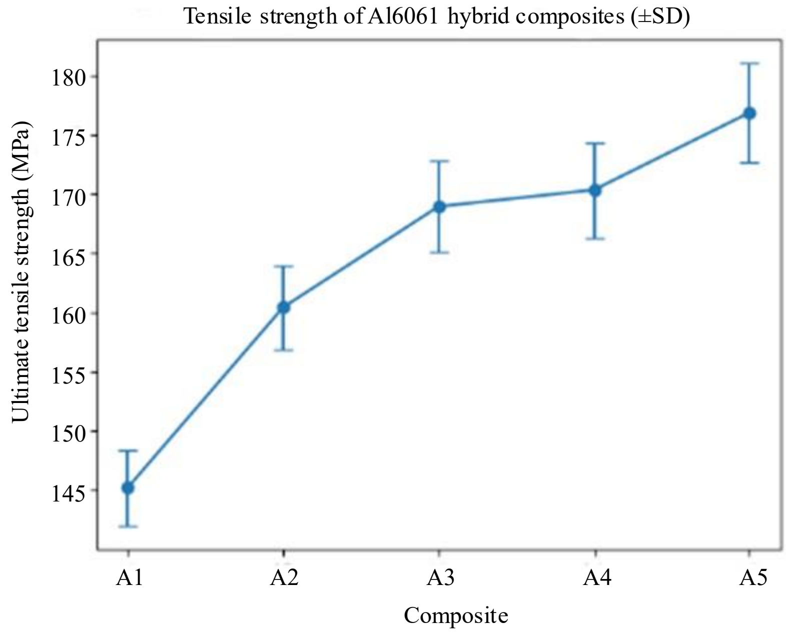

Figure 4. Tensile readings graph with error bars.

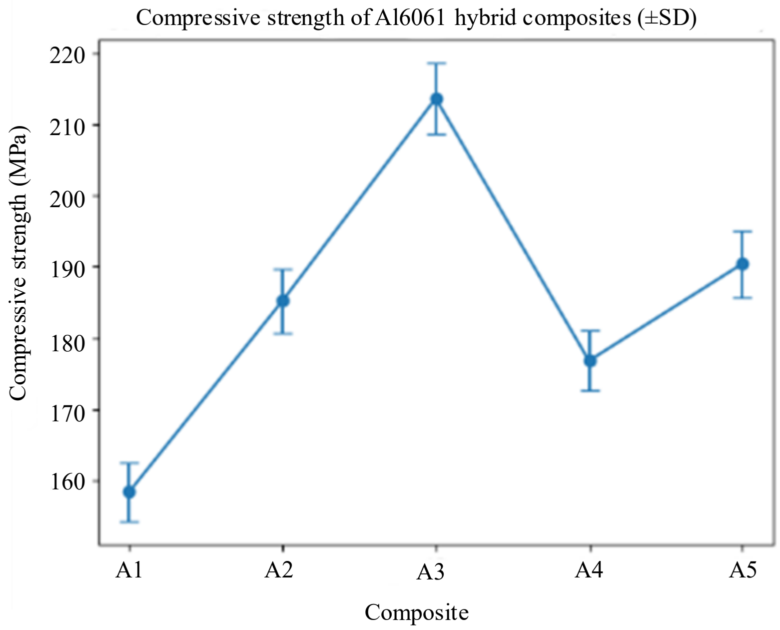

Figure 5. Compressive strength with error bars.

Compressive Strength

Compressive strength testing, performed as per ASTM E9 standards, revealed significant improvements with the incorporation of B_4C and fly ash. The base alloy (A0) recorded the lowest compressive strength of 158.4 MPa. Composite A2 exhibited the highest value of 213.6 MPa, underscoring the reinforcing effect of B_4C in resisting compressive deformation. The ceramic particles act as barriers to dislocation movement, enhancing the load-bearing capacity of the matrix. Composites A1 and A4 showed moderate improvements, while A3 had the lowest strength among the reinforced samples [23]. This suggests that excessive fly ash, despite its economic and weight advantages, may compromise mechanical integrity due to its lower stiffness compared to B_4C. A balanced combination of both reinforcements is essential to achieving optimal mechanical performance in hybrid aluminum matrix composites. Figure 5 depicts the compressive strength versus samples.

CONCLUSION

The present study successfully demonstrated the fabrication and mechanical evaluation of Al6061-based hybrid metal matrix composites reinforced with boron carbide (B_4C) and fly ash using the stir casting technique. Microstructural analysis confirmed a uniform dispersion of angular B_4C and spherical fly ash particles within the aluminum matrix, with minimal porosity and strong interfacial bonding—particularly in composite A2 (7.5 wt.% B_4C + 7.5 wt.% fly ash), which exhibited the most homogeneous structure and superior mechanical performance. Hardness testing revealed a significant increase in surface resistance with higher B_4C content, while fly ash contributed to weight reduction and cost efficiency. Tensile strength improved progressively with reinforcement addition, reaching a maximum of 176.8 MPa in composite A4, although a corresponding reduction in ductility was observed due to the brittle nature of ceramic particles. Compressive strength was highest in composite A2, attributed to the stiffening effect of B_4C and the synergistic role of fly ash in load distribution. Overall, the results highlight that a balanced combination of B_4C and fly ash not only enhances mechanical properties but also supports sustainable material development.

The optimal reinforcement ratio of 7.5 wt.% B_4C and 7.5 wt.% fly ash offers a promising solution for lightweight, cost-effective, and high-performance materials in structural and automotive applications. The enhanced strength-to-weight ratio and wear resistance of the Al6061–B_4C–fly ash hybrids make them promising for demanding applications (, e.g., automotive or aerospace components like drive shafts or brake parts) where low cost and durability are critical. However, the high ceramic content tends to reduce ductility and toughness; the fly ash phase diminishes the material's inherent ductility and tensile strength, which may limit impact resistance. Processing challenges, such as achieving uniform dispersion at a large scale and potential tooling wear from hard particles, must also be considered. We briefly note these limitations and suggest that future work address optimization of reinforcement size, fraction, or hybrid processing to mitigate them.

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