

Enhancing Mechanical and Tribological Properties of AA6063 Matrix Composites Through Nanoscale Boron Carbide Reinforcement

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Abstract

In this study, an investigation was conducted to assess the influence of nanoscale boron carbide (nB_4C) particles on the mechanical and tribological properties of AA6063 matrix composites. Using a mechanical stirrer, researchers mixed together AA6063 matrix composites with various amounts of nB_4C (from 0 to 2.0 wt.%). The experimental results demonstrated that the addition of nB_4C not only increased the elastic modulus of the material but also led to an enhancement in its brittle behavior, consequently reducing the failure strain significantly. Furthermore, the addition of nB_4C exhibited notable improvements in the shear modulus and flexural shear modulus of the composites. Notably, the introduction of nB_4C into the AA6063 matrix resulted in reduced subsurface fatigue wear and increased wear resistance, attributed to the beneficial lubricating properties of B_4C . Various tests were conducted to evaluate parameters such as wear, microstructure, morphology, density and voids, hardness, flexural and tensile strength. The results indicated that the addition of nB_4C led to enhanced wear resistance and tensile strength in the composites. Specifically, the highest wear resistance and tensile strength were achieved with the inclusion of 2 wt.% nB_4C in the aluminum (Al) metal matrix composite. Microscopical analysis further revealed a consistent and uniform distribution of B_4C particles throughout the Al matrix, indicating a promising dispersion of the reinforcement material within the composite.

Keywords

Composite, Boron carbide, Tribological properties, Wear properties, Mechanical properties

Introduction

Modern materials with improved qualities are gaining popularity as a possible solution to existing problems or as a replacement for established materials like metals. Cutting-edge composite matrix composite materials have been developed as a result of this study, and these materials are now used in the design and production of a wide variety of products, including automobile and aero plane parts, construction materials, sports equipment, and even biomedical devices [1]. It is known that fiber-reinforced composite matrix composites perform better than their unreinforced counterparts. However, the matrix overloading features of these composites often limit their usefulness in the long run [2]. Modern composite materials that handle these issues are of highest importance for specific

architectural applications, and their research is crucial to expanding the range of composites' tertiary use.

One of the most widely used multi-stage materials, fiber-reinforced Al matrix composites are prized for their light weight and excellent strength-to-weight ratio [3]. Amazing mechanical and tribological capabilities, good resistance to chemicals and corrosion, and remarkable dimensional stability are only some of the features of composites with an Al matrix [4]. Some of the features governed by matrices, including in-plane and interlaminar shear, are quite good. However, there is need for improvement in matrix solidity, toughness, and hardness. Fusing filler particles with Al is a common traditional practice for improving properties [5]. Previous studies have demonstrated that the mechanical characteristics of matrix-dominated material composites can be enhanced by including ceramic fillers including SiO₂, mica, CaCO₃, glass beads, clay, alumina trihydrate, and fly ash [6]. Increases in hardness, thermal distortion temperature, stiffness, strength, and mould shrinkage are only some of the benefits. Variations in filler concentration, filler shape, filler size, filler packing properties, filler particle content, and interfacial interaction with the matrix can all affect quality. Improving properties of metal matrix composites is most strongly correlated with their reduction in particle size from the micro to the nanoscale [7-9].

An exciting strategy for developing novel composite matrix materials with enhanced capabilities is the incorporation of fillers with unique properties into an existing matrix [10]. Large particle concentrations cause hurdles and potential property disadvantages, such as resistance to creep and fatigue, brittle behavior, and so on, despite the rule of mixing exhibiting superior mechanical performance for the larger division of reinforcing stage [11, 12]. Reinforcements made from materials such B₄C, graphene and TiO₂ can be used to create multifunctional designing parts with excellent thermal and electrical conductivity, as well as great mechanical performance and dependability [13, 14]. In particular, B₄C offers the lowest price while combining all of these desirable qualities.

Enterprises place a premium on the research and development of solutions that are both lightweight and resilient in terms of mechanical quality, seizure tendency, wear, and electrical loss. Among the potential uses for metal substitution are biosensors, radar shielding, electronic bundling, and electromechanical management frameworks [15]. Tribological and mechanical features of B₄C-reinforced Al composites are studied here. The ultimate objective is to create a novel metal-ceramic composite material that excels in both mechanical and wear qualities.

Extensive research has shown that the characteristics improve, plateau, or deteriorate with increasing B₄C concentration [16]. Mechanical and tribological parameters, such as tensile modulus, strength, deformation, wear rate, and COF (Coefficient of friction), are being compared across composites with increasing percentages of B₄C in an Al matrix. Different mechanical and tribological factors have been studied in an effort to zero in on the best possible combination [17].

Materials and Method

Materials

In this research, nB₄C (0.4, 0.8, 1.2, 1.6, and 2.0 wt.%) was embedded in an Al matrix material (AA6063). Physical and mechanical properties of AA6063 and nB₄C are tabulated in table 1. Al6063 alloy's chemical composition is summarized in table 2.

Table 1: Characteristics of materials.

Material	AA60603	B ₄ C (50 - 70 nm)
Density (g/cm ³)	2.69	2.52
Melting point (°C)	615	2445
Theral conductivity (W/mK)	201 - 218	30 - 42
Co-efficient of thermal expansion (°C)	2.34 x 10 ⁻⁵	5 x 10 ⁻⁶
Modulus of elasticity (GPa)	68.3	450 - 470

Table 2: AA6063 chemical composition.

AA6063	Percentage
Fe	0.35
Si	0.2 - 0.6
Mg	0.45 - 0.90
Mn	01.0
Cr	0.10
Cu	0.10
Zn	0.10
Ti	0.10
Al	Balance

Sample preparation

The desired effect was achieved by employing a ceramic reinforced metal network composite in this work. AA6063 was used as the foundation, and nB₄C powder was used as the filler. The metal casting process was used to prepare the Al metal composite [18, 19]. Al is melted in an electric furnace to 800 °C, and samples are taken out for later comparison with composites that have B₄C added to them. The molten Al was then combined with a preheated ceramic. If the molten Al has froth on top, that froth must be removed before the B₄C may be added. B₄C powder must be mixed with a little amount of magnesium before it can be properly applied on Al. For 10 min at 400 rpm, a mild steel stirrer combines molten metal with powdered B₄C. When the AA6063 and B₄C liquid mixture has cooled in the air for 30 min, it is poured into a mold. For each concentration of reinforced ceramic, the same procedure was repeated. The detailed steps involved in creating an Al + nB₄C composite is displayed in figure 1.

Density and void testing

When it comes to using composites in engineering constructions, the existence of manufacturing-induced defects such voids are a major obstacle. The process to be followed during the void assessment test is detailed in the ASTM D 2734-94 standard [20]. Both the geometric solution and the Archimedes method were used to calculate the densities of AA6063-B₄C composites. Using table 1, theoretical bulk

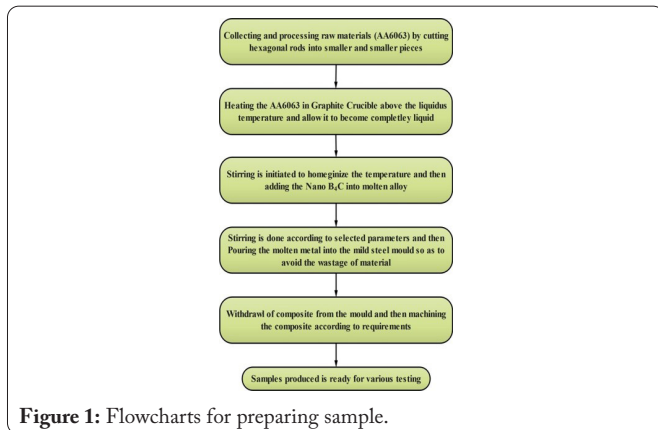


Figure 1: Flowcharts for preparing sample.

thickness values for AA6063 and B_4C , the relative density was calculated. The discrepancy between the theoretical and experimental values of porosity was resolved.

Mechanical testing

The figure 2 shows the machines used to conduct tensile and flexural testing with a 10 kN load cell. AA6063- B_4C composite samples were tensile tested at a crosshead rate of 1 mm/min in accordance with ASTM C1557-14, and 3-point bending flexural tests were performed at a crosshead rate of 5 mm/min and a span length of 100 mm in accordance with ASTM C1161-02C [21, 22]. For the purpose of gauging reproducibility, at least three separate tests of each type were conducted, and the means and standard deviations of these values were recorded.

Hardness

A Vickers diamond indenter and a UHL micro-hardness tester were used to measure the micro-hardness of the finished composites, and the results are displayed in figure 3. The in-

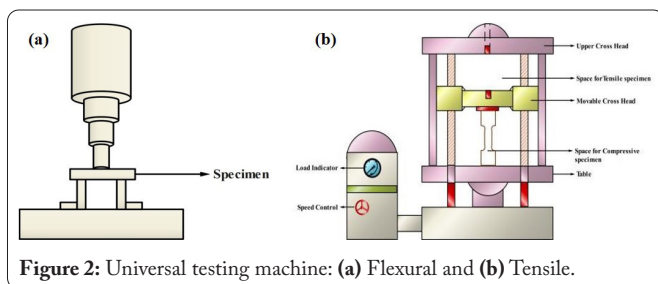


Figure 2: Universal testing machine: (a) Flexural and (b) Tensile.

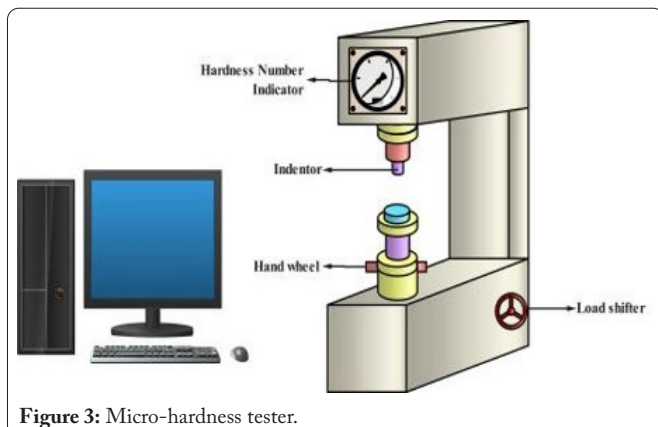


Figure 3: Micro-hardness tester.

dentation process lasted for 15 s, during which time the load was applied at a speed of 50 mm/s [23]. Specialized software on the connected computer used the indentation image to calculate an approximation of the material's Vickers hardness. Five distinct tests were averaged for this analysis.

Wear testing

The wear characteristics of Al- B_4C composites were also characterized with the aid of a multi-tribo tester. A revolving roller made of EN8 steel with a chromium coating to apply pressure to $20 \times 20 \times 8 \text{ mm}^3$ samples (Hardness 55 HRC) was used [24, 25]. The test was conducted at 20 kN of normal load continuously with no lubrication at a linear speed of 4 mm/s at room temperature. Over the course of 5 min, or 600 cycles, or 600 mm in total spacing, the test results were replicated. Each specimen underwent three wear tests to ensure accurate results, during which the coefficient of friction was also measured.

Results and Discussion

It was only possible to add 2 wt.% of B_4C platelets due to the method utilized to insert them into the Al structure. The microstructure and distribution of the delivered materials are consistent. Surface roughness can be reduced by the addition of B_4C , as observed above; while polished Al still has noticeable ridges and bumps, increasing the amount of B_4C results in increasingly polished Al. It is speculated that this occurs because B_4C has a self-lubricating effect.

The surface roughness of the materials produced is affected by the amount and kind of voids introduced during the manufacturing process [26]. The Al shows obvious gaps between agglomerated B_4C platelets at a B_4C addition of 2.0 wt.%. The presence of B_4C is anticipated to contribute significantly to the growth of the same by increasing their viscosity and making packing more difficult. Adding more B_4C increases the viscosity and makes it harder to eliminate air bubbles after mixing. When a mechanical load is applied to the framework, the agglomerates de-cohere.

AA6063/ B_4C is kept in place in wet environments by the platelets' basal architecture, which provides a broad contact area and a rough surface, increasing the diversity and quantity of contact sites with the matrix. This ensures a mechanically anchored connection between the matrix and reinforcement.

Void content

Table 3 displays the results of an analysis of void content caused by the accumulation of air bubbles during casting. According to the presented data, the percentage of empty space in the composite samples increases with increasing filler loading, reaching a maximum at a loading of 2%. The addition of the B_4C fillers raises the composite's viscosity, which keeps the bubbles created during stirring suspended in the molten material. Since the viscosity of the mixture increases with increasing filler content, more air bubbles will be trapped in the material. With more filler, there's more area for the bubbles to stick to. The manufactured composite material was determined to have a maximum void content of less than 0.07 %, making it suitable for use in industrial settings.

Table 3: AA6063 and AA6063 + B₄C composite density and void content.

Composition code	Material of construction	Theoretical density (g/cm ³)	Experimental density (g/cm ³)	Void fraction (%)
A	AA6063	2.95	2.948	0.022
B	AA6063 + 0.4%B ₄ C	2.952	2.951	0.029
C	AA6063 + 0.8%B ₄ C	2.954	2.9527	0.033
D	AA6063 + 1.2%B ₄ C	2.955	2.9543	0.04
E	AA6063 + 1.6%B ₄ C	2.957	2.956	0.043
F	AA6063 + 2.0%B ₄ C	2.959	2.9571	0.067

Hardness

The composite's hardness is a function of both the hardness of the matrix phase and reinforcement. Since nB₄C particles have a high hardness value, they should increase the composite's hardness. Figure 4 displays the outcomes of a Vickers micro-hardness examination. It demonstrates that the hardness increases with increasing nB₄C reinforcement volume fraction but plateaus at around 2%. When working with composites, the number of added reinforcing particles determines the maximum penetration possible. The reinforcing particle increases the produced contact stress, which controls the degree of deformation and wear between the mating surfaces. The reinforcing volume fraction increases the hardness of a material, although the hardness itself falls or stays about the same after agglomeration.

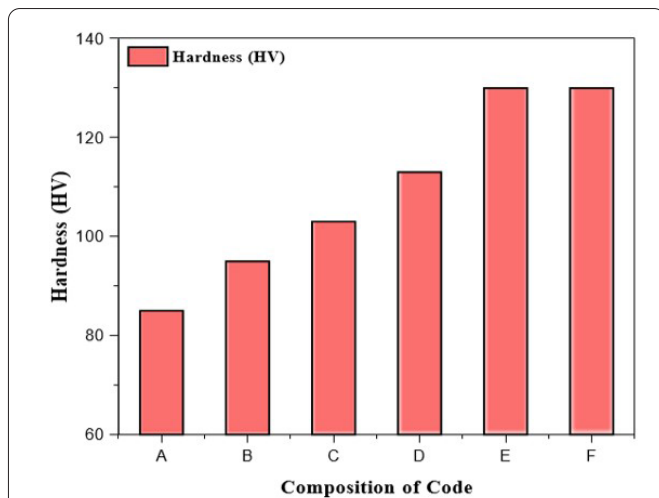


Figure 4: The value of Vicker's hardness for both Al and composites of varying reinforcing percentages.

Mechanical properties

Microstructural changes that worry about mechanical characteristics are stifled by increasing nB₄C filler amounts in the composites. Pure AA6063 and nB₄C reinforce AA6063 network composites with 0, 0.4, 0.8, 1.2, 1.6, and 2.0 wt.% nB₄C platelets had their tensile properties tested and plotted on different graphs (Figure 5).

Young's modulus is greater in all Al-B₄C composites compared to the pure Al matrix, with an increase in general with increasing B₄C content [27]. It is hypothesized that nB₄C will cause localized matrix growth around individual platelets, hence enhancing the material's overall stiffness. Mechanical anchorage and chemical bonding are expected to provide the necessary strong B₄C-Al bonding [28]. This is also true of tensile strength, which is shorthand for ultimate tensile strength, however the behavior of tensile strain and deformation as a function of B₄C concentration is inconsistent.

Since a higher platelet concentration reduces matrix distortion in that area, adding nB₄C should make the material stiffer compared to Al, which is much more malleable, but the addition of just 2% hardly makes a difference. This is related to agglomeration phenomena once more. The existence of holes and voids presumably accounts for the worse blending capability due to increased viscosity in the very stacked composites, which in turn impacts the trend of the findings. Tensile and flexural characteristics follow the same general pattern, and both patterns can be explained using the same mechanisms.

Tribological properties of the composites

The purpose of this study was to compare the tribological parameters of a pure Al matrix to those of composites with varied quantities of nB₄C in an effort to gain a better

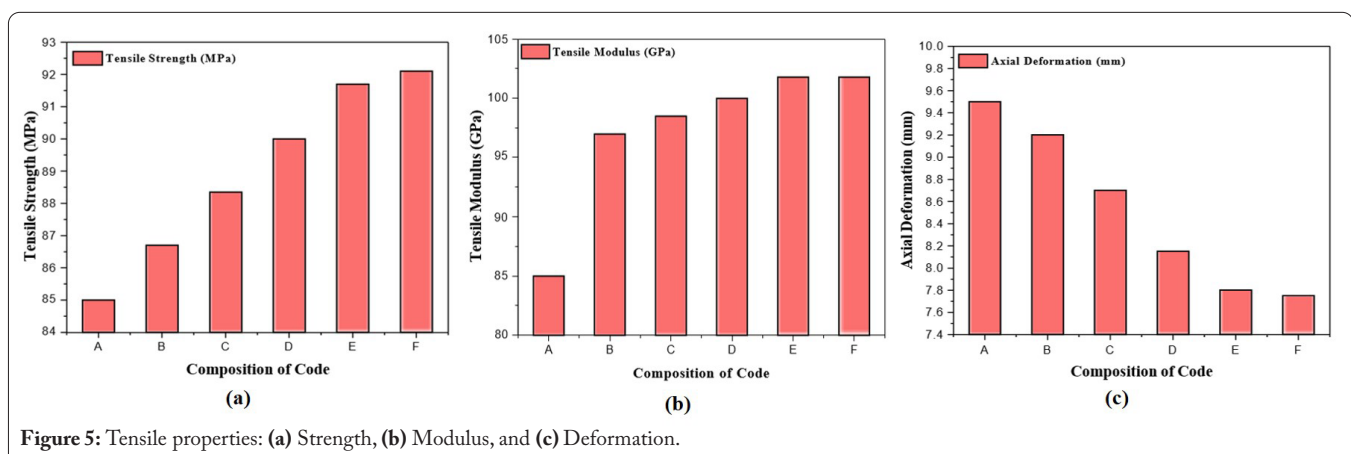


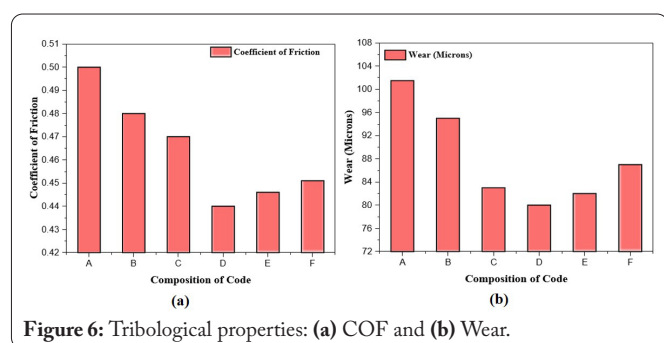
Figure 5: Tensile properties: (a) Strength, (b) Modulus, and (c) Deformation.

understanding of the effect that nB_4C has on sliding wear resistance (0.4, 0.8, 1.2, 1.6, and 2.0 wt.%). In this study, the wear characteristics of an Al- nB_4C metal matrix composite were analyzed. Figure 6a shows the wear test results for metal matrix composites made with Al- B_4C . The deterioration is not uniform. The confluence of many causes has led to this effect. The hardness and, by extension, the wear, increase with increasing nB_4C content, up to a point (about 1.2%), but beyond that point the particle fillers begin to detach from the matrix as a result of the high concentration and temperature created between the surfaces. The filler, in this case B_4C , has a lubricating quality, so it polishes the worn-out surface quickly, which in turn reduces wear and friction.

At the same time, a friction force sensor on the multi tribo-tester measured the COF. Values for the COF were calculated by dividing the frictional forces by the normal load, and the resulting data is shown in figure 6b. The behavior mirrored that of the wear attribute, and the two can be explained in the same way.

These findings show that matrix wear and the adherence of supplied wear debris are significantly affected by the B_4C content of the composite. Wearing composites should result in a coating of nB_4C on the discharged wear particles, reducing the accumulation of debris made of the composite material. This finding is corroborated by measurements showing that an increase in nB_4C concentration resulted in a thinner layer of compacted wear debris on the worn surface.

The COF and wear are found to decrease with increasing amounts of nB_4C , but they essentially plateau at around 1.2% reinforcement because increasing the amount of nB_4C does not significantly alter the characteristics.



Conclusion

In experiments, void percentages were shown to be less than 0.07%. This value is within the allowable range, which provides additional support for the selected technique of preparation and establishes a manufacturing strategy that can consistently generate low void samples. Micrographs taken during the morphological study revealed that the nanofillers were evenly dispersed in the matrix, pointing to a stable adhesion between the two components. Among the several tested mechanical parameters, the addition of nB_4C filler increased hardness by about 66%. Tensile and flexural characteristics both saw an increase of around 20%, revealing similar trends.

Although the tribological characteristics (wear and friction) improved by around 10%, this improvement was not monotonic and was lost with weight additions of more than 1.2% nB_4C fillers. However, even the poorest value achieved is an improvement over the virgin material, thus the addition must have enhanced the tribological behavior. Because of their superior mechanical strength, the novel materials developed in this work can be used to produce crucial and high-performance components with benefits like lower weight, higher quality, and more efficiency. The addition of nB_4C at concentrations between 1.6% and 2.0% does not significantly improve several properties, as demonstrated. After reviewing the results of the many experiments, it is clear that AA6063 with a 1.6 wt.% of nB_4C addition is the best option.

Acknowledgements

None.

Conflict of Interest

None.

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