Review

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Recent Advances on Aluminum-Based Boron Carbide Composites: Performance, Fabrication, and Applications

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Review

Recent Advances on Aluminum-Based Boron Carbide Composites: Performance, Fabrication, and Applications

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Abstract

As a promising class of structure/function integrated materials, aluminum-based boron carbide composites exhibit exceptional mechanical properties, neutron-shielding capabilities, and excellent thermophysical properties, demonstrating significant potential for applications in nuclear energy, aerospace, and national defense industries. This paper systematically reviews recent research progress on aluminum-based boron carbide composites with a focus on technical advancements and persistent challenges in fabrication, material properties, and applications. Future research directions are outlined, aiming to provide a guideline for further advancing this field.

Keywords: aluminum-based composites; boron carbide; fabrication; mechanical properties; neutron shielding

1. Introduction

Aluminum-based boron carbide (B_4C/Al), an important branch of metal matrix composites, has received extensive attention due to its unique performance combination. The aluminum matrix endows excellent thermal conductivity, plasticity and processing performance, while the boron carbide (B_4C) reinforced phase provides extreme hardness (Mohs hardness>9.3), low density (2.52 g/cm^3)[1]and excellent neutron absorption cross-section (up to 600 barn[2]for thermal neutron absorption cross-section). This "strength-toughness" synergistic effect enables high mechanical properties of B_4C/Al composites while maintaining the lightweight of aluminum alloys, making them irreplaceable key materials in modern industry.

In recent years, the rapid growth of the nuclear energy and aerospace industries has driven accelerating research into B_4C/Al composites. These materials are critical for nuclear applications, including spent fuel storage and reactor shielding, because of their lightweight and neutron-absorbing properties[3,4]. Due to its high specific strength, it is an ideal protective material for armored vehicles in defense and military industry[5–7]. Also, its regulating thermal expansion and excellent thermal conductivity offer unique advantages for electronic packaging applications[8,9]. The ongoing optimization of material properties has spurred persistent innovation in fabrication methods, progressing from conventional powder metallurgy[10] and stir casting[11,12]to advanced techniques like laser additive manufacturing (AM) and equal-channel angular pressing(ECAP)[13–16].

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This paper systematically reviews recent advancements in B_4C/Al composites and provides a comprehensive analysis of their preparation methods, performance characteristics, and potential applications. Various synthesis techniques are evaluated, including powder metallurgy, stir casting, and AM, along with examination of material mechanical properties, thermal conductivity, and radiation shielding efficiency. Furthermore, the paper addresses critical challenges such as interfacial reactions, poor wettability and scalability issues that limit large-scale adoption. By proposing future research directions, including interface engineering, hybrid reinforcement strategies and sustainable processing, this review aims to facilitate the further development and widespread application of B_4C/Al composites.

2. Material Fabrication

The performance of B_4C/Al composites highly depends on their preparation process. Different fabrication methods can result in significant differences in the reinforcement distribution, interfacial bonding states and microstructure, ultimately affecting mechanical, thermal and functional properties. As shown in Figure 1(I-III) [17,18], the morphology and distribution of B_4C particles (from micro to nano-scale) play a critical role in determining interfacial bonding strength and dislocation interactions during powder consolidation. This section will provide a detailed overview of the current major preparation techniques and their recent advancements.

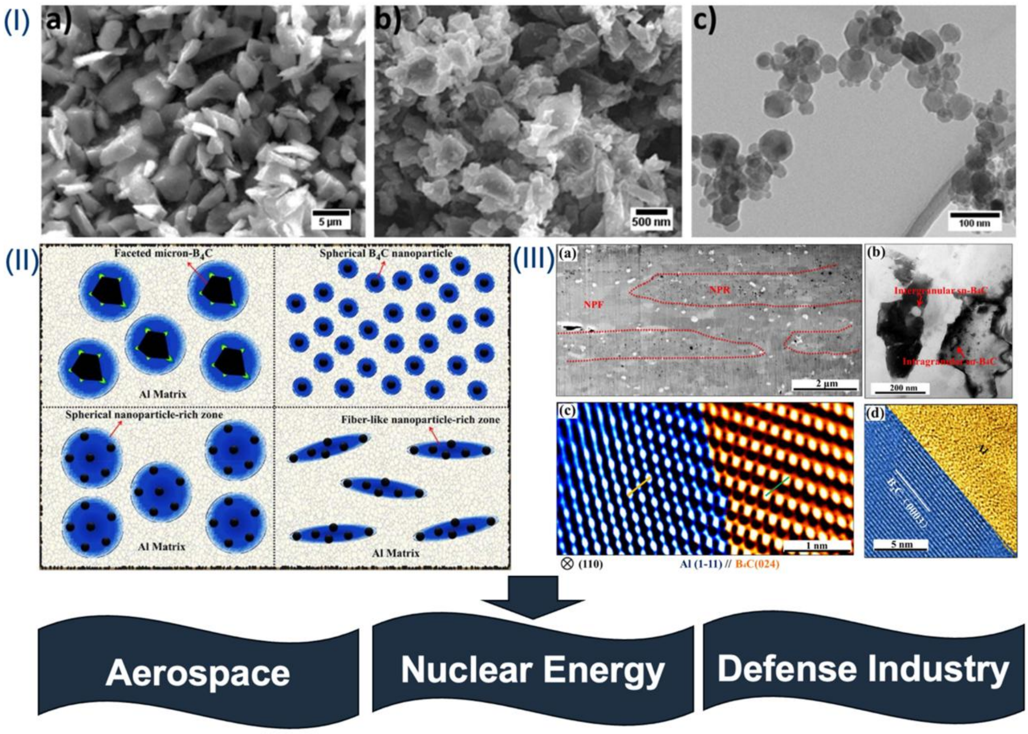

Figure 1. (I) Morphology of B_4C particles used as reinforcements in B_4C/Al composites; a) SEM of micro B_4C particles, b) SEM of submicron B_4C particles, c) TEM of nano B_4C particles.Reproduced with permission[17]; (II) Schematic of the distributions of B_4C particles and dislocation interaction zones in composites; and (III) (a) STEM and (b) TEM to show intragranular or intergranular B_4C; (c-d) HRTEM shows the interface orientation between an intragranular B_4C and the Al matrix[18].

2.1. Powder Metallurgy Method

Pang et al. [19]fabricated Al/B_4C composites with 30 wt% B_4C via semi-solid hot isostatic pressing (HIP).Research has demonstrated that, under process conditions of 650°C and 30 MPa, the

6061 Al matrix forms a 15 vol% liquid phase, effectively filling the internal pores of the material. This results in a composite material density of 99.6% of the theoretical value, significantly outperforming the traditional vacuum sintering process (91.9%). The formation of liquid-phase Al not only improves the wettability between B_4C particles and the matrix, creating a strongly bonded interface structure, but also enhances the tensile strength of the composite material to 300 MPa, more than three times that of traditional methods. It is noteworthy that the semi-solid HIP process precisely controls the temperature window (640°C-660°C), thereby avoiding interface side reactions caused by high-temperature melting while ensuring the uniform distribution of B_4C particles.This approach fundamentally addresses the issues of poor density and compositional segregation inherent in traditional processes. A microstructural analysis reveals that the liquid-phase Al, in its overflow state, uniformly coats the material surface, thereby enhancing the composite material's overall integrity. This enhancement in material performance, accomplished through high densification and microstructural optimization, offers a novel technical approach for developing high-performance neutron shielding materials based on the isotopic properties of 10B. It is particularly noteworthy that the structure, which is nearly fully densified (porosity <0.4%), and the uniform B_4C distribution obtained through this process, lay a critical material foundation for achieving stable neutron absorption performance in subsequent applications.

Thiruppathi et al.[20]conducted a comparative study of aluminum-based brake pad composites fabricated via spark plasma sintering (SPS) and microwave sintering, revealing that SPS-processed specimens exhibited superior density and microhardness. This enhancement was attributed to two key mechanisms; localized high temperatures generated by pulsed current and plasma activation effects, which collectively accelerate particle diffusion bonding and densification (Figures 2 and 3) Pul et al.[6] fabricated B_4C/SiC hybrid-reinforced 7075 aluminum alloy composites via SPS, demonstrating that a 20% reinforcement ratio optimized the balance between machinability and ballistic performance. The combination of mechanical alloying and powder metallurgy has proven to be an effective approach for fabricating nanostructured B_4C/Al composites. Li et al.[21] successfully dispersed B_4C nanoparticles within an Al5083 matrix using high-energy ball milling, with subsequent hot pressing, to produce composites of ultrahigh compressive strength (1065 MPa). This exceptional mechanical performance was attributed to synergistic strengthening mechanisms, including Hall-Petch grain refinement, Orowan strengthening and the Taylor dislocation mechanism. Further demonstrating the versatility of this approach, Zhang et al.[22] developed tri-modal B_4C/Al composites through similar processing routes. Their work revealed that the formation of amorphous multilayer interfaces and MgO nanocrystalline regions significantly enhanced interfacial bonding strength, contributing to improved composite performance.

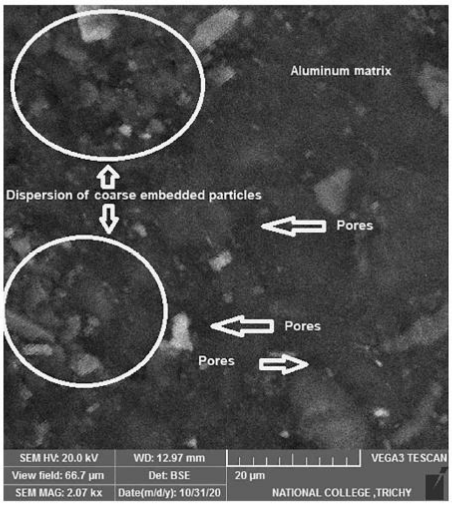

Figure 2. BSE-SEM image of the microwave-sintered sample [20].

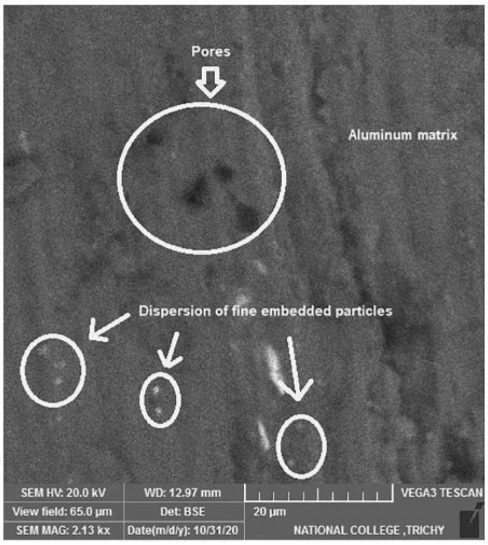

Figure 3. BSE-SEM image of the SPS sample [20].

2.2. Liquid Preparation Technology

Liquid preparation technology primarily involves methods like stir casting and melt impregnation, which offer the advantages of low cost and scalability for mass production. However, in the preparation of B_4C-rich composite materials (>15 %), challenges such as poor wettability and particle segregation arise. Among liquid preparation methods, stirred casting remains the most widely used process. Thangadurai et al.[23] conducted a systematic study on the fabrication and properties of AA6061-B_4C particulate composites produced via stirred casting. Their results demonstrated that as the B_4C content increased from 0 to 15 wt.%, the material hardness improved significantly while the density exhibited a decreasing trend. Notably, the composite containing 15 wt.% B_4C exhibited optimal performance under mechanical loading, showing superior axial stress, circumferential stress and hydrostatic stress resistance compared to other compositions[23]. Bhowmik et al.[24] identified melt temperature, stirring speed and time as critical parameters in the stirred casting that determine product quality and demand precise control. To enhance particle dispersion in Al6063-B_4C-Gr composites, Thakur et al.[25] added K_2TiF_6 as a wetting agent during fabrication, which significantly improved interfacial bonding characteristics. Melt impregnation technology is particularly suitable for fabricating B_4C composites of high volume fraction, offering distinct advantages in achieving uniform particle distribution and dense matrix packing. Pramono et al.[26] fabricated B_4C/Al composites through self-propagating high-temperature synthesis coupled with melt impregnation. Their results demonstrated that this hybrid approach enables effective control of interfacial reaction kinetics. Furthermore, the semi-solid processing technology employed in this work combines the advantageous characteristics of both liquid- and solid-state fabrication methods. Pang et al.[19]systematically evaluated the mechanical properties and microstructural characteristics of B_4C/Al composites using a WANCE100 universal testing machine and SIRION200 field-emission SEM. Their results demonstrated that the semi-solid HIP can produce near theoretical density B_4C/Al composites with optimal material integrity.[27]

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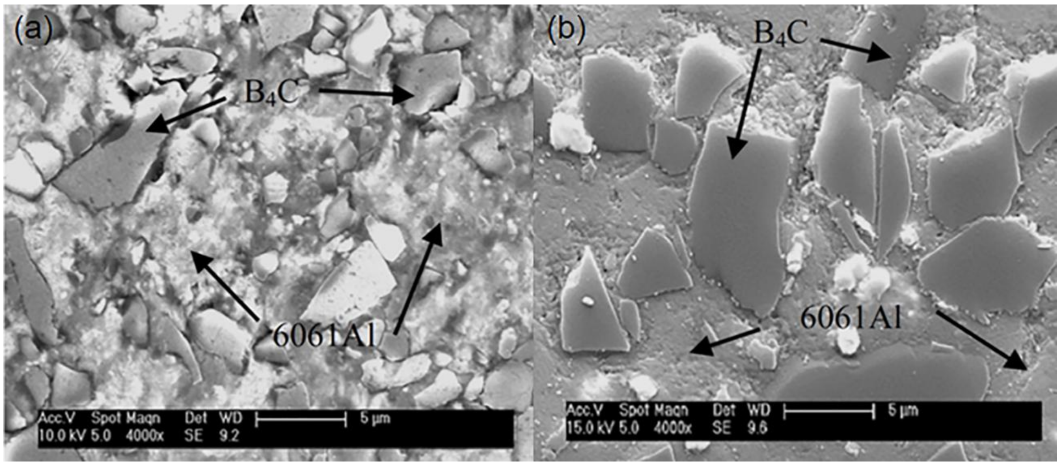

Figure 4. Microstructures of B_4C/Al composites prepared by conventional vacuum sintering-(a) and semisolid HIP-(b)[19].

2.3. Solid-State Processing Technology

Solid-state processing technologies primarily comprise intense plastic deformation processes, including ECAP and friction stir processing (FSP), which are particularly effective for microstructural refinement and property enhancement in as-cast or sintered composite materials. Sharath et al.[15]processed Al2618-B_4C composites via ECAP and demonstrated that increasing the number of extrusion passes led to significant improvements in both hardness and wear resistance. These enhancements were correlated with microstructural refinement and more uniform distribution of reinforcing particles. Butola et al.[28]employed response surface methodology to optimize FSP parameters for aluminum-based surface nanocomposites. Their model predicted optimal mechanical properties (ultimate tensile strength and microhardness) at a tool rotation speed of 1300 rpm, traverse speed of 30 mm/min, and with three processing passes[29]. Khodabakhshi et al. [30] developed an innovative accumulative fold forging process for fabricating nanolayered AA8006-B_4C composites. Through 26 forging steps with intermediate annealing treatments, they achieved an ultrafine-grained structure (average grain size <50 nm) at room temperature. The resulting material exhibited a remarkable increase in hardness from 30 HV to 205.4 HV (Table 1), representing one of the highest hardness values reported for Al matrix composites.

Table 1. Prediction of strength and indentation Vickers micro-hardness for processed UFG and nanocomposite layered materials under different strengthening mechanisms [30].

Strengthening contributions	Modeling of yield strength (MPa)							Predicted strength (σCom, MPa)	Layers	Predicted hardness (HV)	Experimental hardness (HV)
Material	σ_0	$\Delta\sigma_{GB}$	$\Delta\sigma_{TM}$	$\Delta\sigma_{EM}$	$\Delta\sigma_{Load}$	$\Delta\sigma_{Dis}$	$\Delta\sigma_{Orowan}$		Hlayers		
UFGed AA8006 alloy	13	89.4	-	-	-	46.7	13.9	151.1	8.8	72.2	61.5 ± 6.6
UFGed AA8006-B_4C nanocomposite	13	213.8	30.5	23.1	0.8	156.6	340.3	603.4	5.7	258.9	189.3 ± 16.1

2.4. Additive Manufacturing (AM) Technology

AM technology offers a novel approach for fabricating complex-shaped B_4C/Al composite components.Xiao et al.[31]utilized laser directed energy deposition (LDED) technology to prepare B_4C/Al composite materials and investigated the effects of varying laser powers on the microstructure, mechanical properties, and corrosion resistance of the materials. The findings of the study demonstrated that this process had the potential to yield composite materials that exhibited

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both exceptional ductility and moderate strength. The enhancement in performance was predominantly ascribed to dislocation formation, grain refinement, and precipitation effects. Additionally, Sun et al.[32] developed a low-cost multi-material additive manufacturing method—wire powder arc additive manufacturing (WPA-AM)—that successfully achieved the controlled addition of ceramic particles such as B_4C, SiC, TiC, and WC/W_2C in aluminum-based composite materials. This method significantly improved the mechanical properties of the materials through optimized process parameters. Among the various additive manufacturing technologies, laser powder bed fusion (LPBF) has become one of the most widely used methods in B_4C/Al composite material research due to its ability to produce multi-material structures and functional gradient materials[33].Yilbas et al.[34]systematically investigated the effect of laser treatment on surface properties of B_4C/Al composites, revealing the formation of a dense sub-micron grain layer and AlN compounds on the surface. This treatment led to significant enhancements in both microhardness and surface hydrophobicity.

2.5. Surface Composite Technology

Surface composite technology can produce B_4C/Al composite coatings on substrate materials, offering both functional performance and cost efficiency. Abenojar J. et al.[35]found that aluminum-based composites containing Fe/B exhibited reduced corrosion resistance at lower sintering temperatures of 650°C–950°C. However, mechanical alloying treatment significantly improved the corrosion resistance of boron carbide-containing aluminum alloys.However, the electrochemical potential difference between the aluminum matrix and B_4C reinforcement led to preferential interfacial corrosion, resulting in reduced corrosion resistance compared to pure aluminum[36]. Ziani et al.[37]employed ion beam sputtering deposition to fabricate Al/Mo/SiC tri-component periodic multilayer films, achieving reflectance of 48% and 27.5% at wavelengths of 17.3 nm and 28.2 nm, respectively. This advancement provided critical technical support for the solar orbiter mission's extreme ultraviolet (EUV) imaging system. As illustrated in Table 2, the process characteristics and typical performance indicators of the main preparation methods for B_4C/Al composite materials are summarized.

Table 2. Comparison of fabrication methods for B_4C/Al composites.

Fabrication Method	Process Characteristics	B_4C Content (wt.%)	Typical Properties	Ref.
HIP	Densification under high temperature/pressure; uniform reinforcement distribution	10-35	Tensile strength >300 MPa; elongation >3%	[19]
SPS	Rapid sintering process; refined grain structure	10-20	High relative density; significantly enhanced microhardness	[20]
Stir Casting	Low-cost; suitable for mass production	5-15	Hardness increases with B_4C content	[24]
ECAP	Significant grain refinement; improved mechanical properties	5-15	Enhanced hardness and wear resistance with increasing passes	[15]

3. Performance Characteristics

B_4C/Al composites exhibit critical performance characteristics across four key domains; mechanical properties, radiation shielding capability, thermophysical behavior, and tribological performance. These functional attributes are fundamentally governed by material composition and microstructural features. The following section provides a systematic analysis of these property relationships and their determining factors.

3.1. Mechanical Properties

The mechanical properties of B_4C/Al composites represent a critical performance metric, fundamentally determining their structural application viability. Extensive research demonstrates that optimized material design and processing can produce B_4C/Al composites with superior strength, hardness and wear resistance compared to conventional aluminum alloys.

3.1.1. Strength Characteristics

The strength of B_4C/Al composites is governed by several critical factors, including the matrix alloy composition, B_4C particle content and spatial distribution, and the interfacial bonding quality between reinforcement and matrix. Li et al.[21] achieved an ultrahigh compressive strength of 1065 MPa in their B_4C-reinforced Al5083 nanocomposites. This exceptional performance was attributed to synergistic strengthening mechanisms, including Hall-Petch effect (grain boundary strengthening), Orowan strengthening (dislocations by passing particles),and Taylor mechanism (geometric necessary dislocations).Pang et al.[19]demonstrated that the aluminum matrix undergoes a transformation into a liquid phase composed of 15 vol% under the conditions of the hot isostatic pressing (HIP) semi-solid process, which involves a temperature of 650°C and a pressure of 30 MPa. This liquid phase diffuses into the pores of the material, leading to an increase in its density to 99.6% (2.66 g/cm^3). The resultant material exhibits a tensile strength of 301 MPa, which is significantly higher than the tensile strength of 86 MPa observed in conventional vacuum sintering processes. This enhancement in tensile strength is attributed to the presence of the liquid phase, which contributes to the material's increased resistance to deformation. EDS analysis indicates that B_4C particles form strong interface bonds with the aluminum matrix, and the fracture surface exhibits a ductile dimple structure, indicating high load transfer efficiency. Notwithstanding the high B_4C content (30 wt%), which engenders a low elongation rate (<3%), the HIP process has been shown to enhance the mechanical properties of the composite material by eradicating pores and optimizing interfaces.

Hybrid reinforcement is an effective strategy for enhancing the overall performance of B_4C/Al composites. Khan et al.[38]engineered a hybrid-reinforced aluminum matrix composite by incorporating both hexagonal boron nitride and multi-walled carbon nanotubes. The resulting material exhibited a remarkable 189% enhancement in tensile strength, which the researchers attributed to the homogeneous dispersion of reinforcement phases, in-situ formation of hard aluminum carbide precipitates and effective load transfer through the nanoscale reinforcement network (Figure 5). Raja et al.[39]engineered an Al7075 hybrid composite incorporating 9 wt.% B_4C and 3 wt.% TiB_2 reinforcements, achieving a tensile strength of 233 MPa. This performance surpassed that of composites with either reinforcement alone, demonstrating the synergistic benefits of the dual-phase reinforcement system.

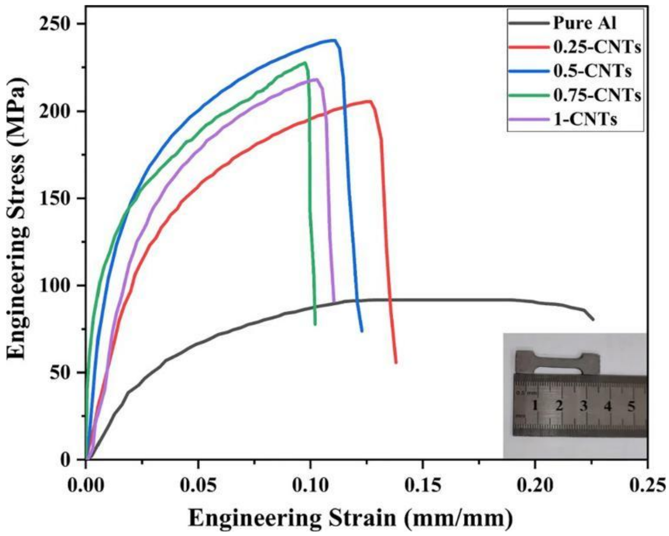

Figure 5. The tensile strength of pure Al and Al-3BN-CNTs composites[38].

3.1.2. Hardness and Toughness

The incorporation of B_4C particles can substantially improve the hardness of the aluminum matrix. This reinforcement effect can be further enhanced in hybrid systems, as demonstrated by Khan et al.[38], where the synergistic combination of h-BN and CNTs in aluminum matrix composites resulted in a 106% increase in Vickers hardness compared to the unreinforced matrix. Figure 6 shows the micro-Vickers hardness variations of pure aluminum, BN/Al and BN-CNTs /Al composites. As shown in Figure 6 (a), the microhardness of the aluminum matrix exhibits a significant increase from (31 ± 1) HV to (49 ± 1.5) HV with h-BN content increasing from 0 to 3 wt.%, demonstrating the effective hardening capability of h-BN reinforcement. At the optimal 3 wt.% h-BN concentration, the composite achieves peak hardness due to h-BN's superior dispersion and significantly higher intrinsic hardness compared to pure aluminum. These results clearly demonstrate that h-BN incorporation can substantially enhance the hardness of aluminum matrix composites. Furthermore, Figure 6 (b) demonstrates the synergistic effect of CNT addition (0-1 wt.%) to the Al-3BN composite. The incorporation of 0.25 wt.% CNTs increased the microhardness from (49 ± 1.5) HV to (58 ± 2) HV (87% higher than pure aluminum). At 0.5 wt.% CNTs, the hardness further improved to 64 ± 2 HV, representing a 30.6% increase relative to the Al-3BN composite and 106.4% compared to pure aluminum. Alizadeh et al.[40] observed a linear increase in composite hardness with rising B_4C content, accompanied by a threefold improvement in wear resistance under 20 N loading conditions. Khodabakhshi et al.[30] fabricated AA8006-B_4C nanocomposites via accumulative fold forging, achieving a record hardness of 205.4 HV for aluminum matrix composites. However, this exceptional hardness enhancement typically comes at the expense of reduced toughness, illustrating the characteristic strength-toughness trade-off in metal matrix composites..Pandey et al.[41] demonstrated that when Al_2O_3 content surpassed 30 wt.% and B_4C exceeded 15 wt.%, the composite's fracture mechanism transitioned from ductile dimple rupture to brittle cleavage fracture. To achieve an optimal balance between hardness and toughness, Thakur et al.[25]engineered an Al6063 composite co-reinforced with B_4C and graphite. The graphite's solid lubricating effect effectively inhibited crack propagation, thereby significantly improving the material's fracture toughness while maintaining enhanced hardness from B_4C.

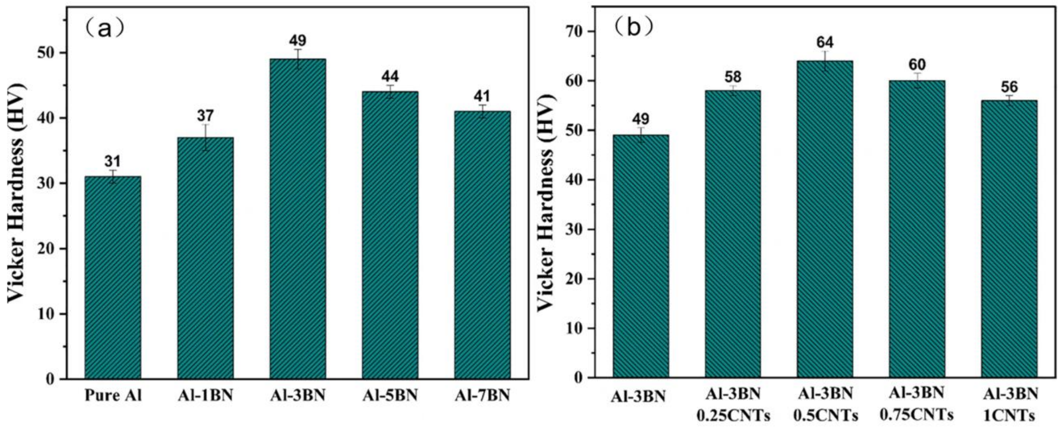

Figure 6. The micro-Vickers hardness of 3BN/Al-(a) and 3BN-CNT/Al-(b) [38].

3.2. Shielding Performance

Neutron shielding performance represents the most critical functional property of B_4C/Al composites, establishing their irreplaceable role in nuclear energy applications. The material's neutron shielding effectiveness is primarily governed by three key factors; the concentration of 10B isotopes, material thickness and incident neutron energy spectrum.

3.2.1. Neutron Absorption Characteristics

Through Monte Carlo simulations, Dai et al.[42] investigated the neutron shielding performance of B_4C/Al composites, revealing two key relationships; the neutron transmission coefficient decreased linearly with increasing B_4C content, and it exhibited exponential decay with the increase of material thickness. The absorption fraction A of the material follows the Beer–Lambert law.[43]

$$A = 1 - \exp\left(\frac{-z}{\delta_p}\right) \tag{1}$$

$$\delta p = \frac{V}{N_{f.u.}\sigma_{abs/f.u.}\varepsilon} \tag{2}$$

where the penetration depth can be determined in terms of the unit cell volume, V z is the material thickness, V the unit cell volume, σ_{obs} absorption cross-section, ϵ packing fraction of the material, and $N_{f.u.}$ is the number of formula units. The material thickness required to achieve specific absorption rates is a critical design parameter. As shown in Figure 7, B_4C/Al composites require only centimeter-scale thickness to achieve 99% neutron absorption in the thermal energy region (<1 keV), demonstrating their potential for compact shielding structures. This efficiency stems from the high ^{10}B areal density (0.035 g/cm^2–0.0389 g/cm^2) and optimized packing fraction (90%) as calculated in Ref. [44]

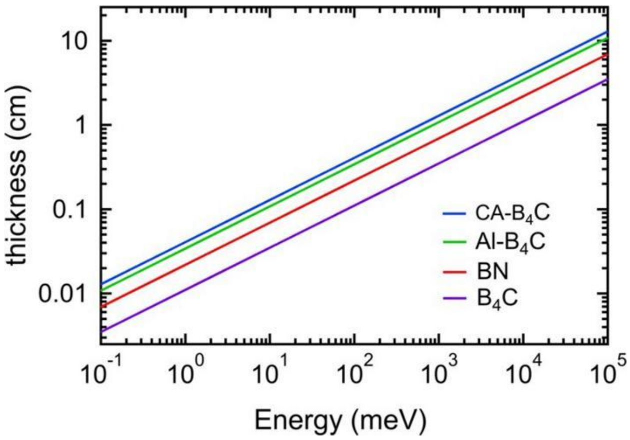

Figure 7. Thickness required for 99% neutron absorption in B_4C/Al composites as a function of neutron energy[42].

3.2.2. Irradiation Stability

In the domain of nuclear applications, the stability of B_4C/Al composite materials under radiation exposure is a critical performance metric. Xian et al.[45]reported that Al6061-31vol.% B_4C composite materials prepared using the hot isostatic pressing (HIP) process at 580°C exhibited excellent microstructural stability, with B_4C particles uniformly distributed in the matrix and minimal interface reactions. This uniformity guarantees the stability of the material's mechanical properties and neutron absorption performance under irradiation conditions. Quantitative measurements of the distribution of particles in the composite material demonstrated an average B_4C content of (31 ± 0.5)%, with the standard deviation indicating optimal dispersion uniformity. This uniform distribution is critical for maintaining stable neutron shielding performance, as particle aggregation or uneven distribution may lead to localised performance degradation or reduced absorption efficiency. Furthermore, the composite material's density is nearly equal to the theoretical value (2.642 g/cm^3), exhibiting minimal porosity. This characteristic has been demonstrated to enhance the material's radiation resistance and effectively suppress defect formation caused by neutron irradiation.

3.3. Thermophysical Properties

The thermal conductivity and coefficient of thermal expansion (CTE) of B_4C/Al composites are critical performance parameters, particularly for electronic packaging applications where efficient heat dissipation and dimensional stability are essential. Ambigai et al.[8]characterized the thermophysical properties of centrifugally cast aluminum-based B_4C functionally graded composites (FGCs). Their study revealed that incorporating 100 μm reinforcement particles enhanced thermal conductivity by 46.4% and thermal diffusivity by 27.8%, relative to the matrix material. This improvement was attributed to the formation of more continuous thermal conduction pathways through percolation of large B_4C particles. Nano-alumina reinforced B_4C/Al composites have been developed,which demonstrate exceptional thermal conductivity. These advanced materials show particular promise for defense, military, and aerospace applications where efficient heat dissipation is critical. Through first-principles calculations, Zhang et al.[46]demonstrated that SiC and phosphorus-doped graphene form strong interfacial bonds with the Al matrix, significantly enhancing the composite's thermal conductivity, as shown in Table 3.

Table 3. Electronic configuration and radius cut-off for the elements used in this study [46].

Element	Electron configuration	Radius cut-off (Bohr)
Aluminum (Al)	3s2 3p1	1.90
Carbon (C)	2s2 2p2	1.51
Silicon (Si)	3s2 3p2	1.91
Phosphorus (P)	3s2 3p3	1.91
Boron (B)	2s2 2p1	1.70
Nitrogen (N)	2s2 2p3	1.20

3.4. Friction and Wear Performance

B_4C/Al composites exhibit outstanding wear resistance, positioning them as promising candidates for high-performance friction components, including braking systems and bearings.Hynes et al..[47]analyzed the wear performance of AA6061-B_4C composites with varying reinforcement content (5wt.%, 10wt.%, and 15 wt.%) and demonstrated that the wear rate decreased significantly with increasing B_4C content, as illustrated in Figure 8. The composite with 15% B_4C exhibited the lowest wear rate, highlighting the role of hard ceramic particles in enhancing abrasion resistance and reducing surface degradation.Emiru et al.[48]demonstrated that incorporating SiC, B_4C and MoS_2 nanoparticles into Al6061 alloy synergistically enhanced wear resistance through dual mechanisms; the solid lubrication effect of MoS_2 and in-situ formation of a protective B_2O_3 layer, enhanced the wear resistance of the multiphase reinforced composite compared to the unreinforced alloy. Ali et al.[49]identified an optimal composition in AA6351 hybrid composites, where the synergistic combination of 1 wt.% graphite and 1 wt.% B_4C nanoparticles yielded superior tribological performance.

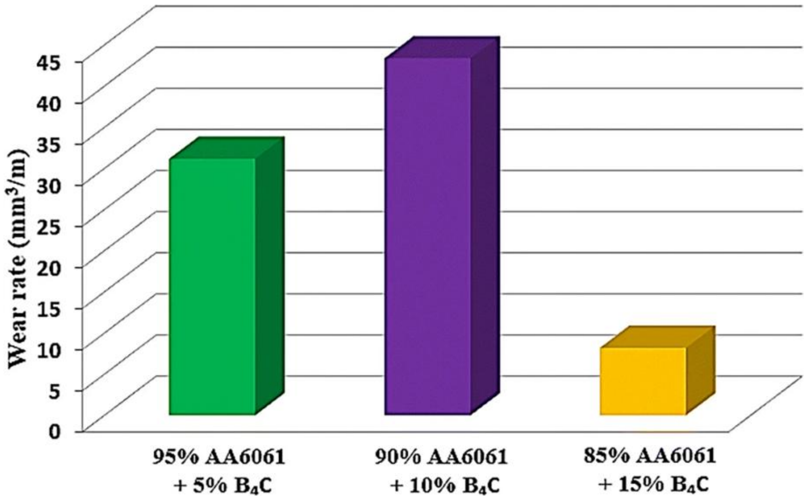

Figure 8. Wear rate of specimens [47].

3.5. Other Performances

3.5.1. Corrosion Resistance

Han et al.[50] conducted a systematic investigation of the electrochemical behavior of B_4C/Al composites, revealing an inverse correlation between B_4C volume fraction and corrosion resistance. This degradation was attributed to two primary mechanisms; galvanic coupling between the aluminum matrix and B_4C particles, and an oxygen diffusion-controlled corrosion process at the reinforcement-matrix interfaces.Huang et al.[51] used low-pressure cold spraying technology to create an Al-30% B_4C composite coating on a 5083 aluminum alloy substrate. Friction and wear tests revealed that the coating's wear rate was one-third that of the base aluminum alloy. However, electrochemical tests showed that the coating's corrosion rate was slightly higher than that of the base material. The study revealed that the unique fragmentation and embedding behavior of B_4C particles during deposition significantly influenced the coating's microstructure, thereby determining its neutron absorption performance and wear- and corrosion-resistant properties. The residual content of B_4C particles is a key factor in the coating's functional properties.

3.5.2. Processing Performance

The processing characteristics of B_4C/Al composites critically influences their industrial applicability. Mohankumar et al.[52]developed a predictive model for water-jet cutting angles in Al6063-B_4C composites, effectively addressing dimensional precision challenges in machining hard particle reinforced lightweight alloys. Kumaran et al.[53] achieved significant improvements in processing quality through parameter optimization of pulsed: YAG laser machining for Al6351-B_4C composites. Table 4 comprehensively summarizes the key performance metrics and critical influencing factors for typical B_4C/Al composite systems. The optimization of machining parameters, including cutting speed, feed rate, and cutting depth, has been demonstrated to reduce surface roughness and energy consumption during the milling process of aluminum-based composite materials (AMCs) [54]. A thrust prediction model during drilling is imperative for the optimization of machining such composites [55]. The utilization of acoustic emission technology in the context of monitoring wire electrical discharge machining (WEDM) has been demonstrated to yield valuable Ref. information for the machining process [56]. In the domain of laser processing, attaining optimal surface quality necessitates meticulous selection of processing parameters [57].

Table 4. Typical Properties and Influencing Factors of B_4C-Reinforced Aluminum Matrix Composites.

Performance Category	Typical Indicators	Primary Influencing Factors	Optimization Strategies	Ref.
Tensile Strength	200-365 MPa	B_4C content, interfacial bonding, heat treatment	Hybrid reinforcement, interface modulation	[39,40]
Compressive Strength	Up to 1065 MPa	Reinforcement phase size, uniform distribution	Nano-reinforcement, severe plastic deformation	[21,30]
Hardness	Increased by 50-106%	B_4C content, particle size	Optimized reinforcement ratio, heat treatment	[40]
Neutron Shielding	Transmission coefficient reduced by 90%	10B areal density, material thickness	High B_4C content, gradient design	[2]
Thermal Conductivity	Increased by 46.4%	Reinforcement phase size, distribution	Large-sized particles, functional gradient	[22]
Wear Resistance	Improved by 3-20 times	B_4C content, lubricating phase	Addition of solid lubricants	[49]
Corrosion Resistance	Decreases with increased B_4C	Interfacial galvanic corrosion	Surface treatment, alloying	[53]

4. Application Fields

B_4C/Al composites have been successfully implemented in multiple high-tech fields including nuclear energy, defense and military systems, and aerospace due to their exceptional multifunctional performance, high mechanical properties (such as specific strength, hardness, and wear resistance), excellent neutron-shielding capabilities, superior thermophysical properties (e.g. thermal conductivity and tunable coefficient of thermal expansion), and lightweight characteristics. Their

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application scope continues to expand into emerging technological domains, advanced electronic packaging, high-performance transportation components, and specialized tool manufacturing. This section details their principal industrial applications, along with representative case studies.

4.1. Nuclear Energy Engineering

In nuclear energy applications, B_4C/Al composites serve as critical neutron absorbing materials, particularly in spent fuel storage systems and reactor shielding components. These composites offer three key advantages, including an exceptionally high neutron absorption cross-section, superior thermal conductivity and optimal mechanical strength for structural applications.

4.1.1. Spent Fuel Storage

Spent fuel storage stands as the most prominent and well-established application of B_4C/Al composites. The B_4C/Al nuclear waste storage system incorporates two key design innovations; a reinforced auxiliary structure with moisture-resistant treatment, and synergistic integration of reinforced boron (high 10B neutron absorption cross-section) and tungsten-nickel-iron alloy (excellent γ-ray shielding). This optimized configuration enables radiation reduction, long-term stability of the shielding layer and environmental resilience.Shirvanimoghaddam et al.[58] fabricated B_4C/Al neutron absorption plates for nuclear fuel assemblies using the stir casting method.They optimized the casting temperature to improve the mechanical properties of the neutron absorption plates.

4.1.2. Reactor Shielding

Aluminium-based boron carbide (B_4C/Al) composite materials have been demonstrated to have unique application value in reactor radiation shielding. This is due to their high-efficiency neutron absorption capability and comprehensive advantages in radiation safety.

With regard to the optimization of shielding performance, the neutron shielding effect of B_4C/Al composite materials is closely related to material composition and thickness. Dai et al.[42]discovered that the neutron transmission coefficient of B_4C/Al composite materials decreases linearly with increasing boron carbide content and exponentially with increasing material thickness through Monte Carlo simulations. Furthermore, the samples demonstrated heightened sensitivity in terms of energy response characteristics within the thermal neutron energy range. This superior performance in shielding is a notable advantage over conventional shielding materials.

In the context of irradiation safety verification, ensuring the stability of the material under reactor irradiation conditions is of paramount importance. Mi et al.[59] conducted a thermal safety analysis using computational fluid dynamics (CFD) simulations to verify the structural integrity and thermal stability of B_4C/Al composite materials under in-core irradiation conditions. This analysis ensured the safety of the materials as reactor shielding materials.

4.2. National Defense and Military Industry

Boron carbide (B_4C) reinforced aluminum matrix composites have emerged as an ideal new-generation armor material due to their high hardness, low density and excellent ballistic resistance. The aluminum matrix provides lightweight characteristics, while the B_4C reinforcement phase endows the material with outstanding impact resistance capabilities.

Boron carbide has unique advantages in armor applications, with exceptional comprehensive properties such as extremely high hardness (Mohs hardness 9.3), low density (2.52 g/cm^3) , and excellent thermochemical stability.[1]These characteristics establish B_4C as an indispensable material for advanced armor systems. Pul et al.[6] systematically investigated the ballistic performance of 7075 aluminum alloy composites reinforced with SiC and B_4C particles. Their study demonstrated that increasing the reinforcement ratio progressively improves ballistic resistance, with an optimal 20% reinforcement content achieving the ideal balance between ballistic protection and machinability.

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Moorehead et al.[60] identified that microstructural defects (such as aggregates and carbonaceous thin sheets) in hot-pressed B_4C ceramics, significantly degrade mechanical performance. Through high-resolution micro-CT characterization (Figure 9), they quantitatively mapped the size distribution and spatial arrangement of these mesoscale defects, establishing a critical foundation for optimizing armor material properties through defect engineering. Zhang et al.[22] engineered three-modal B_4C/Al composites featuring amorphous multilayer interfaces, which demonstrated significantly improved impact resistance showing 40% increase in fracture toughness and 30% higher energy absorption compared to conventional composites under ballistic testing.Kumar et al.[61] demonstrated that garnet and B_4C-reinforced aluminum matrix composites exhibit superior tensile strength and hardness, while significantly reducing the wear rate properties, making them highly suitable for high-stress military vehicle transmission components.

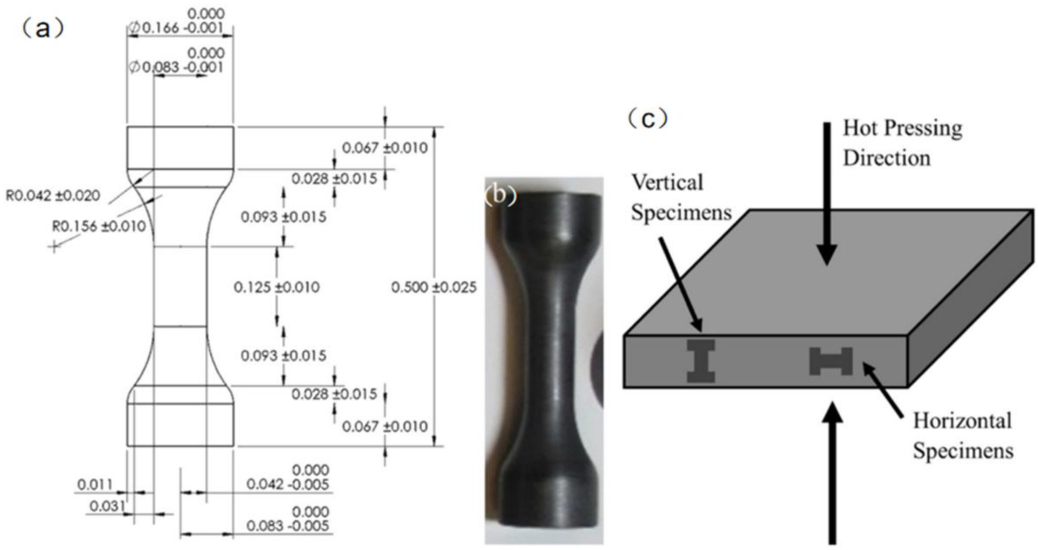

Figure 9. Schematic-(a) and image-(b) of machined compression dumbbell samples. Schematic illustration of orientation for each sample group with respect to bulk plate-(c). Dimensions in a are in inches[60].

4.3. Aerospace

B_4C/Al composites are ideal for aerospace due to their lightweight, high strength, and excellent high-temperature resistance. Their low density, reinforced stiffness, and thermal stability make them suitable for aircraft and spacecraft components. The h-BN and CNTs co-reinforced aluminum matrix composites developed by Khan et al.[38] exhibit outstanding properties, achieving a high relative density of 97.7%. These composites demonstrate a remarkable 106% increase in Vickers hardness, and a 189% enhancement in tensile strength (Figure 5, Table 5), making them highly promising for aerospace applications. Their superior strength to weight ratio and enhanced mechanical performance position them as ideal candidates for high strength, lightweight structural materials in the aerospace industry. Ma et al.[62] emphasized that particle-reinforced Al matrix composites offer significant advantages for aerospace lightweight applications. Their research highlights that the size and spatial distribution of both matrix grains and reinforcing particles play a crucial role in determining the material's mechanical properties, making these composites highly suitable for high-performance aerospace structures. Through optimized friction stir welding process parameters, Jamaludeen[63] achieved a significant reduction in wear rate to 154.21×10^{-5} mm^3/m for AA6092/B_4C composites, substantially improving their reliability for aviation applications. Sekhar et al.[64] developed a sustainable high-performance composite by reinforcing recycled aluminum can matrix with granite particles and B_4C. The material exhibited exceptional, mechanical properties, achieving

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compressive strength of 1124 MPa along with 28% enhanced wear resistance, successfully combining resource recycling with superior performance. Ambigai et al.[8] developed a centrifugally cast Al-based B_4C FGCs with remarkable thermomechanical properties. Their study revealed that a 50 µm reinforcing phase improved the tensile strength by 31%, while the 100µm reinforcing phase enhanced the thermal conductivity by 46.4% and the thermal diffusivity by 27.8%. These tailorable properties make the composite ideal for aerospace thermal management systems, particularly for graded heat exchangers and heat sinks accommodating variable thermal loads.

Table 5. Theoretical, sintered, relative densification and porosity (%) of BN/Al and 3BN-CNTs/Al composites [38].

Compositions		Theoretical density (g/cm³)	Sintered Density (g/cm³)	Relative Densifications (%)	Porosity (%)
Pure Al	Al	2.7	2.54	93.7	6.2
BN/Al Composite	1BN/A	2.69	2.55	95.5	4.4
	Al-3BN/A	2.68	2.6	96.8	3.1
	Al-5BN/A	2.67	2.56	95.1	4.8
	Al-7BN/A	2.65	2.53	94.7	5.2
BN-CNTs/Al Composites	3BN-0.25CNTs/Al	2.69	2.61	97	2.9
	3BN-0.5CNTs/Al	2.69	2.63	97.7	2.2
	3BN-0.75CNTs/Al	2.69	2.59	96.2	3.7
	3BN-1CNTs/Al	2.69	2.57	95.5	4.4

4.4. Transportation

B_4C/Al composites are highly competitive for automotive and rail transport applications due to their optimal combination of lightweight properties, excellent wear resistance, and cost efficiency. The low-density aluminum matrix enables significant weight reduction, while the B_4C reinforcement enhances surface durability. These advantages, along with competitive manufacturing costs, make B_4C/Al composites particularly suitable for high-performance moving components where reducing mass and extending service life are critical requirements.

4.4.1. Automobile Parts

Chandel et al.[65] demonstrated that Al matrix composites incorporating both hard ceramic particles and soft reinforcements achieve optimal performance-significantly enhancing strength, hardness and wear resistance while reducing brittleness. This balanced approach effectively meets automotive industry requirements for lightweight materials with high strength and superior wear resistance. Thakur et al.[25] developed an Al6063-B_4C-Gr hybrid composite with optimized reinforcement ratios, demonstrating superior wear resistance for high-speed applications. Madhu et al.[11] innovatively incorporated rubber ash and B_4C in varying ratios into Al-based FGCs, achieving both cost reduction and enhanced tensile strength through synergistic reinforcement-offering a novel solution for automotive lightweight applications. Aabid et al.[66] enhanced the dry sliding wear performance of aluminum hybrid composites, offering potential for developing lubricant-reduced automotive braking systems.

4.4.2. Rail Transit

Venkatesan et al.[67] developed an optimized die contour technology combining cosine and cubic polynomial profiles, which significantly reduced extrusion loads while ensuring uniform metal flow in B_4C/Al composites. This advancement provides an efficient new manufacturing process for producing large structural components in rail transit applications.

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4.5. Electronics Industry

In electronics industry, B_4C/Al composites have become essential materials for electronic packaging and thermal management systems, owing to their tunable CTE and superior thermal conductivity. These tailored thermophysical properties enable optimal heat dissipation while minimizing thermal stresses in sensitive electronic components. Ziani et al.[37]developed an Al/Mo/SiC tri-component periodic multilayer film exhibiting high EUV reflectivity (48% at 17.3 nm), which has been successfully implemented in the solar orbiter mission's EUV imager. Zhang et al.[46] demonstrated that strong interfacial bonding between SiC/P-doped graphene and Al matrix can simultaneously enhance the composite's mechanical strength and thermal performance, offering a novel design strategy for advanced electronic packaging materials. The laser surface treatment of B_4C/Al composites by Yilbas et al.[34] significantly enhanced both surface microhardness and hydrophobicity through the formation of a dense sub-micron grain layer containing AlN compounds, making these modified composites particularly suitable for electronic device enclosure applications. Alattar et al.[68] demonstrated that incorporating 5% B_4C particles into Al matrix composites yields a uniform fine-grained microstructure, optimizing both hardness and ultimate tensile strength, properties particularly advantageous for heat-sensitive electronic components requiring efficient thermal dissipation.

4.6. Other Applications

Beyond these primary applications, B_4C/Al composites are also utilized in specialized domains such as tool manufacturing and sports equipment. Mironovs et al.[69] developed a powder metallurgy recycling process for aluminum-based B-W fiber composites, enabling the reuse of high-strength fiber waste in cutting tool manufacturing. Panneerselvam et al.[70] demonstrated that AA6063-B_4C-$ZrSiO_4$ hybrid composites exhibit superior wear resistance and a reduced coefficient of friction in tribological tests, rendering them ideal as high-performance sports equipment materials. Table 6 summarizes the key performance metrics and representative applications of B_4C/Al composites across different application fields.

Table 6. Primary Applications and Typical Cases of B_4C/Al Composites.

Application Field	Critical Performance Requirements	Typical Application Cases	Advantages/Features	Ref.
Nuclear shielding	High neutron absorption (Σa), radiation resistance	Reactor control rods, spent fuel containers	^{10}B enrichment (≥19.8%), low activation	[2]
Military armor	Ballistic limit (V50), hardness (≥70 HRC)	Vehicle armor plates, personal protection	High hardness-to-density ratio (8.5 GPa·cm³/g)	[6]
Aerospace components	Specific strength (≥380 MPa·cm³/g), thermal stability	Satellite structural parts, UAV frames	Low CTE (6.5×10^{-6}/K), vibration damping	[8,38,63]
Automotive lightweight	Wear resistance (≤3×10^{-6} mm³/Nm), cost efficiency	Brake rotors, suspension arms	40% weight reduction vs steel	[8,65]
Thermal management	Thermal conductivity (≥180 W/m·K), dimensional stability	CPU heat sinks, power modules	Tunable CTE matching Si	[34,37,46]

5. Summary and Outlook

After decades of development, significant advancements of B_4C/Al composites have been achieved in processing techniques, performance optimization, and engineering applications, yet critical challenges remain. This section summarizes current research milestones, analyzes persistent limitations, and outlines future development priorities.

5.1. Summary of Research Progress

From a material system perspective, B_4C/Al composites have progressed from simple binary formulations to advanced multi-component hybrid architectures. Khan et al.[38]developed an Al matrix composite co-reinforced with h-BN and CNTs, achieving 97.7% theoretical density while significantly enhancing mechanical properties. Raja et al.[39] developed a multi-scale Al7075 composite reinforced with hybrid B_4C-TiB_2 particles, achieving optimal comprehensive performance. This multi-component design strategy has emerged as a critical approach for advanced material optimization. Regarding fabrication methods, conventional processing techniques continue to undergo refinement while novel approaches are rapidly advancing. Chen et al.[3]optimized the HIP process for manufacturing large-scale B_4C/Al composite plates.Sun et al. [31–33]were the first to develop additive manufacturing (AM) technology, which facilitates the economical and precise fabrication of aluminum-based composite structures. The implementation of wire powder arc additive manufacturing (WPA-AM) methodologies enabled the effective incorporation of ceramic particles, including B_4C, SiC, TiC, and WC/W_2C, into the aluminum matrix. Through the optimization of process parameters, a substantial enhancement in the mechanical properties of the material was attained.The following text is intended to provide a comprehensive overview of the subject matter. Khodabakhshi et al.[30] pioneered an innovative accumulative fold-forging process to fabricate ultrafine-grained nanocomposites. This breakthrough in processing technology establishes a robust foundation for enhancing material properties. Performance investigations have progressively advanced from macroscopic mechanical characterization to comprehensive understanding of microscopic deformation mechanisms. Li et al.[21] elucidated the synergistic reinforcement mechanisms in Al-based composites, demonstrating enhanced performance through multi-scale strengthening effects. Dai et al.[42]established quantitative composition-performance relationships for radiation shielding applications. Collectively, these studies provide fundamental theoretical guidance for advanced material design. The engineering applications of these composites have significantly expanded beyond traditional nuclear shielding to emerging fields including armor protection systems and high-performance electronic packaging, reflecting their versatile property portfolio. The diverse applications of B_4C/Al composites, including nuclear waste storage tanks [71], high-performance armor systems[6] and EUV optical components [37] demonstrate their exceptional versatility across multiple engineering domains[49].

5.2. Key Issues

Despite significant advancements, critical challenges still exist for B_4C/Al composites.

5.2.1. Interface Response Control

Interface control remains a critical research challenge in B_4C/Al composites. Excessive formation of brittle phases at the B_4C/Al interface significantly reduces both fracture toughness and plastic deformation capacity. However, systematic methodologies for precisely regulating interfacial reaction products through process optimization remain largely underdeveloped. Han et al.[50] demonstrated that higher B_4C content exacerbates galvanic corrosion in B_4C/Al composites, revealing the critical role of interface stability in corrosion resistance [35]. Future research must address three key priorities; elucidating the thermodynamic and kinetic mechanisms of interfacial reactions, establishing quantitative structure-property relationships at interfaces, and developing universal interface engineering strategies.

5.2.2. Process Repeatability

Process repeatability remains the critical bottleneck limiting large-scale industrial adoption. As Bhowmik et al.[24] demonstrated, both controlled and uncontrolled variables in stir casting processes significantly impact final product quality. However, comprehensive quantitative models correlating process parameters with material properties remain underdeveloped [52]. Butola et al.[28] optimized FSP parameters using response surface methodology, demonstrating that theory-guided process design is essential for ensuring material property consistency. To achieve precise process control, future efforts should focus on developing real-time monitoring and intelligent control systems.

5.2.3. Irradiation Damage Mechanism

The limited understanding of irradiation damage mechanisms remains a critical barrier for nuclear applications.Tthe long-term irradiation effects on microstructure evolution and performance degradation require further investigation [72]. Although the graphitized nanocarbon helium-absorption method [46] demonstrates effectiveness, a more comprehensive irradiation damage mitigation strategy is still required. Future research should integrate advanced characterization techniques with multiscale simulations to develop predictive irradiation damage models.

5.3. Future Development Direction

To address these challenges, future research on B_4C/Al composites can focus on the following key directions.

5.3.1. Multi-Scale Interface Design

Future research can develop multiscale interface design methodologies to precisely control interfacial performance in B_4C/Al composites. By integrating atomic-scale first-principles calculations[46], nanoscale interface engineering, and macroscale alloy design, this hierarchical approach enables the construction of gradient functionalized interfaces that simultaneously enhance strength, fracture toughness and environmental stability. Critical implementation strategies will leverage surface modification, nano-coating technologies[73] and precision microalloying to optimize reinforcement-matrix compatibility and bulk property uniformity.

5.3.2. Intelligent Preparation Process

Future study can focus on developing intelligent manufacturing processes to improve property consistency and repeatability in B_4C/Al composites. By integrating machine learning and digital twin technologies, a quantitative process-structure-property prediction model can be established, enabling real-time process optimization[74]. Advanced digital manufacturing techniques including AM and cold spraying will play increasingly critical roles in achieving these objectives.

5.3.3. Prediction of Extreme Environmental Behaviors

To enhance the prediction and evaluation of material behavior in extreme environments, future research should focus on developing multi-physics coupled irradiation damage models. By integrating artificial intelligence with these models, one can accurately predict material performance evolution under complex conditions, including long-term irradiation, high-temperature, and high-pressure exposures, thereby providing reliable guidance for engineering applications[75].In-situ characterization techniques and accelerated testing methodologies will be critical to validating these predictive frameworks.

5.3.4. Sustainable Development

Future work on Al-based composites must prioritize sustainable development and closed-loop material cycles. As demonstrated by Mironovs et al.[69], developing energy-efficient fabrication processes with minimal emissions, along with establishing robust recycling protocols, will be critical for reducing environmental impact [76]. These efforts should be complemented by advanced design strategies such as functional gradient architectures and structure-function integration, which optimize material utilization efficiency across multiple lifecycles. The integration of these approaches combining green manufacturing techniques, effective end of life recovery methods, and intelligent material design represents a comprehensive pathway toward sustainable composite technologies.

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