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# Enhancing Aluminum Matrix Composites With Hexagonal Boron Nitride (HBN) Particulates: A Mini Review

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**Abstract**

This present mini-review article elucidates the role of hexagonal boron nitride (hBN) particulates in enhancing the properties of aluminum matrix composites (AMCs). The article delves into various methodologies for incorporating hBN, such as powder metallurgy and stir casting, emphasizing theoretical aspects and process parameters. It synthesizes data from numerous studies to illustrate improvements in mechanical and tribological properties imparted by hBN. Furthermore, the article provides a theoretical analysis of the distribution of hBN within the aluminum matrix and its impact on composite performance. Future research directions are outlined, including exploration of novel composite materials and advanced manufacturing techniques. The environmental implications of hBN in AMCs are also discussed, highlighting sustainability and recyclability concerns. This review is a significant resource for researchers and industry professionals in material science, offering insights into current trends and future potentials of hBN-enhanced AMCs.

***Keywords:*** Hexagonal Boron Nitride; Aluminum Matrix Composites; Mechanical Properties; Manufacturing Techniques; Environmental Sustainability.

## 1 Introduction

Aluminum alloys are renowned for their lightweight characteristics, and the integration of hexagonal boron nitride (hBN) reinforcement preserves this advantage while concurrently enhancing mechanical properties [1]. This amalgamation is exceedingly valuable in sectors such as aerospace, where lightweight materials are instrumental in augmenting fuel efficiency and overall performance [2]. Aluminum Matrix Composites (AMCs) fortified with hBN have demonstrated superior hardness and tensile strength compared to the base metal. The choice of reinforcement material is a critical aspect in the design of composite materials, necessitating adequate wettability for robust bonding and homogenous dispersion. In the realm of aerospace, aluminum alloys are utilized for their notable strength and wear properties, which can be further improved by varying the reinforcement particles in weight or volume. The incorporation of hBN reinforcement into aluminum alloys introduces significant properties, making it an innovative material for aerospace applications [3]. The enhancement of mechanical strength, wear resistance, and tribological performance is a direct consequence of adding hBN reinforcement to aluminum composites. The ceramic particles bolster the matrix, offering resistance to deformation and fracture. An increase in stiffness or Young's modulus of the composite is observed with hBN reinforcement, enhancing resistance to bending and deformation under load [4]. The hardness of the composite may also escalate due to the presence of hBN, serving beneficially in applications where wear resistance and surface durability are paramount.

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Specifically, hBN reinforced aluminum composites are apt for applications involving sliding or abrasive wear, such as bearings, seals, bushings, and various mechanical components. The hBN particles function as solid lubricants, diminishing friction and wear during sliding or abrasive interactions. The coefficient of friction can be reduced owing to hBN, rendering the composite more suitable for scenarios where minimizing friction is essential [5]. The inherent lubricating properties of hBN particles contribute to decreased friction and wear, particularly under dry or high-temperature conditions. Achieving an even dispersion of hBN particles within the aluminum matrix is crucial for attaining the desired properties. Particle agglomeration can lead to localized stress concentrations and compromised material properties. The methodology employed for integrating hBN particles into the aluminum matrix, such as powder metallurgy or stir casting, influences the distribution and interaction of the reinforcement with the matrix, thereby affecting the final properties. The enhanced mechanical, thermal, and tribological properties resultant from hBN reinforcement make these composites suitable for a wide array of applications. These encompass aerospace components, automotive parts (e.g., engine components, brake discs), industrial machinery (e.g., cutting tools), and electronic packaging. Attaining uniform dispersion and balancing the properties are pivotal in optimizing these composites for specific applications [6].

The confluence of hBN's unique properties, including hardness, lubrication, thermal stability, and chemical resistance, renders it an appropriate reinforcement choice in Aluminum Matrix Composites (AMCs) [7]. These properties significantly contribute to the overall performance enhancement of the composite material, making hBN-reinforced AMCs valuable for diverse industrial applications. hBN particles act as solid lubricants in the composite, reducing friction and wear in scenarios involving sliding or abrasive contact, an attribute especially advantageous in applications where minimizing friction is critical [8]. Smaller hBN particles are likely to disperse more uniformly within the aluminum matrix, leading to improved load transfer and mechanical properties [9]. The increased surface area of smaller particles can enhance the bond between the matrix and the particles, potentially increasing hardness while the unique lubricating properties of hBN can contribute to improved specific strength by mitigating friction-induced wear [10]. Finer hBN particles can lead to increased hardness due to their capacity to effectively inhibit dislocation movement and deformation within the matrix [11]. The uniform distribution of smaller particles can enhance strength as they obstruct crack propagation and augment the overall load-bearing capacity of the composite [12]. Furthermore, appropriate processing techniques and optimization are essential to maximize the benefits of hBN reinforcement [13]. The exceptional strength-to-weight ratio of AMCs, along with their other advantageous properties, renders them highly sought-after for aerospace and defense applications, where structural integrity and weight reduction are paramount [14].

The study focuses on the production of composite materials wherein aluminum acts as the matrix or base material. This amalgamation of the matrix material (aluminum) with selected reinforcements endows the resultant composite with specific attributes. The synthesis process encompasses methods like powder metallurgy, stir casting, or other techniques aimed at facilitating the uniform dispersion of the reinforcement particles within the aluminum matrix. A variety of techniques are employed to scrutinize different facets of the composites, including their microstructure, mechanical properties, and tribological performance. The primary objective of this study is to underscore and review the findings related to the impact of different reinforcements of hexagonal boron nitride (h-BN) — varying in sizes and types — on the properties of the aluminum matrix composites. This mini-review intends to delve into discussions on the empirical evidence underlying the observed phenomena, potential applications of the composites, and prospects for future research. These discussions are crucial for advancing understanding of the material properties and guiding the development of advanced composites for various industrial applications.

## 2 Theoretical Aspects of Methodologies in hBN Reinforcement

Incorporating hexagonal boron nitride (hBN) into aluminum matrices via methodologies such as powder metallurgy and stir casting involves critical parameters influencing the composite's final properties. In powder metallurgy, parameters such as compaction pressure, sintering temperature, and holding time play pivotal roles. Higher compaction pressures typically enhance the densification of the composite but may also lead to particle fragmentation. Sintering temperature, crucial for achieving adequate bonding between hBN and aluminum, must be optimized to prevent thermal degradation of hBN. Figure 1 illustrates the powder metallurgy process used for incorporating hBN into aluminum matrices. Similarly, in stir casting, factors such as stirring speed and duration impact the distribution of hBN particles within the matrix. Optimal stirring ensures uniform dispersion, avoiding particle agglomeration. Additionally, the choice of particle size of hBN affects the interfacial bonding and, consequently, the mechanical properties of the composite. The stir casting process, as shown in Figure 2, highlights the critical steps and control points Smaller particles often lead to better bonding but may introduce challenges in handling and uniform distribution. These theoretical insights into process parameters offer a foundational understanding, guiding experimental methodologies for enhanced composite performance.

## 3 Mechanical and Tribological Properties

Several studies have explored the mechanical and tribological properties of aluminum composites reinforced with hexagonal boron nitride (hBN). Lokesh et al. (2022) examined hybrid composites with enhanced hardness properties attributed to the incorporation of nickel-coated hBN particles within the Al-7075 matrix [15].

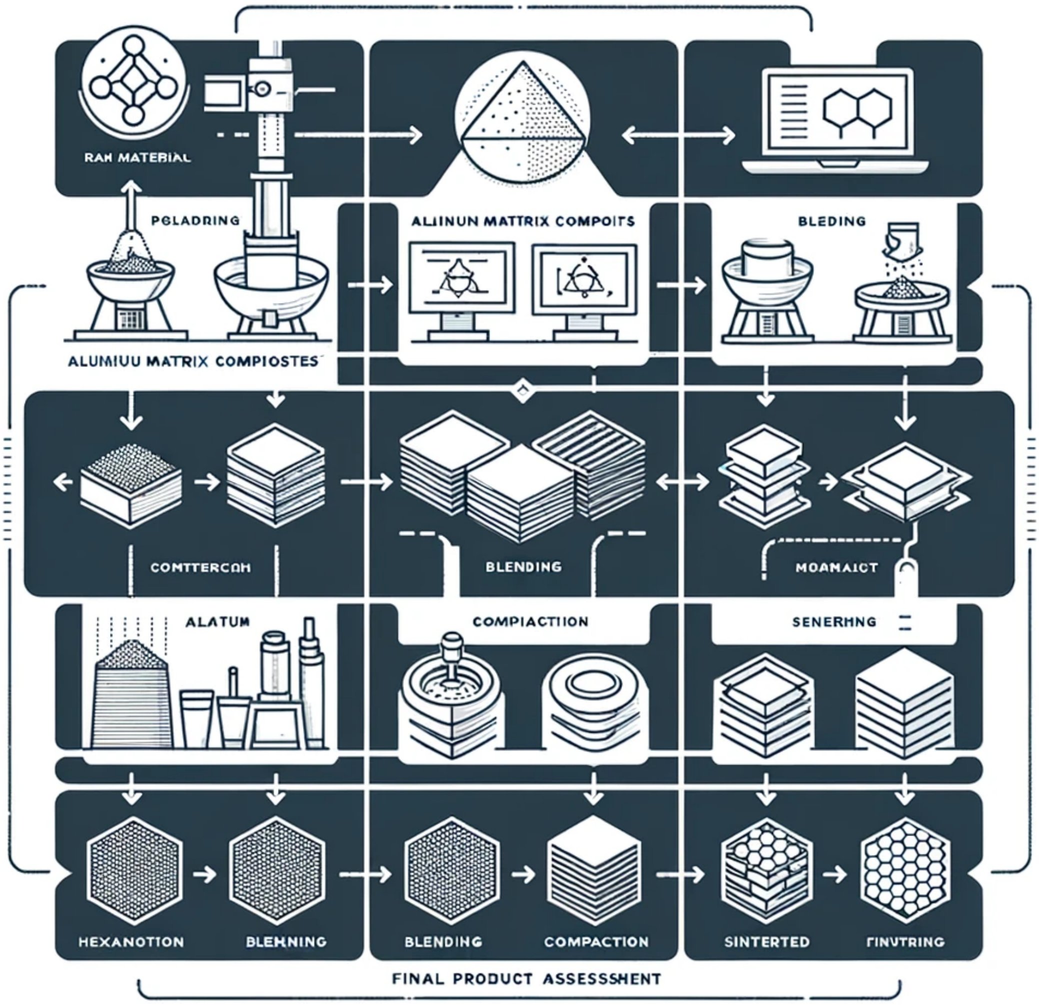


Figure 1: Steps involved in the powder metallurgy process for creating aluminum matrix composites with hexagonal boron nitride (hBN).[Images generated by AI (DALL-E, OpenAI)]

These reinforced particles contributed to increased resistance against deformation and wear, leading to improved hardness. The hybrid reinforced composite exhibited superior tensile properties compared to both the base metal (Al-7075) and the composite reinforced solely with nickel-coated hBN. Rajkumar et al. (2021) investigated the fabrication of AA2024/hBN composites using a liquid-state process with varying weight percentages of hBN particles [16]. The insertion of hBN particles in the AA 2024 matrix led to a noticeable increase in hardness, peaking at 20 wt.% hBN. The compressive strength and ultimate tensile strength of the composites improved up to 15 wt.% hBN insertion but declined beyond this point. Joel et al. (2022) investigated the surface modification of Al 2024 through the incorporation of Boron Nitride via Friction Stir Processing (FSP) [17]. The processed zone exhibited increased hardness and tensile strength, with the highest values observed at specific FSP parameters. Loganathan et al. (2020) studied an AA7075 composite fabricated using the stir-squeeze cast technique, reinforced with ZrB2 and hBN solid lubricant particles [18]. The composite demonstrated superior wear resistance, attributed to the formation of a self-lubricating film composed of B2O3 and H3BO3. Ayyanar et al. (2020) focused on hybrid composites made from AA6061 alloy, B4C, and h-BN [19]. The addition of B4C and h-BN reinforcements led to improvements in tensile strength and wear resistance, with significant increases observed in the hybrid composite containing 15% B4C and 5% h-BN. Essam et al. (2022) employed the friction stir process (FSP) to create hybrid metal-matrix-surface composites (HMMSC) [20]. The introduction of hBN nanoparticles, along with other carbides, led to substantial improvements in mechanical properties and wear resistance. Rakshath et al. (2019) investigated particulate-reinforced Al-7075 metal matrix composites using a two-step stir casting method [21]. The introduction of hBN reinforcement resulted in decreased density and enhanced hardness and wear resistance of the composites.

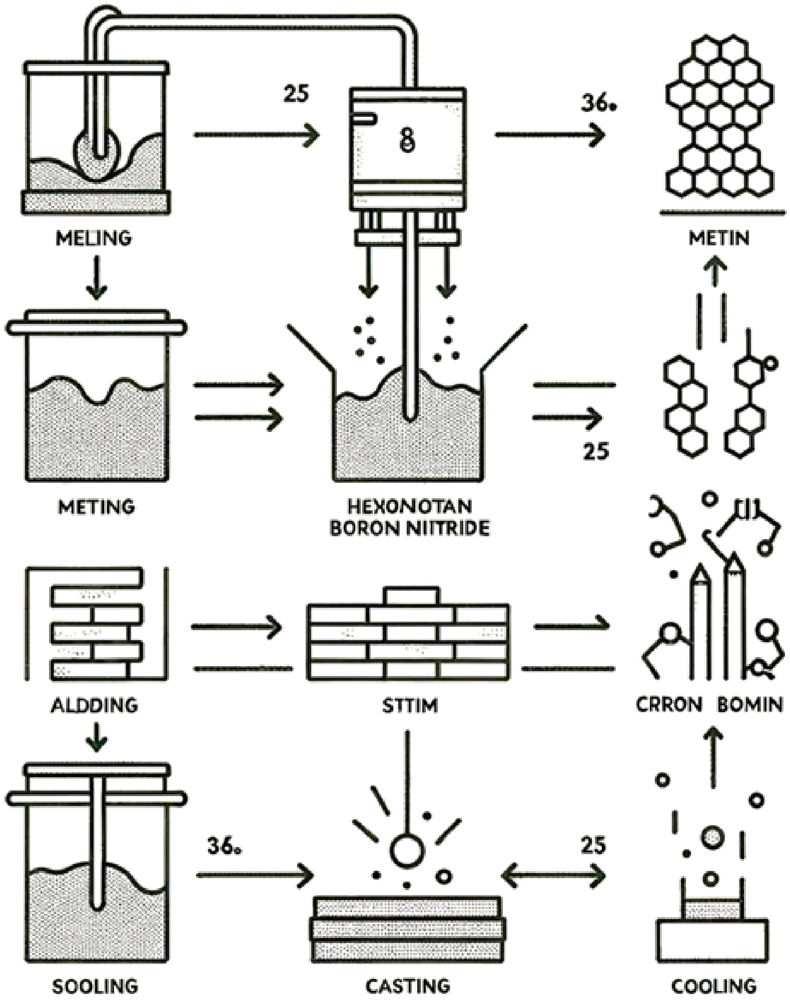


Figure 2: Stir casting process, highlighting the key steps and control points for creating hBN-enhanced aluminum matrix composites [Images generated by AI (DALL-E, OpenAI)].

Table 1: Synthesis and Characterizations of AMCs Using Various Techniques

| **Material** | **Reinforcement (hBN)** | **Process** | **Characterizations** | **Remarks** |
|---|---|---|---|---|
| Aluminum (Al) | hBN: (2wt.% and 5wt.%) | Powder Metallurgy | High-energy ball milling effective for reducing particle size of h-BN. Micro-hardness increased. | Influences thermal, mechanical, and physical properties [22]. |
| Aluminum Powder | BNNSs (boron nitride nano-sheets): 0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% by volume. | Shift-speed ball milling and Direct Current Sintering (DCS) | Strong bonding at interface, tensile strength up to 220MPa. | Enhanced tensile properties, dispersing high-content BNNSs [23]. |
| Aluminium (39.4 $\mu$m) | (h-BN-200 nm) and (TiB2-20 $\mu$m) 100%TiB2, 50% TiB2 + 50%BN and 100% BN | Friction Stir Processing (FSP) | Uniform dispersion of reinforcements, enhanced sliding wear resistance. | Improved wear resistance with nano-sized BN particles [24]. |
| Aluminium (10 $\mu$m) | BNNPs (boron nitride nano-particles with140 nm): 0.5, 1.5, 3, 4.5, 6 and 7.5 by wt.%. | Spark Plasma Sintering Process | Increased strength under tensile loading, especially at elevated temperatures. | Enhances mechanical properties, particularly at higher temperatures [25]. |

**Table 1 continued from previous page**

| Material | Reinforcement (hBN) | Process | Characterizations | Remarks |
|---|---|---|---|---|
| AA 6061 | (h-BN 10$\mu$m:CBN-1 $\mu$m) | Stir Casting Process | Over 90% of theoretical density achieved, indicating successful manufacturing. | Enhanced wear resistance with HBN and CBN reinforcements [26]. |
| Aluminium (Al) | Ti : BN (h-BN-5 $\mu$m and Ti-38 $\mu$m) | Vacuum Infiltration | Changes in microstructure with increased titanium content. | Improved fracture toughness with higher titanium content [27]. |
| A380 | hBN: 0, 0.5, 1 and 1.5 by wt.% | Ultrasonic Cavitation Process | Uniform distribution of nano-powder, increased tensile strength and hardness. | Improved tribological properties, suitable for sliding contact applications [28]. |
| AA7050 | Nano hexagonal boron nitride (h-BN) by wt.% | Spark Plasma Sintering Process | 33% increase in hardness, 65% reduction in wear rate. | Reduced wear rate and increased hardness with 0.5 wt% h-BN reinforcement [29]. |

# 4 Impact of Reinforcement

The cited literature review elucidates the significant impact of reinforcing ceramic material, particularly hexagonal boron nitride (hBN), in aluminum-based materials. This review accentuates several critical aspects regarding the influence of hBN reinforcement on material behavior:

- The incorporation of hBN reinforcement into aluminum-based materials induces a strengthening effect, consequently rendering the composite material more robust and resistant to deformation and failure.
- hBN particles modify the behavior of the material by enhancing its mechanical properties, thus rendering it more applicable for various scenarios requiring augmented strength.
- The review highlights hBN's role as an exemplary solid lubricant. Beyond its strengthening impact, the integration of hBN into aluminum-based materials offers the advantage of solid lubrication. This property ensures effective performance under dry sliding conditions across diverse loads and velocities, pivotal in contexts where reducing friction and wear is crucial.
- Aluminum-hBN composites demonstrate superior microhardness and strength compared to the pure alloy or base powder material. This enhancement in mechanical properties stems from the reinforcing action of hBN, which impedes dislocation movement, thereby contributing to the increased strength of the material.
- The addition of hBN reinforcement to materials, inclusive of aluminum, leads to grain refinement. This process involves the diminution of individual crystal grains in the material, an essential factor for establishing robust interfacial bonding between the reinforcement and the matrix material, subsequently responsible for the amplified mechanical properties of the composite.

The literature review underscores the positive ramifications of hBN reinforcement in aluminum-based materials, encompassing improved mechanical properties, enhanced solid lubrication performance, and advanced grain refinement. The presence of hBN fosters a strengthening effect, making the material more resilient to deformation and wear. This reinforcing effect is associated with improved bonding at the interface between the hBN reinforcement and the matrix material, verifiable through sophisticated analytical techniques such as XRD, SEM, and TEM. The results obtained provide an extensive understanding of the behavior and potential utility of Al-hBN based composites. These findings lay the foundation for future research and practical application of these materials in various industries. The potential observations derived from the results include:

- The dual benefit of hBN reinforcement, offering both strengthening and lubrication, is a particularly intriguing aspect. This combination is advantageous in applications where high mechanical strength and reduced friction/wear are essential. The dual role of hBN as a reinforcing agent and a solid lubricant suggests broad utility in industries ranging from aerospace to automotive, where performance under demanding conditions is crucial.
- The review emphasizes the improved microhardness and strength observed in aluminum-hBN composites, indicating that hBN particles effectively hinder dislocation movement, thereby strengthening the material.
- The importance of strong interfacial bonding between hBN and the aluminum matrix is underscored, raising considerations about the methods used to achieve and quantify this bonding.

- Identifying the optimal hBN content for mechanical properties and prevention of aggregation is crucial. Understanding the threshold at which aggregation becomes problematic can guide the design of future experiments.
- While the literature review does not specifically address the processing techniques for incorporating hBN into aluminum, discussing various methods such as powder metallurgy and stir casting could deepen the review. Stir casting, or liquid metallurgy, is a relatively straightforward and cost-effective method due to its simplicity. The choice between stir casting and powder metallurgy hinges on the specific objectives, available resources, and the desired balance between cost-effectiveness and composite performance.

Summarizing the discussion by pinpointing potential areas for further research provides a roadmap for future studies. Investigating alternative reinforcement materials, exploring the effects of varying processing conditions, and examining the composites' behavior under more complex loading scenarios could yield valuable insights. Incorporating these discussion points ensures a comprehensive exploration of the implications and nuances of hBN reinforcement in aluminum matrix composites.

## 5 Applications of Al/hBN based AMCs

Aluminum matrix composites reinforced with hexagonal boron nitride (Al-hBN) possess a range of valuable applications across various industrial sectors. Figure 1, as referenced, underscores some of these applications, highlighting the enhanced capabilities imparted by hBN reinforcement in pure alloys. The integration of hBN reinforcement into aluminum matrices culminates in the formation of composites that boast a unique amalgamation of properties. These include lightweight design, elevated strength, wear resistance, and corrosion resistance. Such attributes render Al-hBN composites eminently suitable for diverse industrial applications, ultimately augmenting the overall performance of materials within these domains.

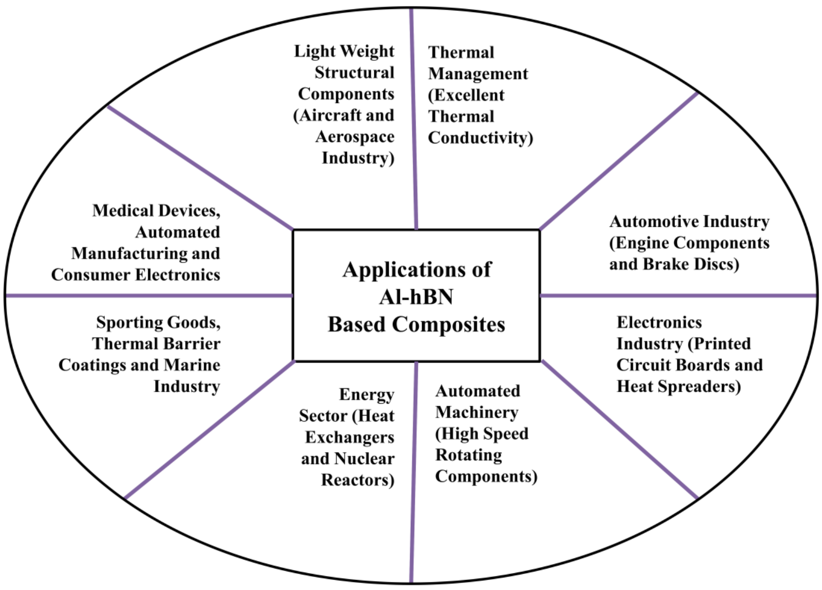


Figure 3: Applications of Al-hBN based composites.

## 6 Future Research Directions in hBN Enhanced Aluminum Composites

The exploration of hBN in aluminum matrix composites (AMCs) opens several avenues for future research. One promising direction involves investigating alternative composite materials that could synergize with hBN to offer enhanced properties. For instance, the integration of carbon nanotubes or graphene alongside hBN could lead to composites with superior strength and thermal conductivity. Another area of research is the improvement of manufacturing techniques. Innovations in additive manufacturing, such as 3D printing of metal composites, could revolutionize the production of hBN-enhanced AMCs, allowing for more complex geometries and tailored material properties. Additionally, the long-term durability and performance of these composites under various environmental conditions remain a fertile ground for investigation. This includes studying the effects of exposure to extreme temperatures, corrosive environments, and cyclic loading conditions. Lastly, the scalability and economic viability of producing hBN-enhanced AMCs for large-scale applications should be a key focus, ensuring that these advanced materials are not only effective but also accessible for widespread industrial use.

# 7 Environmental Impact Considerations of hBN in Aluminum Composites

The incorporation of hexagonal boron nitride (hBN) in aluminum composites must be evaluated in the context of environmental sustainability. hBN, like other boron compounds, is relatively inert and non-toxic, making it a preferable choice in terms of environmental and health safety compared to more hazardous materials like asbestos or certain heavy metals often used in composites. However, the complete environmental impact of hBN usage extends beyond its intrinsic properties. It encompasses the entire lifecycle, from extraction and processing of raw materials to manufacturing and eventual disposal of the composites. The energy-intensive production of hBN and aluminum should be considered, especially focusing on reducing emissions and improving energy efficiency. Additionally, research should investigate the recyclability of hBN-enhanced aluminum composites. While aluminum is highly recyclable, the presence of hBN may alter its recyclability profile. Understanding and optimizing these aspects are crucial for developing sustainable composite materials that align with the growing emphasis on reducing the carbon footprint and promoting circular economies in material production.

# 8 Conclusions

The study conclusively demonstrates that the incorporation of hBN reinforcement into aluminum matrix composites notably enhances their mechanical and tribological properties. This enhancement is particularly evident in the improved microhardness, strength, and wear resistance of the composites, indicating a transformative impact on the base material that surpasses the pure alloy's performance. The presence of hBN reinforcement not only contributes to increased resistance to deformation and wear but also significantly augments the wear resistance behavior, making these composites ideally suited for applications that demand durability under frictional conditions. Furthermore, the role of hBN in impeding dislocation movement strengthens the material, while its lubrication effect reduces friction and wear during sliding interactions. Among various fabrication methods, stir casting stands out as a cost-effective and practical approach due to its simplicity and lower equipment costs, making it an advantageous method for producing Al-hBN composites. The potential of Al-hBN based composites to revolutionize various industries is immense, offering lightweight, high-strength materials with enhanced wear resistance. The continued exploration into novel reinforcement materials, including nano-materials and advanced ceramics, is expected to yield composites with even better properties such as increased strength, wear resistance, and thermal stability. Future research endeavors are likely to focus on optimizing the composite composition and microstructure to meet specific performance requirements, involving more precise control over particle distribution, size, and orientation within the matrix.

# Declaration of Competing Interests

The authors declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

# Funding Declaration

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# Author Contribution

**Hartaj Singh**: Conceptualization, Methodology; **Kapil Singh**: Data curation, Visualization; **Sachit Vardhan**: Validation and Overall supervision and Editing.

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