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Advancing Automotive Materials with Hexagonal Boron Nitride: Toward Sustainable and High-Performance Vehicles

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Abstract: This detailed review focuses on the utilization of hexagonal boron nitride (hBN) reinforced in automotive parts. As investigations into new automotive materials continue to grow, the requirements for improved performance, durability, and energy efficiency of today's vehicles are increasingly reliant on advanced materials. hBN is considered "white graphene" because of its similarly layered structure. hBN is a beautifully arranged material with great thermal, mechanical, and tribological properties that can be applied in numerous automotive applications. The paper is a review of the research on hBN and its use in brake systems, engine lubricants, thermal management solutions, tire components, and structural composites. The paper features several ways hBN can bring positive changes, including reduced friction and wear, enhanced thermal conductivity, and increased mechanical strength. The main issues faced while using hBN as a trustworthy replacement or complement to other materials, like their dispersion and the cost, effectiveness of the materials, have been discussed by the authors of the paper. Still, they have also reviewed potential future research paths for hBN and its potential to advance automotive materials research in sustainability, efficiency, and high-performance vehicles.

Keywords: Hexagonal Boron Nitride (hBN); Automotive and Reinforcement; Thermal Management; Mechanical Properties; Composites and Lubricants; Brake Systems; Friction and Wear.

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1. Introduction

The automotive sector is rapidly changing, influenced by factors such as environmental compliance regulations, consumer preferences for safety and comfort, and the ongoing quest for better performance and fuel economy. Such a change requires developing new materials and upgrading existing ones with advanced materials that can resist wear, withstand thermal loads, and maintain the vehicle's overall structural integrity, even under extreme conditions [24]. During this process, two-dimensional (2D) materials emerged as a new class with exceptional properties, offering great potential for the further development of

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various branches of engineering [25]. One of the most attractive members of this class of materials for automotive purposes is hexagonal boron nitride (hBN) [1]. hBN is a material structurally similar to graphene. On the one hand, like graphene, it exhibits several classes of properties that are not unique but also exceed those of traditional materials [2]. hBN has a hexagonal layer lattice structure with strong covalent bonds within the plane and weak van der Waals forces between the layers (Figure 1). This arrangement leads to outstanding mechanical anisotropy, extremely high thermal stability (up to 1000 °C in air), very high heat conduction (from 300 to 2000 W/mK), and significantly better electrical insulation properties of hBN as compared to other materials, which is also indicated by its relatively large bandgap of about 5.9 eV [3].

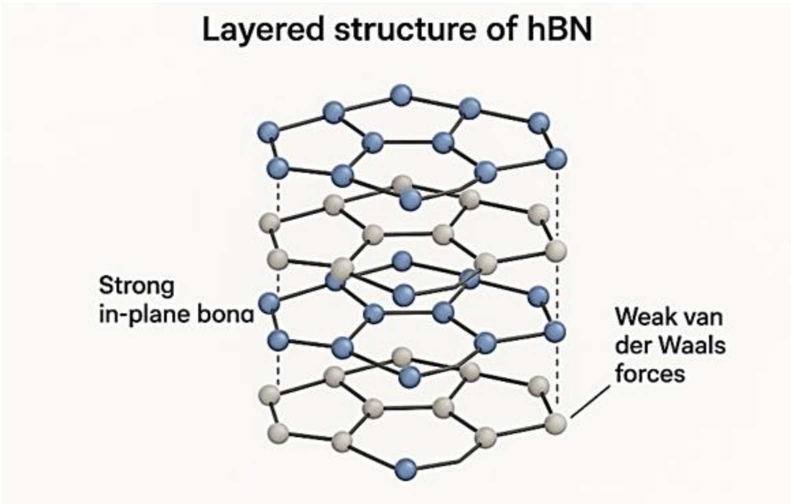

Figure 1: hBN layered structure

Such features make hBN an excellent contender for reinforcing various matrices, including polymers, metals, and ceramics, to produce top-notch composites targeted for the most demanding automotive environments. hBN can be seen in many main applications across the automotive industry where friction, wear, heat removal, or mechanical properties are the focal points [26]. For example, hBN has been extensively analysed in braking systems, owing to its potential to modulate the coefficient of friction and its contribution to thermal management, resulting in better or more stable braking performance [4]. Additionally, hBN nanoparticles in engine lubricants can act as tribological additives, reducing friction and wear and thereby increasing engine efficiency and extending component lifespan [5]. Its thermal conductivity also offers a range of options for thermal management, dissipating heat from critical electronic components and powertrain systems [6]. Moreover, hBN can be used in tire components to improve durability or wear resistance, as well as in structural composites to enhance mechanical properties [7]. Even though this material has attractive features, hBN will have to surpass certain challenges before it can be widely used in automotive applications.

In particular, studies must address the challenges of uniform dispersion of hBN across various matrices, the mechanisms of interfacial bonding, and the cost and effectiveness of using this material in a mass-production scenario [8]. On the other hand, it is necessary to thoroughly investigate synthesis and processing methods to mitigate the challenges before hBN can be considered a major, beneficial material choice for future automotive engineering designs [27]. In the end, researchers have presented a state-of-the-art review of hBN reinforcement, particularly in the automotive industry. Researchers have combined the most critical findings from a wide range of studies to refine the specific advantages and disadvantages of hBN across various components [31]. Besides that, the paper presents a timeline of potential hBN applications, providing insight into its impacts on tribological performance, thermal management, and mechanical properties. The investigation is at the same time relevant and resourceful to the scholarly community, engineers, and other industry players who wish to use hBN when deliberating the advantages of new materials for the "next generation" of automotive applications.

2. Automotive Tribological Applications

Tribology, the science and engineering of surfaces in contact and relative motion, including friction, wear, and lubrication, is of paramount importance to the automotive industry. Friction and wear affect many components of a vehicle, such as the brake system, engine parts, and bearings, and eventually become the main cause of component failure by leading to energy loss and material deterioration. Hexagonal boron nitride (hBN), a unique material, is very similar to graphite in that it has a layered structure; however, it exhibits strong lubrication properties. It is a fact that this material has been among the most efficient in improving tribological performance across a wide range of automotive applications [9].

2.1. Brake Systems

Brake systems are often considered a major safety aspect of any vehicle, and their functionality largely depends on the friction materials used. Many brake pads in the past have contained metallic components, such as copper, which has been heavily criticized lately for its harmful effects on the environment, especially aquatic organisms. This criticism has led to the search for environmentally friendly replacements that deliver the same or better performance. Hexagonal boron nitride (hBN) has shown great promise as a replacement for copper and other solid lubricants in automotive friction materials [10]. Studies show that reinforcing brake pads with hBN resins could be a viable solution to improve their frictional and wear performance. An examination of low-steel composite brake pad materials for railway applications that share brake system characteristics with automotive brake systems revealed that adding hBN can increase the coefficient of friction at lower disk surface temperatures. Additionally, the hBN-reinforced brake pad additives may exhibit a reversal of this enhancement behavior, showing temperature-dependent tribological behavior above certain thresholds (260, 300 C) [4].

In motor vehicle brake applications, aluminum oxide has been blended at 1.5 wt%, as its presence can help counteract fluctuations in the coefficient of friction during braking under extreme environmental conditions. In contrast, the friction properties of hBN can be maintained up to 700 C due to its stable chemical structure and oxidation resistance [4]. Besides friction and wear, hBN is also important for thermal management in brake systems. Braking is a heat-producing process, and the heat generated can lead to brake fade and premature wear. The very high thermal conductivity of hBN material, therefore, allows for the quick and efficient removal of the heat dissipated during braking. In addition to reducing friction and wear, hBN is significant for thermal management in braking systems. When brakes are applied, a lot of heat is generated, which, if not managed, can lead to increased wear and tear. Since hBN is highly thermally conductive, it can help in heat dissipation more effectively. Studies have shown that adding hBN can elevate the thermal conductivity of brake friction materials. One study reports that thermal conductivity was raised from 0.86 W/mK to 1.40 W/mK with 8 wt% hBN [11].

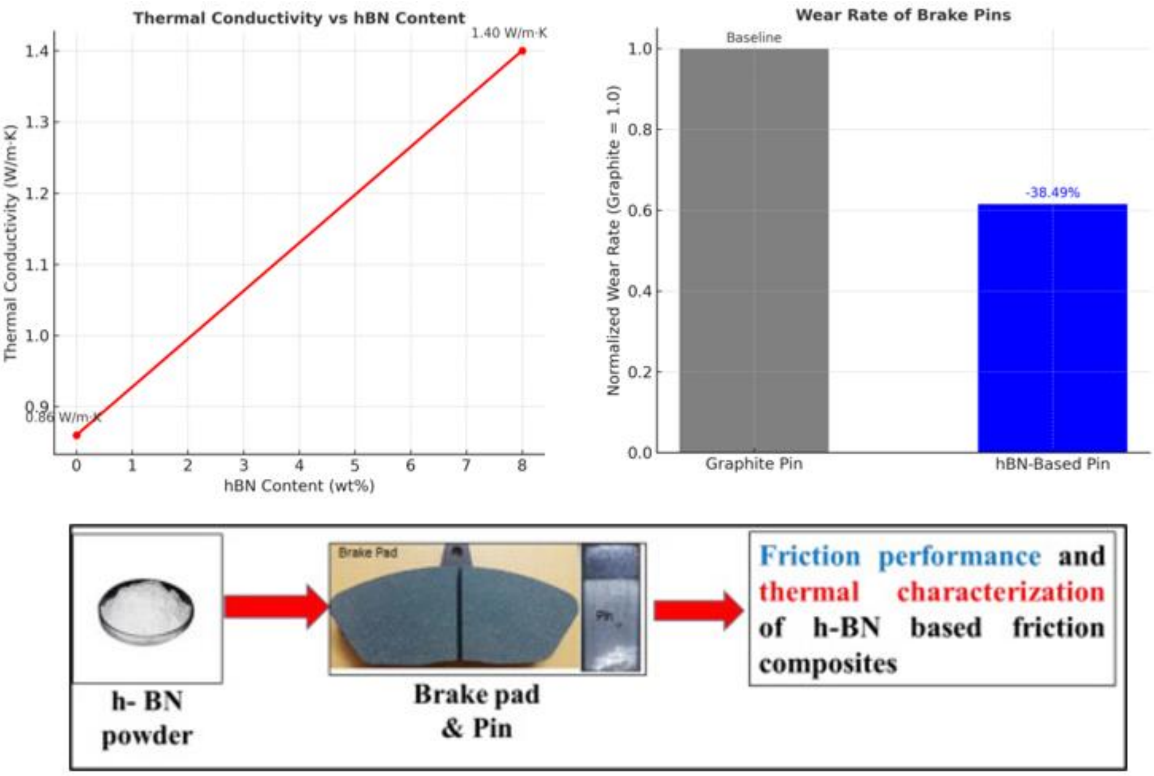

Figure 2: Performance enhancement of brake materials with hBN [11]

The improved thermal management results in more consistent physical properties and friction performance under severe brake conditions. In the braking system, the wear rate of the hBN-based pins was 38.49% lower than that of the conventional graphite pins when grey cast iron counter discs were used as a reference [15]. Such a significant decrease in wear means longer part life and lower maintenance costs, as shown in Figure 2.

2.2. Engine Lubricants

Engine lubricants are indispensable in engine applications to reduce friction and wear of moving parts, aid heat dissipation, and minimize corrosion within the engine. The demand on engine designers to create engines with better fuel efficiency and lower emissions has led to the development of new lubricants containing nanoparticles as additives. Hexagonal boron nitride (hBN), in particular, has been identified as a very efficient tribological additive in engine oils [5]. When MoS_2-hBN hybrid nanoparticles were suspended in diesel-based engine oil, the coefficient of friction and wear scar diameter were reduced by 68.48% and 35.54%, respectively [5].

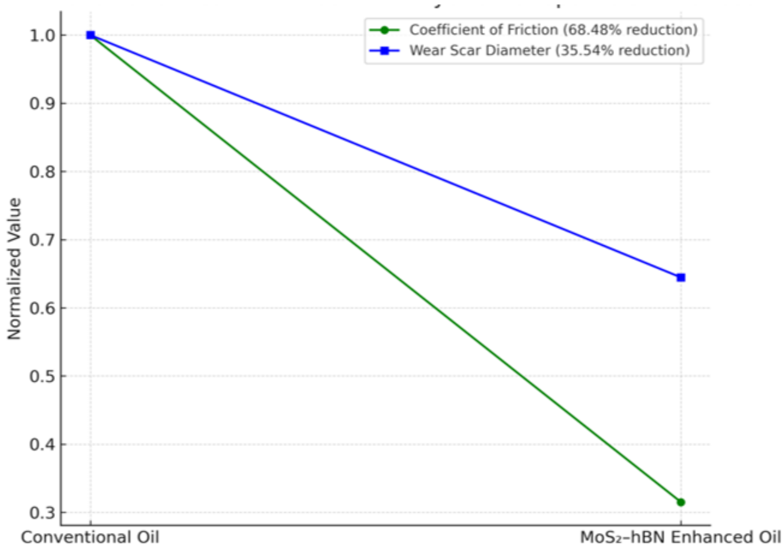

Figure 3: Tribological performance of hBN enhanced materials [5]

Figure 3 demonstrates the changes in friction coefficient and wear rate resulting from hBN across different automotive applications. A significant tribological performance is associated with hBN's layered crystalline structure, which allows the layers to be easily sheared and to form a lubricating protective film on the contact surfaces. The outstanding tribological performance is attributed to the layered crystal structure of hBN, which allows the layers to shear easily, forming a protective lubricating film at the contact surfaces. Among other factors, hBN exhibits strong ionic bonding within its plane and lacks dangling bonds or surface charges, all of which contribute to its high tribological performance and chemical inertness [5]. The use of hBN together with other solid lubricants, such as MoS2, exhibits a synergistic effect that further improves overall performance, for instance, engine performance and the longevity of machinery. Some researchers have also examined the possibility of hBN nanoparticles returning as effective additives in engine oils to keep small diesel engines running longer and performing better [12]. Very low frictional coefficients and increased wear protection were among the successful tribological performance features achieved by using hBN nanoparticles in a military-approved diesel engine oil [13]. Furthermore, the study of the cylinder liner surface of heavy-duty diesel engines running under lab conditions with hBN as a nano-additive in the lubricant showed the potential for extended engine life [14].

3. Other Tribological Applications

Besides brake systems and engine lubricants, the research is exploring the tribological properties of hBN in automotive systems, specifically coatings on engine parts or bearing surfaces. When applied to coatings, hBN's properties can significantly increase wear resistance and reduce friction. It is worth noting that HVOF-sprayed Cr3C2 and NiCr coatings containing hBN have shown improved tribological performance. Approximately 10 wt% hBN addition reduced the friction coefficients to the lowest Levels. On the other hand, if too much hBN is added to the coatings, it can cause hardness to drop and crack formation to increase, as the hBN in the coating lacks sufficient cohesion. So, the use of suitable deposition systems is very important [16]. Research on the compatibility of hBN with self-lubricating coatings has yielded promising results. This is especially true for applications involving hBN and tool steel for high-temperature aluminum forming in the automotive manufacturing sector [17]. At the same time, the mention of hBN in polymer composites, particularly in the context of tires, in a patent suggests significant potential to improve the durability and wear resistance of tire components [7]. Furthermore, it is anticipated that adding hBN particles to cast polyurethane will improve the mechanical and tribological properties of tires, thereby enhancing tire durability and performance (Figure 4).

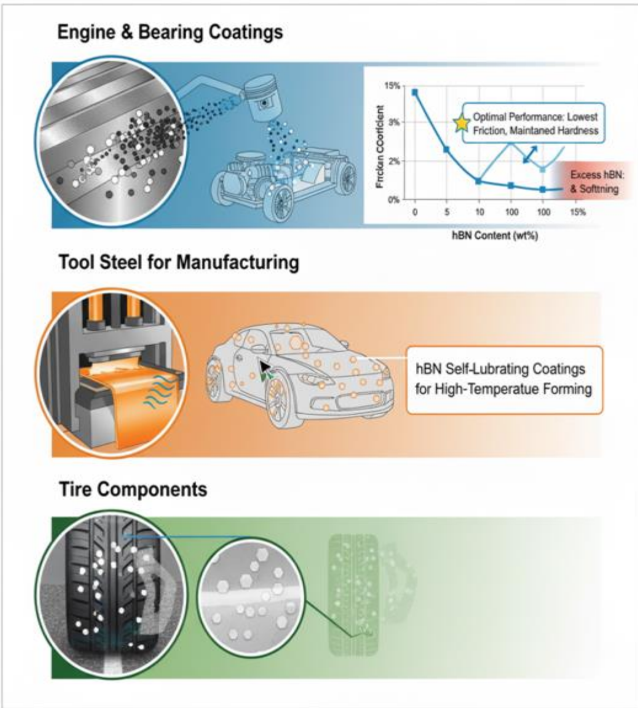

Figure 4: Tribological applications of hBN reinforcement

4. Thermal Management Solutions

The automotive industry is becoming more discerning in its use of advanced thermal management devices, as it continues to be flooded with electronic control units, power electronics in electric and hybrid vehicles, and high-performance engines. These components will become less efficient and will degrade faster if they overheat, and in some instances, the failure will be so serious that it will be almost like an explosion. Hexagonal boron nitride (hBN) is sometimes called "the miracle in white" or "white graphene" because of its very large energy bandgap (about 5.5 eV) and exceptional thermal stability, which make it a perfect material for addressing a major heating problem [6]. hBN exhibits a remarkably high thermal conductivity of 300-2000 W/m · K, which is far superior to that of many conventional materials. As a filler, it can be incorporated in composite materials and thus act as a heat sink. In solid nonmetals such as hBN, phonon conduction or transport accounts for most of the thermal energy transfer. The atomic-layered structure of hBN creates a transport pathway that supports phonon propagation along the basal planes [18]; [11]. In the paper highlighting BN's naturally low dielectric constant, the authors deposited titanium oxide (TiO) nanoparticles on the BN surfaces. This change enabled vertically aligned anisotropic BN particles to form under the influence of an external electric field, something that could not be achieved with pure BN, thereby greatly improving thermal management. The composite obtained showed a 1.9-fold increase in through-plane thermal conductivity (from 0.78 to 1.54 WmK) at 20 vol% filler loading, along with improved mechanical properties at a similar thermal conductivity [19].

4.1. Electric Vehicle Applications

The thermal management system is one of the very few systems that have faced unprecedented challenges and opportunities as the world shifted to electric vehicles (EVs). hBN is an essential material for solving these problems, with battery thermal management systems (BMSs) at the top of the list [20]. Boron nitride possesses properties that make it the best material for battery modules and packs. At the same time, it is a premium filler at every level of the battery assembly, thereby limiting thermal runaway and enhancing thermal diffusion to address operational safety and performance [20]. In the field of automotive electronics, hBN has demonstrated the ability to serve as both a thermal conductor and an electrical insulator, enabling the next generation of high-performance automotive thermal management systems. These functionalities enable modifications to ADAS (Advanced Driver Assistance Systems) designs, featuring more precise electronic cooling (LiDAR, radar) sensors and central ECUs (Electronic Control Units) to maintain performance under various operational constraints [21].

4.2. Polymer Composites for Thermal Management

hBN-filled polymer composites offer excellent potential for vehicle cooling systems. Epoxy composites reinforced with high-performance particles containing industrial-grade hBN have been synthesized and tested, showing a remarkable increase in thermal conductivity. It was found that composite materials containing 29 wt% exfoliated hBN exhibited the best performance, and the improvement in thermal properties was attributed to the increased hBN content [22]. Among different strategies for enhancing thermal conductivity in polymer composites, some advanced approaches have been developed specifically for thermal management materials. The results show that samples filled with 10 wt% modified hBN epoxy have higher thermal conductivity than those filled with raw hBN, indicating that surface modification techniques play a vital role [23]. Figure 5 depicts the anisotropic thermal transport mechanism in hBN-polymer composites, where aligned nanoplatelets serve as the primary pathways for heat dissipation. Thus, it is a good illustration of the composite design principle, which can be used for thermal management applications in advanced electronics and automotive engineering.

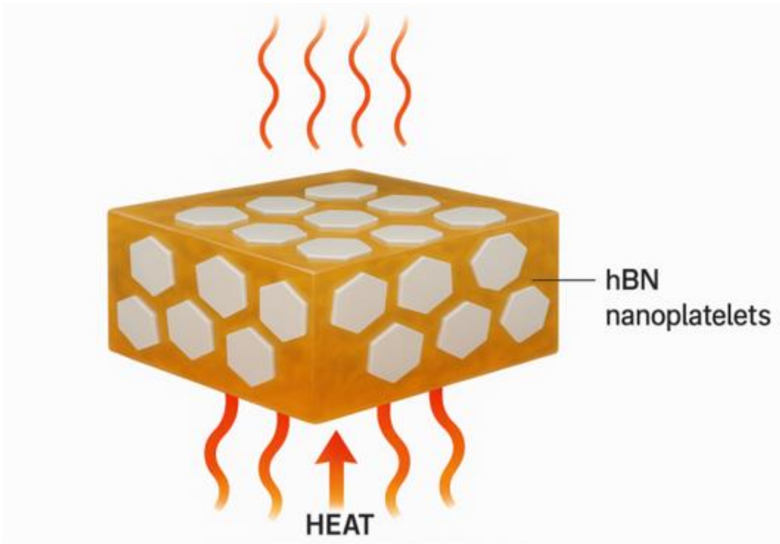

Figure 5: Thermal conductivity enhancement with hBN addition

5. Fabrication and Evaluation of hBN for Automotive Applications

The application of hBN in the automotive sector depends heavily on the synthesis and characterization techniques employed. A comprehensive review of scalable production methods for hexagonal boron nitride has presented several options for both current and future utilization [28]. The fabrication of hexagonal boron nitride heterostructures for 2D van der Waals electronic devices has enabled breakthrough innovations in automotive sensor applications [29].

5.1. Surface Modification Techniques

Surface modification of hexagonal boron nitride nanomaterials has been thoroughly reviewed, including a wide range of methods reported to achieve stronger interfacial bonding and better dispersion in various composite matrices [30]. These modification techniques are essential to maximize hBN's performance in automotive applications, as strong interfacial bonding and fine dispersion contribute to its uniform distribution within the host material.

5.2. Quality Control and Characterization

Improving fast, accurate automatic optical detection methods for exfoliated graphene and hexagonal boron nitride using deep neural networks is a step forward in the quality control of hBN production (31). Such progress is crucial in the automotive sector, where uniformity of material properties is necessary for safety, reliability, and performance.

5.3. Environmental Impact and Sustainability

When researchers look at the environmental and sustainability aspects of hBN in the automotive industry, the first step is to consider how the industry is becoming more sustainable. Secondly, researchers should compare the environmental benefits of hBN with those of standard materials. Compared with conventional materials, hBN offers certain environmental benefits, such as chemical inertness, non-toxicity, and the potential for recycling [33]. To mitigate environmental issues associated with copper leaching in marine environments, hBN in brake pads can be used as a substitute for copper [10]. Moreover, adding hBN to lubricants improves engine efficiency and reduces wear, resulting in lower fuel consumption and lower emissions [5].To gain deeper insight into the environmental impacts of hBN-based automotive components, thorough life-cycle assessments are required to account for the entire life cycle, from raw material extraction and manufacturing through use and end-of-life disposal or recycling.

5.4. Key Challenges and Future Outlook

Polymer composites with hBN have recently attracted significant attention for enhancing thermal conductivity while preserving electrical insulation [7]. The automotive sector is undoubtedly one of the driving forces for hBN applications, as hBN materials can serve different roles, for instance, as lubricants in the engine or as thermal management materials in the electrical engine [9]. Nevertheless, the application of hBN in the automotive sector is still a long way off, and several issues need to be resolved before it can be commercialized. Mainly, the problems of uniformly dispersing hBN particles in different matrices, the bonding strength at interfaces, and the costs [8].

5.5. Dispersion Challenges

Distributing hBN evenly within polymer, metal, or ceramic matrices is a major obstacle for using hBN in automotive applications. Since hBN layers are held together by van der Waals forces, this can lead to clumping, reducing the efficiency of hBN reinforcement. To prevent hBN from clumping, numerous surface modification methods, along with processing techniques, have been investigated, including treatment with coupling agents and high-energy mixing [30].

5.6. Cost Considerations

The cost of very pure hBN is still a barrier to its wider use in automotive applications. Partly, this is due to the price, but other factors related to the quality of the hBN and the specific goals of the application also play a role. Nevertheless, progress in synthesis methods and the effects of scale are anticipated to result in a significant reduction in the price of hBN over the next few years. Some scalable synthesis methods for hexagonal boron nitride have shown potential to lower production costs without sacrificing material quality [28].

5.7. Future Research Directions

Future studies on hBN for automotive use could focus on the directions below:

- Development of even more efficient surface treatment methods for hBN to improve its dispersion and compatibility with the matrix.
- Exploring the potentials of hybrid reinforcement systems by combining hBN with other nanomaterials for synergistic effects.
- Tailoring hBN materials of different grades for specific applications in the automotive industry by selectively optimizing hBN for particular automotive parts.
- Incorporating hBN into smart materials and sensors for automotive applications is certainly another area worthy of investigation in the future. The wide bandgap and chemical stability of hBN offer a promising new option for the development of next-generation automotive electronics [32].

6. Conclusion

This review paper examines the various applications of hexagonal boron nitride (hBN) as a high-quality reinforcement in the automotive industry:

- Among the unique properties of hBN are outstanding thermal conductivity, high dielectric strength, great chemical inertness, and decent tribological performance. These features make the material an attractive candidate for automotive applications.
- The use of hBN tribologically in brake systems and engine lubricants has led to notable performance improvements, with friction coefficient reductions of up to 68.48% and a 38.49% decrease in wear rate compared to conventional materials. In addition, hBN's heat management properties have been very good, leading to enhanced thermal conductivity in polymer composites. This puts hBN in a strong position to be part of the solution for managing heat, a major challenge due to the increasing number of electronics in current vehicles, as well as the switch to electric and hybrid cars.

- One of the great benefits of aluminum and magnesium alloy systems reinforced with hBN has been the improved mechanical characteristics of these lightweight automotive composites. Besides that, at temperatures up to 1000 °C in air, the material can retain its properties, which is a plus for automotive applications.
- Issues related to dispersion, interface bonding, and cost remain hurdles; nevertheless, the research community and innovators remain instrumental in the quest for answers. The development of scalable synthesis methods, surface modifications, and hybrid reinforcement systems indicates that solutions to the problems currently being faced are almost at hand.
- They really are a great help to the automotive industry's sustainability goals, as these hBN environmental benefits include replacing certain environmentally harmful materials (e.g., copper in brake pads) and improving fuel economy through better lubrication.

One area that needs Future research would be application-specific hBN grades, better processing routes for improved dispersion and interfacial bonding, and hybrid systems with other nanomaterials. The application of smart materials and automotive sensors is a promising new area with a strong potential to increase vehicle performance and safety. In summary, hBN is a revolutionary material in the automotive sector that addresses key tribological, thermal, and mechanical challenges. Further research and breakthroughs in production will gradually position it as a key component of green, long-lasting, high-performing automotive technologies.

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