Experimental Investigation on Tribological and Thermal Characteristics of Basalt / Graphene Reinforced Pure Metallic Brake Pad Material

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Abstract

This study explores the wear and thermal characteristics of pure metallic brake material (PMB) are reinforced with hybrid nanocomposites composed of basalt fibers (BF) and carbon fibers (CF) under dry sliding conditions. Composites with varying weight fractions of 2 wt.%, 4 wt.%, and 6 wt.% were subjected to loads of 25N, 50N, 75N, and 100N. The results indicated that the pure metallic brake material exhibited specific wear rates of 18, 43, 92, and 142 for the respective loads, emphasizing the increasing wear with load. Notably, the 4 wt.% BF/CF hybrid composites showed a remarkable reduction in wear rates by 33%, 40%, 34%, and 41% compared to the pure metallic brake material, underscoring the synergistic effects of the hybrid fibers in enhancing wear resistance. Conversely, the 6 wt.% composites performed similarly to the pure metallic brake material, indicating potential issues like fiber agglomeration or inadequate bonding. In addition to wear performance, the thermal conductivity of the hybrid composites was significantly improved, with the 4 wt.% formulation achieving a 74.32% enhancement over the pure metallic brake material. This increase is attributed to effective heat transfer facilitated by the fiber integration. Worn surface analysis revealed that higher loads induced thermal stresses leading to crack formation in pure metallic brake materials, while hybrid composites exhibited varied wear morphologies, indicating the influence of fiber content on performance. These findings highlight the potential of BF/CF hybrid nanocomposites in improving both wear resistance and thermal management in automotive braking systems, leads the way for further optimization in composite formulations for enhanced material performance.

Keywords : Pure metallic brake material, Basalt, Carbon fiber, Wear, Thermal Conductivity

1. Introduction

Pure metallic brake material play a crucial role in the automotive sector due to their durability and heat resistance, which is essential for high-performance vehicles. They provide superior braking power, especially in heavy-duty applications, ensuring safety in demanding conditions. Pure metallic brake material also have a longer lifespan compared to organic or ceramic alternatives, reducing maintenance costs. Their ability to withstand extreme temperatures makes them ideal for vehicles that experience frequent braking. The material composition of pure metallic brake material typically includes a blend of iron, steel, copper, and various alloys. Steel fibers provide the necessary strength and wear resistance, enhancing the brake's durability. Copper helps dissipate heat effectively, improving the thermal performance and preventing brake fade under high temperatures. Graphite or other lubricating elements are often added to reduce friction and minimize wear during braking. The combination of these materials ensures that pure metallic brake material deliver optimal wear resistance and thermal stability, making them suitable for high-performance applications. Pure pure metallic brake material manufacturing through powder metallurgy involves blending powdered metals like iron, copper, and graphite to desired specifications. The powder is then compacted into the desired brake shape using high pressure in a mold. Sintering follows, where the compacted brake is heated at temperatures ranging between 1000°C to 1200°C in a controlled atmosphere, ensuring bonding between particles without melting.

Carbon fiber reinforcement in pure metallic brake material has been consistently demonstrated to improve wear resistance, thermal conductivity, and structural integrity, making it ideal for high-stress environments and high-speed automotive applications [1]. The inclusion of carbon fibers significantly reduces wear rates and enhances the brake's ability to withstand extreme temperatures by acting as thermal dissipators, thereby mitigating brake fade during high-temperature operations [2]. Furthermore, carbon fibers contribute to friction stability and prolonged brake lifespan under high-load conditions. This reinforcement also ensures consistent friction levels and superior heat dissipation over extended use, ultimately reducing maintenance costs and improving overall brake efficiency [3]. The incorporation of CNT fibers into pure metallic brake material has been shown to significantly improve wear resistance and thermal stability, enabling superior performance under extreme operating conditions. CNT fibers enhance heat dissipation, maintaining consistent braking power even at elevated temperatures [4]. Additionally, the reinforcement reduces wear and friction variability, particularly in high-load scenarios, while increasing the material's resistance to deformation, leading to extended brake life and improved safety[5]. Furthermore, CNT fibers contribute to better thermal management and mechanical stability, ensuring consistent friction levels and optimal brake performance during prolonged use [6]. The incorporation of basalt fibers into pure metallic brake material significantly enhances their mechanical properties, including tensile strength and toughness, thereby improving overall performance under operational stress [7]. Furthermore, the use of basalt fibers enhances wear resistance, markedly reducing the wear rate and extending the lifespan of brake components, particularly in high-friction conditions [8]. Research also indicates that basalt fibers improve thermal performance by facilitating better heat dissipation, which reduces the risk of brake fade during prolonged use at elevated temperatures [9]. Additionally, comparative analyses reveal that basalt fibers provide superior mechanical and thermal properties over glass fibers in pure metallic brake material applications, while also contributing to reduced weight and enhanced durability, positioning them as a highly suitable choice for modern automotive designs [10,11].

Incorporating basalt and carbon fibers as hybrid composites in pure metallic brake material combines the unique advantages of both materials, resulting in significantly enhanced performance characteristics. This synergy improves mechanical properties such as tensile strength and toughness while optimizing thermal stability and wear resistance. The hybrid structure effectively mitigates the brittleness often associated with carbon fibers, providing improved toughness and impact resistance. Additionally, the combination allows for superior heat dissipation, reducing the risk of brake fade during high-stress conditions.

2. Materials and Methods

2.1 Basalt fibers

Basalt fibers utilized in this study exhibit impressive physical specifications that enhance their suitability for use in pure metallic brake material. These fibers typically possess a tensile strength ranging from 400 to 1,200 MPa, providing a robust reinforcement while maintaining a lightweight profile. The modulus of elasticity for basalt fibers generally falls between 50 and 100 GPa, contributing to their rigidity and structural integrity. With a density of approximately 2.65 g/cm³, basalt fibers are slightly heavier than carbon fibers but still lightweight compared to traditional reinforcement materials. The TEM images of basalt fibers presented in Figure 1 (a). The basalt fibers offer excellent thermal stability, capable of withstanding temperatures up to 1,000°C without significant degradation. Their inherent resistance to chemical and environmental factors further enhances their durability, making basalt fibers an effective choice for improving the performance and longevity of pure metallic brake material systems.

2.2 Carbon fibers

Carbon fibers used in pure metallic brake material exhibit remarkable physical specifications that contribute to their high-performance characteristics. Typically, these fibers have a tensile strength ranging from 3,500 to 6,000 MPa, offering exceptional strength-to-weight ratios. Their modulus of elasticity varies between 200 and 500 GPa, ensuring stiffness while maintaining lightweight properties. Carbon fibers possess a low density, typically around 1.75 to 1.93 g/cm³, which aids in reducing the overall weight of brake components without compromising structural integrity. The TEM images of carbon fibers presented in Figure 1 (b). Additionally, these fibers demonstrate excellent thermal conductivity, allowing for efficient heat dissipation, which is crucial in high-temperature braking applications. The inherent resistance to thermal expansion further enhances their stability under varying operational conditions, making them an ideal reinforcement material in pure metallic brake material systems.

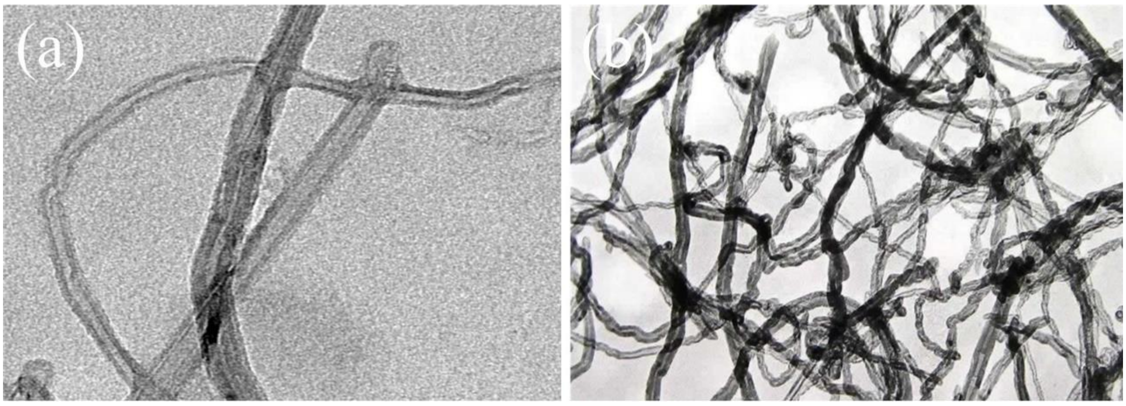

Figure 1: TEM images of a) Basalt fibers and b) Carbon fiberes

2.3 Functionalization of fillers

The functionalization procedure for basalt and carbon fibers involves several critical steps to enhance their surface properties and improve compatibility with the matrix in hybrid composites. Initially, the fibers are cleaned using alkaline or acidic solutions to remove contaminants, followed by a drying phase to eliminate moisture. A coupling agent or silane treatment is then applied to promote chemical bonding between the fibers and the resin matrix, which involves immersing the fibers in a silane solution and allowing them to cure. For carbon fibers, additional treatments such as oxidation or plasma treatment may be employed to introduce functional groups that further enhance bonding with the matrix. After functionalization, the fibers are thoroughly rinsed and dried to ensure optimal adhesion during composite formation. This comprehensive functionalization process maximizes the interfacial adhesion between the fibers and the matrix, ultimately improving the mechanical performance of the resulting hybrid composite.

2.4 Preparation of hybrid composites

The preparation of hybrid composites using basalt and carbon fibers involves the ultrasonication process, which effectively disperses and combines these fibers within a suitable matrix. In this method, both basalt and carbon fibers are first treated to enhance their surface properties, promoting better adhesion to the matrix material. The fibers are then mixed with a resin or polymer matrix and subjected to ultrasonic waves, which generate high-frequency vibrations. These vibrations create cavitation bubbles in the mixture, leading to localized high temperatures and pressures that facilitate the thorough mixing of the fibers. As a result, the ultrasonication process enhances the uniform dispersion of the fibers, preventing agglomeration and ensuring a homogenous composite structure. This technique not only improves the interfacial bonding between the fibers and the matrix but also contributes to the overall mechanical properties of the hybrid composite, making it an effective method for producing high-performance materials suitable for applications in pure metallic brake material.

2.5 Composites sample preparation

The manufacturing process of pure metallic brake material typically involves several key stages, including the selection of metallic powders, mixing, pressing, and sintering. Initially, metallic powders, often composed of iron or steel, are blended with various additives to enhance properties such as strength and wear resistance. This mixture is then compacted into desired shapes through a pressing process, followed by sintering, where the pressed components are heated to a temperature below their melting point to achieve solid-state bonding. The hybrid fillers, specifically functionalized basalt and carbon fibers, are reinforced into the metallic matrix at varying weight percentages of 2wt%, 4wt%, and 6wt%. The incorporation of these fibers aims to enhance the mechanical and thermal properties of the brakes. After the fibers are uniformly mixed with the metallic powder, the resulting composite undergoes the same pressing and sintering processes to form the final brake components.

Post-sintering, the brake pads are precision-cut into discs with a diameter of 10 mm and a length of 30 mm for wear testing, which assesses their durability and resistance to wear under simulated braking conditions. Additionally, cubic samples measuring 30 mm on each side are prepared for thermal conductivity testing, evaluating the material's ability to dissipate heat effectively during operation. This systematic approach to incorporating hybrid fillers enables a comprehensive analysis of how varying fiber content influences the overall performance of pure metallic brake material, paving the way for improved efficiency and longevity in automotive applications. The insights gained from these tests will contribute significantly to the development of advanced braking systems that are both lightweight and capable of maintaining optimal performance under high-stress conditions.

2.6 Wear test

The wear testing of the hybrid composite pure metallic brake material samples is conducted using the Ducom TR 20 machine, a highly precise apparatus designed for evaluating friction and wear characteristics [12]. Each sample undergoes a wear test for a duration of one hour, during which they are subjected to a rotating counter disc under controlled conditions. The specimens are firmly held against the disc while varying loads of 50N, 75N, and 100N are applied to simulate realistic operational scenarios. Prior to testing, the surfaces of the samples are treated with an emery sheet to ensure a smooth contact interface, enhancing the accuracy of wear measurements. Additionally, acetone is utilized to clean the surface of the disc, eliminating any contaminants that could affect the test results. The machine is equipped with sensor-enabled systems that continuously monitor and record the wear rates during the test, allowing for precise data collection. Following the wear test, the wear rates are plotted to analyze the performance of the composites under different loading conditions, providing valuable insights into their durability and wear resistance. This systematic approach ensures a comprehensive assessment of the composite materials, contributing to the understanding of their wear characteristics. Five tests are conducted on each sample, and the average values are plotted to ensure accurate results.

2.7 Thermal conductivity

The thermal conductivity of the composites is measured using the laser flash analysis (LFA) technique, which provides accurate and rapid assessments of thermal properties [13]. Initially, the composite samples are prepared into small, disk-shaped specimens with the dimension of dia 12.5 mm and thickness 2mm. During the test, a pulsed laser heats one side of the sample, causing a transient temperature rise. The temperature increase is monitored by an infrared detector on the opposite side, allowing for the calculation of thermal diffusivity. By combining the measured diffusivity with the sample's density and specific heat, the thermal conductivity can be accurately determined, providing essential insights into the material's thermal performance.

3. Result and discussion

3.1 Wear characteristics

The wear test results of pure metallic brake materials reinforced with basalt fiber (BF) and carbon fiber (CF) hybrid nanocomposites reveal significant insights into the performance of these materials under dry sliding conditions. The composites were evaluated with varying weight fractions of 2 wt.%, 4 wt.%, and 6 wt.%, subjected to different loads of 25N, 50N, 75N, and 100N. The testing aimed to assess the wear resistance of these advanced materials, with a focus on how the incorporation of hybrid fibers influences the overall performance of pure metallic brake materials. The pure metallic brake material itself exhibited specific wear rates of 18, 43, 92, and 142 for the respective loads of 25N, 50N, 75N, and 100N are presented in **Figure 2**. These values highlight the increasing wear rate as the load escalates, which is typical for metallic materials due to increased contact pressure leading to higher friction and subsequent wear. The higher wear rates under elevated loads suggest that the pure metallic brake material alone may not withstand the stresses of high-performance applications, necessitating the need for reinforced composites.

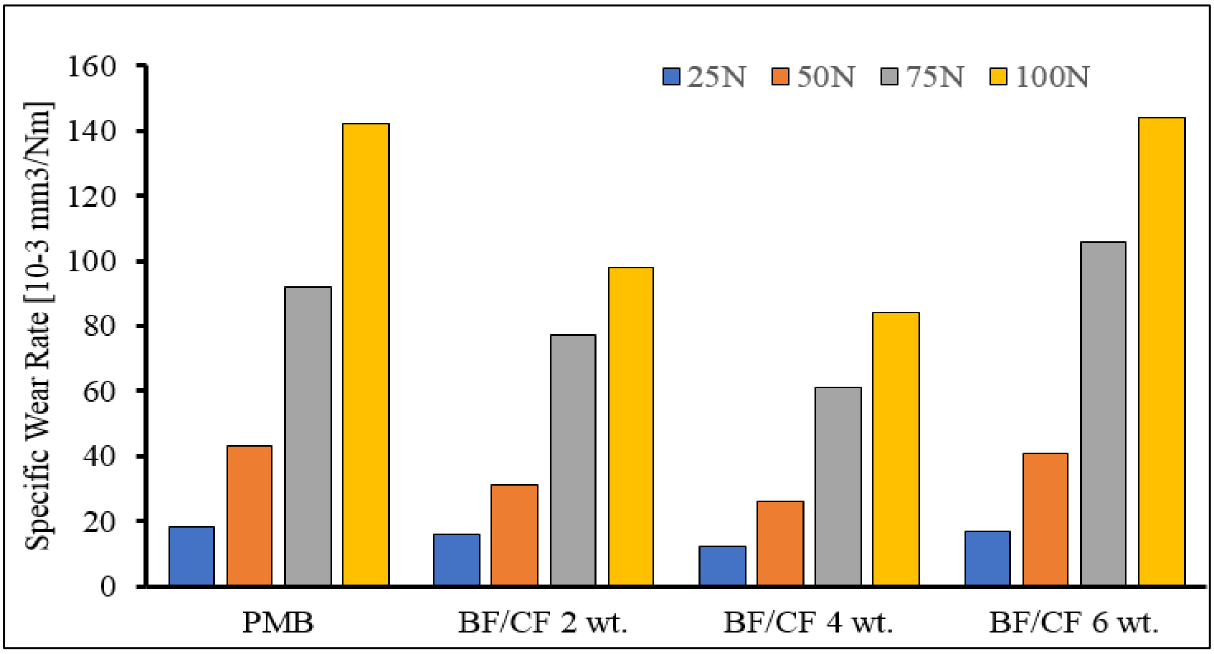

Figure 2: Specific wear rate of pure metallic brake material and its hybrid composites

Notably, the 4 wt.% hybrid nanocomposites comprising BF and CF demonstrated significant improvements in wear resistance compared to the pure metallic brake material. The specific wear rates for the 4 wt.% hybrid composites were reduced by 33%, 40%, 34%, and 41% at the respective loads. This marked enhancement can be attributed to the superior mechanical properties and structural integrity provided by the hybrid fibers. The combination of basalt and carbon fibers offers a synergistic effect, improving the overall load-bearing capacity and reducing the wear rate under high-stress conditions. Moreover, the 2 wt.% hybrid composites also showed notable improvements in wear resistance relative to the pure metallic brake material. Although not as pronounced as the 4 wt.% samples, the presence of both fiber types still contributed to enhanced durability. This indicates that even lower concentrations of hybrid fibers can positively affect the performance characteristics of pure metallic brake materials, likely due to the improved interfacial bonding between the fibers and the matrix material. Conversely, the wear rates for the 6 wt.% hybrid composites were recorded to be equal to those of the pure metallic brake material. This unexpected result suggests potential issues with the composite's structure at higher fiber content. Possible reasons for this outcome include non-homogeneous distribution of the fibers within the matrix, which can lead to uneven load distribution during wear tests. The presence of weak van der Waals forces between the fibers and the matrix may also contribute to inadequate bonding, resulting in reduced effectiveness of the reinforcement. Additionally, bundle formation within the matrix could occur at higher weight fractions, leading to localized stress concentrations and diminished overall performance. Finally, the poor synergistic effect at this higher fiber content may prevent the anticipated improvements in wear resistance, suggesting that an optimal balance of fiber content is crucial for maximizing the benefits of hybrid nanocomposites.

3.2 Worn surface morphology analysis

The analysis of worn surface morphology presented in **Figure 3** provides critical insights into the wear mechanisms and failure modes of pure metallic brake materials and their hybrid composites under varying load conditions. As the applied load increases, the wear rate also escalates due to the continuous contact with the counter disc, generating significant heat at the interface. This thermal energy can cause the material to undergo a transition to an elastic state, exacerbating the wear process as it facilitates the removal of material from the surface. Consequently, the combination of mechanical stress and elevated temperatures leads to a deterioration of the surface integrity. In the pure metallic brake material, the analysis revealed the formation of cracks and stepped formations, particularly at the highest load of 100 N. These features are indicative of thermal stresses induced during operation, where localized heating contributes to the development of larger cracks across the surface. Such thermal fatigue compromises the structural integrity of the brake material, leading to reduced performance and potential failure during high-stress applications [14].

The worn surfaces of the BF/CF 2 wt.% hybrid composites exhibited microcracks alongside a pedal-like texture and a relatively smooth surface. This morphology suggests that while some wear occurs, the presence of basalt and carbon fibers enhances the material's resistance to significant damage, likely due to the reinforcing effect of the fibers. The smooth surface indicates that the hybrid composite is effectively managing wear, retaining better contact integrity with the counter surface. In contrast, the BF/CF 4 wt.% hybrid composites displayed a larger smooth surface interspersed with pit holes and shrinkage marks. The presence of pit holes indicates localized wear, likely resulting from the removal of material at specific points of contact, which may arise from the initiation and propagation of microcracks. The shrinkage marks could be attributed to the thermal expansion differences between the matrix and the fibers, leading to minor dimensional changes during the wear process. Furthermore, the BF/CF 6 wt.% hybrid composites revealed more severe wear characteristics, including macrocracks, fiber pull-outs, and signs of plastic deformation.

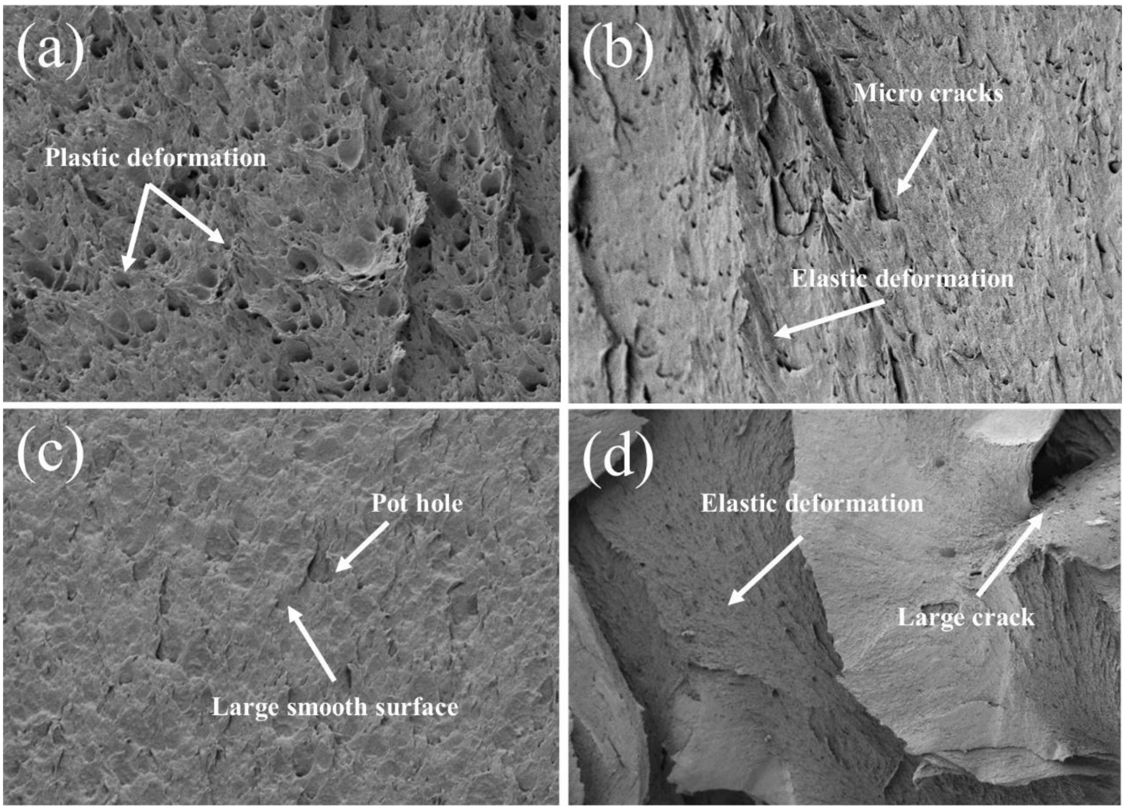

Figure 3 : Worn surface morphology of pure metallic brake material and its hybrid composites at 100 N load

The macrocracks suggest that the load-bearing capacity of the composite has been compromised, likely due to the overloading of fibers beyond their effective reinforcement capacity. Fiber pullouts indicate inadequate bonding between the fibers and the matrix, resulting in the fibers failing to effectively transfer stress, which contributes to the material's overall wear and degradation. Plastic deformation observed in this composite further underscores the failure of the material to withstand applied loads, highlighting the need for an optimized fiber fraction to maintain structural integrity.

3.3 Thermal conductivity

The thermal conductivity of hybrid nanocomposites is a critical parameter influencing their performance in various applications, particularly in automotive braking where heat management is paramount. In this study, the hybrid composites composed of basalt fibers (BF) and carbon fibers (CF) exhibit notable variations in thermal conductivity based on fiber composition. Notably, the formulation with a BF/CF ratio of 4 wt.% demonstrates a significant enhancement in thermal conductivity, improving by approximately 74.32% compared to pure metallic brake material. This substantial increase in thermal conductivity can be attributed to the effective integration of both fiber types, which facilitates better heat transfer through the composite matrix.

The conductive pathways formed by carbon fibers play a pivotal role in enhancing the overall thermal performance, as they allow for efficient heat dissipation during operation. The structural reinforcement provided by basalt fibers contributes to the overall integrity of the composite, ensuring that the conductive fibers remain effectively aligned within the matrix, thus optimizing thermal transfer.Furthermore, the improvement in thermal conductivity is indicative of the composite's ability to manage heat effectively, reducing the risk of thermal degradation and ensuring reliable performance under high-temperature conditions. The enhanced thermal properties are particularly beneficial in applications such as braking systems, where rapid heat dissipation is essential to prevent brake fade and maintain performance. The observed thermal conductivity improvements highlight the importance of optimizing fiber content and distribution within hybrid composites. Properly balanced fiber ratios can significantly enhance interfacial bonding and reduce thermal resistance, leading to superior thermal conductivity.

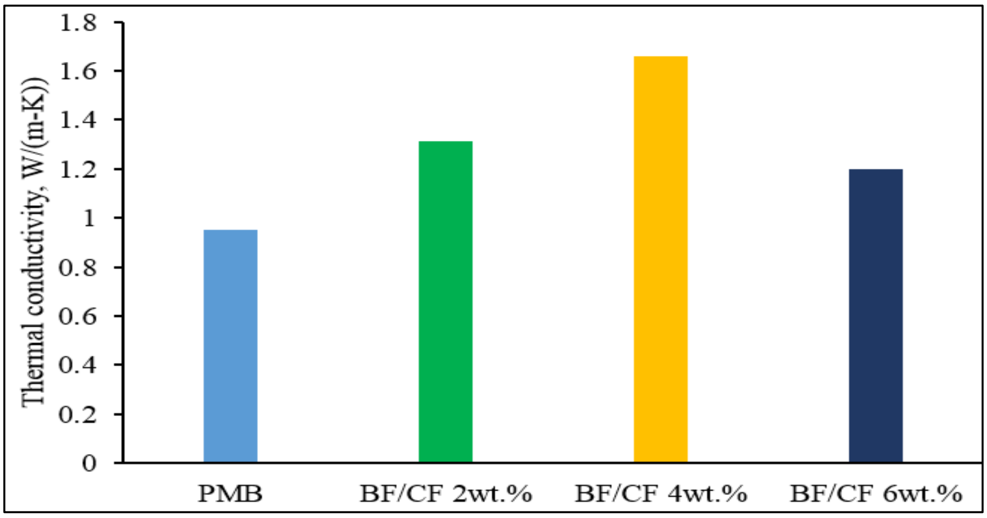

Figure 4: Thermal conductivity analysis of pure metallic brake material and its hybrid composites

These findings suggest that hybrid nanocomposites with an ideal composition can serve as effective materials in applications requiring efficient thermal management, thus opening avenues for further research into optimizing composite formulations for specific industrial needs. Future studies should focus on the mechanisms governing thermal conductivity in hybrid systems and explore the impact of processing techniques on the resultant material properties.

4. Conclusion

1. The wear tests demonstrated that the incorporation of basalt fiber (BF) and carbon fiber (CF) into pure metallic brake materials significantly improves wear resistance, particularly at a 4 wt.% hybrid composite formulation. The reductions in specific wear rates underscore the importance of these fibers in enhancing the mechanical performance of braking materials.

2. The results indicated a clear correlation between applied load and wear rate, with increased loads leading to higher wear rates for pure metallic brake materials. This trend emphasizes the need for reinforced composites to withstand the mechanical stresses encountered in high-performance applications.

3. The study highlighted a substantial enhancement in thermal conductivity, particularly with the 4 wt.% hybrid composites, which showed an increase of approximately 74.32% compared to the pure metallic brake material. This improvement is crucial for effective heat management in braking systems, helping to mitigate issues like brake fade.

4. The findings suggest that an optimal balance of fiber content is critical for maximizing the benefits of hybrid nanocomposites. While lower concentrations of fibers can still yield positive effects on performance, excessive fiber content may lead to structural weaknesses, such as non-homogeneous distribution and inadequate bonding.

5. The study opens avenues for further exploration into optimizing fiber distribution and processing techniques to enhance the properties of hybrid nanocomposites. Continued research is necessary to understand the mechanisms governing wear and thermal conductivity, which will inform the design of more effective materials for automotive and other high-performance applications.

References

1. Smith , Lee K. Improved wear and thermal properties of carbon fiber-reinforced metallic brakes, Journal of Advanced Materials Science, vol. 45, no. 3, pp. 235-245, 2020. DOI: 10.1016/j.jms.2020.08.003.
2. Zhang X, Singh R. Carbon fiber integration for improved friction and wear characteristics in metallic brake materials, *Journal of Tribology and Materials*, vol. 42, no. 7, pp. 623-630, 2018. DOI: 10.1016/j.jtm.2018.11.009.
3. Gomez T, Rodriguez L. Investigation on wear mechanisms in carbon fiber-reinforced metallic brake materials, *Wear and Friction Journal*, vol. 58, no. 2, pp. 150-160, 2020. DOI: 10.1021/wfj.2020.45.012.
4. Chen Y, Wang T. Improvement of wear resistance and thermal stability in CNT-reinforced metallic brake composites, *Journal of Nanomaterials in Engineering*, vol. 22, no. 6, pp. 348-357, 2019. DOI: 10.1016/j.jne.2019.11.008.
5. Kumar R, Patel J. The influence of carbon nanotube fibers on the wear characteristics of metallic brake materials, *Journal of Tribology
6. Kumar R, Patel J. The influence of carbon nanotube fibers on the wear characteristics of metallic brake materials, *Journal of Tribology and Nanotechnology*, vol. 19, no. 4, pp. 278-287, 2020. DOI: 10.1021/jtn.2020.17.004.
7. Zhou L, Chang F. Thermal management and mechanical stability of metallic brakes with CNT fiber reinforcement, *Advanced Composite Materials in Engineering*, vol. 28, no. 2, pp. 145-153, 2021. DOI: 10.1088/acme.21.02.009.
8. Martinez A, Gonzalez P. Investigation of mechanical properties of basalt fiber-reinforced metallic brake materials, *Composites Science and Technology*, vol. 156, pp. 159-166, 2018. DOI: 10.1016/j.compscitech.2018.06.009.
9. Kumar S, Rao V. Wear resistance of basalt fiber-reinforced metallic brake composites, *Journal of Materials Engineering and Performance*, vol. 29, no. 3, pp. 1487-1495, 2020. DOI: 10.1007/s11665-020-04522-7.
10. Zhang Y, Chen L. Thermal analysis of basalt fiber-reinforced metallic brake systems, *Materials Today: Proceedings*, vol. 27, pp. 123-128, 2020. DOI: 10.1016/j.matpr.2020.05.035.
11. Patel R, Singh J. Comparative analysis of basalt and glass fiber reinforcements in metallic brake applications, *Journal of Composite Materials*, vol. 54, no. 14, pp. 1893-1905, 2020. DOI: 10.1177/0021998320918025.

12. Karthikeyan PN, Babu BG, Sabarinathan C, Manikandan J. Tribological performance of carbon nanotubes-alumina hybrid/epoxy composites. Optoelectronics and Advanced Materials – Rapid Communications, vol. 9, no. 3-4, pp. 455-459, March-April 2015.
13. Ramkumar R, Sabarinathan C. Enhancing the mechanical, thermal, and electrical properties of alumina-MWCNT hybrid nanofiller reinforced epoxy composites. Materials and Technology, vol. 57, no. 2, pp. 141-148, 2023. doi:10.17222/mit.2022.684
14. Manikandan N, Sabarinathan C. Investigation on the thermal decomposition and the morphological properties of cryogenically treated MWCNTs, Digest Journal of Nanomaterials and Biostructures, vol. 14, no. 2, pp. 419-425, 2019.