Journal of Ceramic Processing Research. Vol. 25, No. 5, pp. 786~789 (2024)
(Received 12 June 2024, Received in revised form 7 October 2024, Accepted 10 October 2024)
https://doi.org/10.36410/jcpr.2024.25.5.786

J O U R N A L O F
Ceramic Processing Research

Development of carbon fiber and BN reinforced composites for enhanced mechanical performance in sporting goods

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The mechanical properties of epoxy composites reinforced with varying compositions of carbon fiber, carbon powder, and boron nitride (BN) additives. The relationship between the weight percentage of carbon fiber, the size of carbon powder, and the inclusion of BN was explored through measurements of Young's Modulus, Ultimate Tensile Strength (UTS), and Impact Strength. The results indicate a positive correlation between the carbon fiber content and both stiffness and tensile strength. Specifically, composites with higher carbon fiber content (6 wt%) exhibited significantly improved Young's Modulus and UTS compared to those with lower fiber content (2 wt%). Carbon powder size also influenced mechanical properties, with finer powders improving rigidity, while larger particles contributed to increased tensile strength under certain conditions. The addition of BN was found to significantly enhance impact strength, particularly at higher concentrations (6.5 wt%), attributed to its lubricating properties that improve energy absorption during impact. Sample 6, which incorporated 6 wt% carbon fiber, 150 µm carbon powder, and 3.9 wt% BN, achieved optimal mechanical performance with high UTS (26.08 MPa) and superior impact strength (85.47 J/m²). The complex interactions between these components highlight the importance of composite design in optimizing material performance for specific applications. This study provides valuable insights into the development of advanced composites, particularly for applications requiring a balance of high tensile strength, stiffness, and impact resistance.

Keywords: Surface coating, Carbon fibre, Sporting goods, Tensile properties.

Introduction

The durability and wear resistance of sports equipment are critical not only for enhancing athletic performance but also for reducing the risk of injury and ensuring the longevity of the gear. In high-performance sports such as cycling, tennis, and football, equipment is subjected to intense physical demands, and the durability of materials plays a key role in both performance and safety [1-3]. Carbon fiber-reinforced composites have gained widespread attention for their exceptional strength-to-weight ratio and mechanical properties, making them ideal for a variety of sports applications. Meanwhile, hexagonal boron nitride (h-BN), with its unique properties such as high thermal stability and lubricity, offers a promising enhancement to composite materials.

One of the primary benefits of incorporating carbon fiber reinforcement with hexagonal boron nitride (h-BN) in epoxy polymer matrices is the adaptability of this composite to various types of sports equipment. Whether in tennis rackets, bicycle frames, or golf clubs, the composite can be optimized to meet the unique performance demands of each application. For instance, in high-impact sports such as football or hockey, where gear endures repeated collisions and high friction, carbon fiber combined with h-BN offers enhanced wear resistance and impact absorption. Similarly, in endurance sports like cycling or marathon running, where gear is continuously exposed to environmental factors like UV radiation and moisture, h-BN provides improved resistance to degradation and corrosion [4, 5].

The use of carbon fiber and h-BN also opens up avenues for lightweighting sports equipment. By replacing bulkier, heavier materials without sacrificing durability, these composites enable manufacturers to design lighter, more agile gear, improving athletes' performance, speed, and maneuverability [6]. However, challenges remain in refining the composite's formulation, particularly in ensuring optimal distribution and integration of carbon fiber and h-BN within the matrix. Achieving strong adhesion and uniformity is crucial to maximize the composite's mechanical properties [7-9]. Previous studies have emphasized the importance of enhancing wear resistance in sports gear to maintain its structural integrity over time. Repetitive stress and prolonged usage can cause material degradation, affecting both performance and safety. While the combination of carbon fiber and h-BN has demonstrated significant

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improvements in mechanical strength, there is still a need for further research to identify the most effective ratios of these materials to optimize durability in real-world sports environments. This research aims to evaluate how varying weight percentages (wt%) of h-BN and carbon fiber affect the mechanical properties of epoxy composites to better tailor materials for advanced sports applications.

In this study, the focus is on the integration of carbon fiber and h-BN into an epoxy polymer matrix to develop a composite material with superior mechanical properties, tailored specifically for sports goods applications. The mechanical properties, such as tensile strength, stiffness, and wear resistance, are influenced by the weight percentages (wt%) of both carbon fiber and h-BN. The impact of varying wt% of h-BN and carbon fiber on the overall performance of the composite is thoroughly evaluated. The goal is to determine the optimal combination that offers enhanced durability, wear resistance, and mechanical strength for sports equipment, while maintaining the flexibility and lightweight nature of the composite. By exploring these parameters, this research aims to contribute to the development of advanced materials that can push the boundaries of durability and performance in sports gear, ensuring athletes have reliable and long-lasting equipment.

Experimental

The specimen preparation begins by creating a mold using liquid silicone in a container, designed to fit a test specimen with dimensions of 80 × 12 × 12 mm^3. Based on a modified Box-Behnken design, volume fractions in percentages are calculated for three different combinations (2%, 4%, and 6%) for carbon fiber and hexagonal boron nitride (h-BN), resulting in a total of 15 unique combinations. A precision mechanical stirrer is used to ensure thorough and uniform mixing, preventing void formation and ensuring even dispersion of the fillers.

Initially, the required amount of epoxy resin, pre-calculated based on the sample's weight for tensile and impact testing, is poured into a mixing cup. Following this, the appropriate amount of carbon fiber, as determined by the combination, is added to the resin. The resin-carbon fiber mixture is stirred consistently for 20 minutes to ensure proper integration. Afterward, h-BN is introduced into the mixture and stirred again for an additional 20 minutes to achieve a homogenous blend. The hardener, also pre-measured, is then added, and the mixture is stirred for another 10 minutes (Fig. 1). A slight temperature increase is noticed during stirring due to the exothermic reaction. Once fully mixed, the composite is poured into the prepared mold for curing. Carbon fiber-reinforced epoxy composites are subjected to tensile testing to evaluate their tensile behavior. The samples are prepared following the ASTM D 3039 standard with dimensions of 260 × 30 × 3 mm. The crosshead speed during tensile tests is set at 2 $mm \cdot min^{-1}$. The cured composite materials are cut to the required dimensions for tensile testing, and the tests are conducted using a computerized universal testing machine. Both ends of the samples are gripped, and axial stress is applied progressively. A strain rate of 1 $mm \cdot min^{-1}$ is maintained during testing, and the system automatically records all necessary data.

The impact strength of carbon fiber-reinforced epoxy composites is determined using the Impact Izod test. The sample dimensions are 65 × 2.5 × 13 mm. For this test, a Pendulum Izod Charpy Impact Tester with a touch screen is employed, operating at an impact speed of 3.46 m s^{-1} and a resolution of 1 × 10^{-4} JT.

Results and Discussion

The experimental results obtained from the various sample compositions of carbon fiber, carbon powder size, and boron nitride (BN) additives provide valuable insights into the mechanical properties of these composites. The data highlights the relationships between the weight percentage of carbon fiber, the size of carbon powder, the inclusion of BN, and the resulting mechanical performance, specifically focusing on Young's Modulus, Ultimate Tensile Strength (UTS), and Impact Strength. The results indicate a positive correlation between the weight percentage of carbon fiber and both Young's Modulus and UTS. For instance, Sample 2, with 6 wt% carbon fiber, exhibits a significantly higher Young's Modulus (1264.02 MPa) and UTS (26.36 MPa) compared to Sample 1, which has only 2 wt%. This trend suggests that increasing the carbon fiber content enhances the stiffness and load-bearing capacity of the composite, likely due to the superior tensile strength properties of carbon fibers [10].

The size of carbon powder appears to influence the mechanical properties, though the trends are not consistent

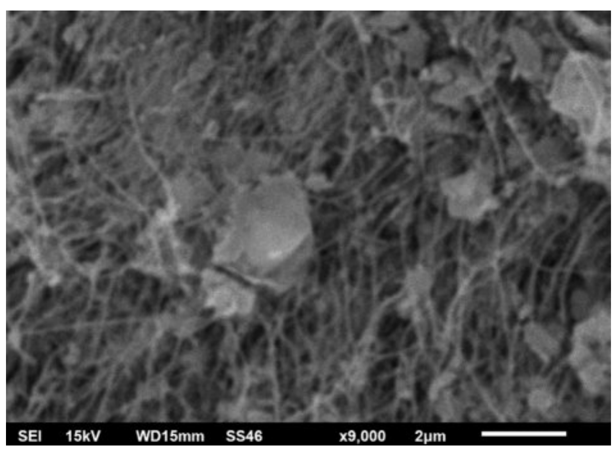

Fig. 1. SEM image of Carbon Fibre and BN composite.

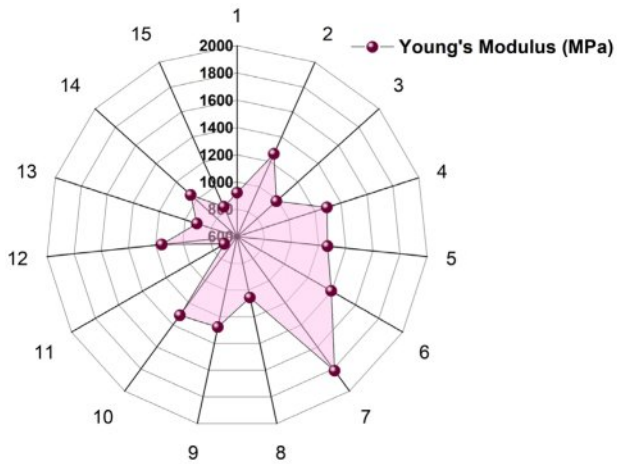

Fig. 2. Young's Modulus of the samples synthesized.

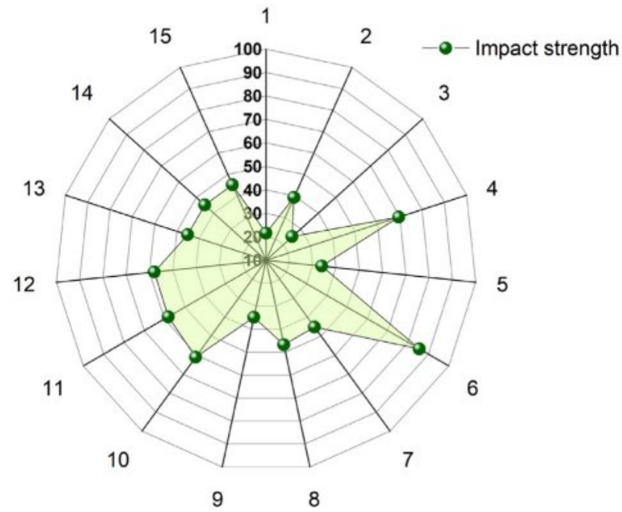

Fig. 3. Impact strength of the samples synthesized.

across all metrics. For example, comparing Samples 2 and 4, which both have 6 wt% carbon fiber but different carbon powder sizes (75 µm vs. 225 µm), it is observed from Fig. 2 that the sample with the smaller powder size (Sample 2) shows better performance in Young's Modulus (1264.02 MPa) but lower UTS (21.58 MPa) compared to Sample 4 (1292.53 MPa). This suggests that finer carbon powder may improve the fiber-matrix interaction, enhancing rigidity, while larger sizes could contribute to increased tensile strength under certain conditions [11].

The varying percentages of BN also show a significant impact on mechanical properties. The experimental data indicates that higher BN content (e.g., 6.5 wt% in Samples 7 and 8) tends to improve the impact strength significantly (Fig. 3). For instance, Sample 7 demonstrates an impact strength of 45.17 J/m². This can be attributed to BN's lubricating properties, which may enhance the toughness of the composite by allowing for better energy absorption during impact.

The interaction between carbon fiber content, carbon powder size, and BN demonstrates complex behavior. For instance, Sample 6 (6 wt% carbon fiber, 150 µm carbon powder, 3.9 wt% BN) achieves a high UTS of 26.08 MPa and an impact strength of 85.47 J/m². This sample illustrates that optimal combinations of these components can lead to enhanced mechanical properties, showcasing the importance of composite design in tailoring materials for specific applications. Interestingly, while some samples with lower UTS also show high impact strength (e.g., Sample 6), others with higher UTS do not necessarily follow this trend (e.g., Sample 2). This variability suggests that while UTS is important, it does not solely dictate the impact resistance of a material (Fig. 4). The microstructural characteristics and the distribution of reinforcing materials play a crucial role in determining how the composite will behave under dynamic loading conditions.

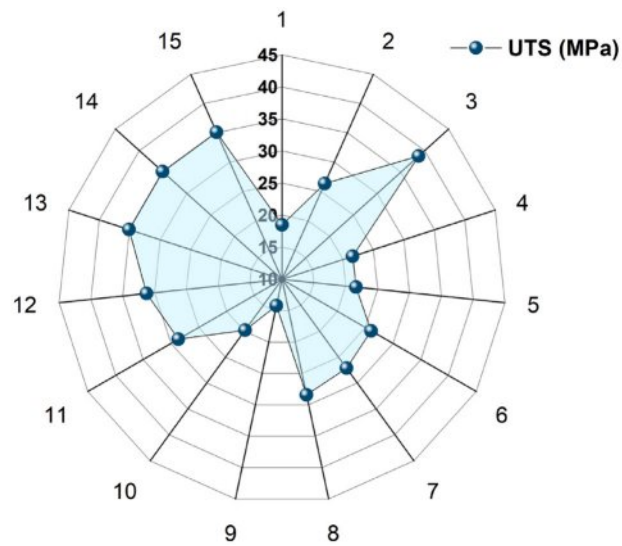

Fig. 4. UTS of the samples synthesized.

Inference

The integration of carbon fiber and hexagonal boron nitride (h-BN) into an epoxy polymer matrix presents a promising approach to enhance the mechanical properties of composites designed for sports goods applications. The results obtained from the experimental study provide key insights into how varying weight percentages of carbon fiber and h-BN influence properties such as tensile strength, stiffness, wear resistance, and overall durability, which are critical for sports equipment performance. The data indicates that increasing the carbon fiber content significantly improves the tensile strength and stiffness of the composite materials. For instance, samples with 6 wt% carbon fiber consistently demonstrate higher Young's Modulus and Ultimate Tensile Strength (UTS) compared to those with only 2 wt%. This enhancement can be attributed to the inherent mechanical advantages of carbon fibers, which possess high tensile strength and stiffness, making them ideal for applications where strength-to-weight ratio is crucial, such as in sports equipment.

The incorporation of h-BN into the composite matrix is particularly beneficial for improving wear resistance and impact strength. Samples containing higher percentages of h-BN (e.g., 6.5 wt%) exhibit notable increases in impact strength, such as Sample 6's impact strength of 85.47 J/m². This is critical for sports goods, where equipment often experiences sudden impacts and dynamic loads. The lubricating properties of h-BN facilitate energy absorption during impacts, thereby enhancing the durability of the composite.

The interplay between carbon fiber and h-BN percentages is crucial for achieving the desired mechanical properties. The results suggest that there is an optimal combination of these materials that maximizes performance. For example, while higher carbon fiber content contributes to tensile strength, the presence of an adequate amount of h-BN ensures that the composite retains sufficient flexibility and toughness. Samples 6 and 8 show that balanced combinations yield composites with both high tensile strength and superior impact resistance, aligning well with the requirements for sports applications.

Maintaining flexibility and lightweight characteristics in composite materials is essential for sports goods. The study shows that despite the increased rigidity from carbon fiber, the strategic inclusion of h-BN helps mitigate brittleness, thereby allowing for a more ductile and flexible final product. This is vital for sports equipment, where user performance and comfort depend on a balance of stiffness and flexibility. The exploration of wear resistance is particularly relevant for sports applications, as equipment is subject to friction and repetitive stress. The mechanical properties observed, especially in terms of impact strength, indicate that these composites are likely to withstand the rigorous demands of sports activities over time. By optimizing the weight percentages of carbon fiber and h-BN, the research highlights the potential for creating long-lasting sports equipment that maintains high performance through prolonged use.

Conclusion

This study significantly contributes to the field of advanced materials by providing empirical data on the effects of composite composition on mechanical performance. The insights gained can serve as a foundation for further research and development, guiding manufacturers in creating high-performance sports gear that meets the increasing demands for durability and reliability. he successful integration of carbon fiber and h-BN into an epoxy matrix represents a substantial advancement in the design of composite materials for sports applications. The research demonstrates that careful optimization of these components can lead to composites that not only meet but exceed the mechanical performance requirements of modern sports equipment. As a result, this study lays the groundwork for future innovations that will enhance the functionality and longevity of sports gear, ultimately benefiting athletes by providing them with reliable and high-performance equipment.

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