

Kevlar-Basalt Hybrid Nanocomposites Reinforced with Multi-Scale Nanoparticles: Mechanical and Thermal Characterization

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Abstract

The development of high-performance composite materials has received a lot of attention due to the increasing need for durable, lightweight, and thermally stable structures in complex engineering applications. In this work, hybrid fiber-reinforced polymer composites are created and characterized by combining Kevlar and Basalt fibers with nanoparticle reinforcement. Through the process of hybridization, the excellent tensile strength and impact resistance of Kevlar are coupled with the compressive properties of Basalt fibers, improving the composite's overall performance. To enhance mechanical and thermal properties, the polymer matrix is supplemented with nanoparticles such as carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), and alumina (Al₂O₃). These nanofillers improve interfacial bonding, stress transfer effectiveness, and resistance to crack propagation. Previous studies have demonstrated that natural fiber reinforced with Nanotube composites significantly improve tensile and flexural strength as graphene-based reinforcements boost stiffness and fracture toughness. The current work investigates the effects of various nanoparticle concentrations on the mechanical properties (tensile, compressive, and interlaminar shear strength) and thermal behavior of hybrid composites using standardized experimental techniques such as ASTM testing, dynamic mechanical analysis (DMA), and thermogravimetric analysis (TGA). The findings demonstrate that adding nanoparticles significantly improves composite performance; nevertheless, an optimal filler concentration is essential since excessive loading leads in agglomeration and reduced efficiency. The findings show how strength, stiffness, and thermal stability are enhanced by the combination of fiber hybridization and nanoparticle reinforcement. These innovative hybrid nanocomposites have a lot of potential for application in the aerospace, automotive, and defense sectors, where high-performance, lightweight materials are crucial.

Keywords: Fiber-Reinforced Polymer (FRP); Al₂O₃ Nanoparticles; Carbon Nanotubes (CNTs); Graphene Nanoplatelets (GNPs); Mechanical Properties; Thermal Properties; Tensile Strength; Compressive Strength; Interlaminar Shear Strength (ILSS); Dynamic Mechanical Analysis (DMA); Thermogravimetric Analysis (TGA); Nanocomposites; Hybridization; Interfacial Bonding; Lightweight Materials; Aerospace Applications

1. Introduction

Complex composite materials are being developed in response to the growing need for strong, lightweight, and thermally stable materials in the automotive, aerospace, and defense industries. Because of its remarkable strength-to-weight ratio, resistance to corrosion, and versatility, fiber-reinforced polymer (FRP) composites are employed extensively. The mechanical and thermal qualities are further improved by hybrid composites, which are created by mixing several fibers[3].

While basalt fibers are more cost-effective and have better thermal stability, Kevlar fibers offer superior tensile strength and impact resistance. Composites made from their hybridization are more robust, rigid, and long-lasting. Additionally, the incorporation of nanoparticles such carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), and alumina (Al₂O₃) improves mechanical and thermal properties by strengthening interfacial bonding and load transfer.[5]

However, an overabundance of nanoparticles can cause agglomeration, which impairs performance. Therefore, it is essential to optimize the concentration of nanoparticles. Despite substantial research on each method independently, few studies have looked at the combined impact of fiber hybridization and nanoparticle reinforcement.[8]

This work investigates the mechanical and thermal behavior of Kevlar–Basalt hybrid composites reinforced with Al₂O₃ nanoparticles in order to identify the optimal nanoparticle content and improve composite performance for advanced engineering applications.[12]

2. Experimental Procedure

2.1 Materials

The composite laminates were made with reinforcing fibers and nanoparticle fillers. Basalt and Kevlar fibers (Kevlar 49) were used as the primary reinforcement due to their exceptional strength and thermal stability. Natural fibers such as sisal and jute were also considered for comparative nanocomposite studies. The matrix material was epoxy resin (LY556) with a suitable hardener (HY951).[25]

Al₂O₃ (alumina), carbon nanotubes (CNTs), and graphene nanoplatelets (GNPs) were used as fillers to enhance interfacial bonding and mechanical performance. The nanoparticle content was altered within a predefined range (often 0.1 weight percent to 1.5 weight percent) to examine its effect on composite properties.[35]

2.2 Preparation of Composite Laminates

The composite laminates were made using the compression molding technique. First, fibers were chopped to the required diameters and placed in a specific arrangement (e.g., alternating layers of basalt and Kevlar, like KBKB).

The nanoparticles were evenly dispersed throughout the matrix using mechanical stirring and ultrasonication after the epoxy resin and hardener were mixed in the correct ratio. Appropriate dispersion is essential for effective reinforcing and to avoid agglomeration.

The resin loaded with nanoparticles was equally injected after the fiber layers were placed within the mold. The laminate was crushed for three to four hours at controlled pressure and temperature (often 80 to 100°C) to ensure proper cure. After curing, the laminates were chilled and removed from the mold.[16]

2.3 Specimen Preparation

According to ASTM rules, the cured composite laminates were cut into standard specimen sizes for a variety of mechanical testing. To ensure accuracy and repeatability of the results, multiple samples were prepared for each configuration.[23]

2.4 Mechanical Testing

- The mechanical characteristics of the composites were evaluated using standard testing methods:
- Tensile Test (ASTM D3039): Tensile strength, elongation, and Young's modulus are obtained by applying a uniaxial load until failure.[16]
- The Compression Test (ASTM D3410) is used to evaluate compressive strength and resistance to deformation under axial load.[19]
- The strength of the connection between layers and resistance to delamination are measured by the Interlaminar Shear Strength (ILSS) Test (ASTM D2344).
- In research using CNT and GNP, the flexural test (ASTM D790) is used to evaluate stiffness and bending strength.[32]
- Impact Test: Evaluates the resilience and energy-absorbing capacity of composites.

2.5 Thermal Analysis

- The following methods were used to examine the composites' thermal behavior:
- Viscoelastic characteristics like storage modulus, loss modulus, and damping behavior over a temperature range are measured using dynamic mechanical analysis (DMA).[14]

- By calculating weight loss as a function of temperature, thermogravimetric analysis (TGA) assesses thermal stability.[15]

2.6 Microstructural Analysis

The dispersion of nanoparticles and fiber–matrix interaction were examined using scanning electron microscopy (SEM). The fracture surfaces of tested specimens were analyzed in order to understand failure processes, crack propagation, and interfacial bonding quality.[23]

2.7 Parameter Variation

- Different composite configurations were produced by altering:
- Fiber types and stacking configurations (Kevlar, Basalt, hybrid)
- Nanoparticle types (Al₂O₃, CNTs, GNPs)
- Nanoparticle weight fractions (e.g., 0.1%, 0.5%, 1%, 1.5%)
- This modification led to the discovery of the optimal composition for enhanced mechanical and thermal performance.[38]

3. Methods of Testing

- Both mechanical and thermal tests were carried out in accordance with conventional testing protocols to assess the performance of the generated hybrid nanocomposites. These tests aid in determining the composites' strength, stiffness, durability, and thermal stability.[22]

3.1 Tensile Test 3.1.1 Mechanical Testing

- The tensile test was conducted using a Universal Testing Machine (UTM) in compliance with ASTM D3039.
- The specimen was subjected to a uniaxial tensile force until it failed.
- Among the metrics that were computed were Young's modulus, elongation, and ultimate tensile strength.
- The fiber-matrix bonding effectiveness and load-bearing capacity are assessed in this test.[44]

3.1.2 Compression Test

- The compression test was carried out in compliance with ASTM D3410.
- The specimen was placed between compression platens and loaded until it failed.
- Compressive strength and deformation behavior were measured.
- This test is essential for studying buckling resistance and structural stability.

3.1.3 Interlaminar Shear Strength (ILSS) Test

- The ILSS test was carried out in compliance with ASTM D2344.
- A short beam was subjected to three-point bending specimen.
- The maximum shear stress between the strata was recorded.
- This test evaluates interfacial bonding and delamination resistance.

3.1.4 Flexural Assessment

- Flexural testing was performed in compliance with ASTM D790.
- A three-point bending rig was used to assess flexural strength and modulus.
- The stiffness and resistance to bending of the material are determined by this test.

3.1.5 Impact Assessment

- Impact testing was used to evaluate toughness and energy absorption capability (Charpy/Izod method).[22]
- The specimen was subjected to sudden loading.
- The amount of energy absorbed during the fracture was recorded.
- This test demonstrates resistance to sudden shocks and dynamic stress.[15]

3.2 Thermal Assessment

3.2.1 Dynamic mechanical analysis, or DMA

- DMA was performed in compliance with ASTM E1640.
- establishes the storage modulus, loss modulus, and damping factor ($\tan \delta$).
- assesses viscoelastic behavior throughout a range of temperatures.
- aids in figuring out glass transition temperature and stiffness.[26]

3.2.2 TGA, or thermogravimetric analysis

- TGA was carried out in compliance with ASTM E2550.
- In a controlled setting, the sample was heated.
- Temperature and weight loss were noted.
- determines the properties of decomposition and thermal stability.[41]

3.3 Microstructural Analysis

- SEM, or scanning electron microscopy
- used to investigate interior structure and fracture surfaces.
- aids in the analysis of failure processes, nanoparticle dispersion, and fiber-matrix adhesion.
- finds flaws such aggregation, voids, and cracks.[16]

3.4 Summary

Tensile, compression, flexural, ILSS, impact, thermal analysis (DMA, TGA), and microstructural analysis (SEM) are all part of the testing methods. These techniques offer a thorough comprehension of the functionality and dependability of hybrid nanocomposites.

4. Results and Discussion

By changing the fiber combinations and nanoparticle concentrations, the generated hybrid nanocomposites' mechanical and thermal performance was assessed. The findings demonstrate how hybridization and nanoscale reinforcement affect the behavior of composites.

4.1 Tensile Properties

Fiber hybridization greatly increases strength as compared to single-fiber composites, according to the tensile test findings. Because of their improved load-bearing capacity, Kevlar-based composites showed higher tensile strength, and basalt fibers added stiffness.[26]

Because of the efficient distribution of stress among the fibers, hybrid Kevlar–Basalt laminates demonstrated increased tensile strength. The performance was further impacted by the addition of nanoparticles: CNTs and GNPs increased tensile strength through improved load transfer and crack-bridging mechanisms.[32]

At a moderate concentration (about 1 weight percent), Al₂O₃ nanoparticles performed at their best.

However, due to agglomeration and stress concentration effects, which cause early failure, a decrease in tensile strength was noted at increased nanoparticle loading.

4.2 Compressive Properties

Compared to individual fiber composites, hybrid composites have a better compressive strength. Basalt fibers improved stiffness under compressive pressures, while Kevlar fibers helped prevent micro-buckling.

Compressive characteristics were enhanced by nanoparticle reinforcement by:

bolstering the interaction between the fiber and matrix

Minimizing internal flaws and gaps

Because of inadequate dispersion and matrix saturation, an excessive amount of nanoparticles resulted in decreased performance.[16]

4.3 Interlaminar Shear Strength (ILSS)

Hybrid composites have better interfacial bonding between layers, according to ILSS studies. ILSS was greatly improved by the incorporation of nanoparticles by:

Increasing fiber-matrix adhesion

Delamination reduction

Because of their strong surface interaction with the matrix, Al₂O₃ and graphene-based particles demonstrated the greatest improvement in shear strength among all fillers.[28]

4.4 Impact and Flexural Properties

Both the inclusion of nanoparticles and fiber hybridization had a considerable impact on flexural strength and impact resistance.

Because their stiffness and ductility were balanced, hybrid composites showed increased flexural strength.

Impact resistance was improved in CNT-reinforced composites, suggesting increased toughness.

At greater concentrations, graphene nanoplatelets somewhat decreased ductility but increased stiffness.

In general, nanoparticles enhanced resistance to crack propagation and energy absorption.[32]

4.5 Thermal Properties (DMA & TGA)

Nanoparticle reinforcement enhances thermal stability, according to thermal analysis:

Improved stiffness was shown by a higher storage modulus in the DMA data.

Restricted polymer chain mobility led to a rise in the glass transition temperature (T_g).

Improved heat resistance was confirmed by TGA data, which showed higher breakdown temperatures for composites enhanced with nanoparticles.

Because basalt fibers are naturally resistant to heat, they also made a substantial contribution to thermal stability.[27]

4.6 Microstructural Analysis (SEM)

SEM research clarifies failure causes and reinforcing behavior:

Uniform nanoparticle dispersion led to better bonding and reduced crack propagation.

Agglomeration at higher filler concentrations resulted in voids and stress concentration areas.

Among the combined failure mechanisms exhibited by hybrid composites were brittle fracture (Basalt) and fiber pull-out (Kevlar).

These results confirm that achieving better performance necessitates suitable nanoparticle dispersion.[36]

4.7 Overall Discussion

The results clearly demonstrate that:

Fiber hybridization improves macro-level mechanical properties.

Nanoparticle reinforcement enhances micro-level interactions.

The optimal concentration of nanoparticles is typically in the range of 0.5 to 1 weight percent.

Performance is deteriorated by excessive filler due to agglomeration.

The synergy between hybrid fibers and nanoparticles creates composites with remarkable mechanical strength, thermal stability, and endurance, making them suitable for cutting-edge engineering applications.[35]

5. Recommendations and Future Scope of Work

5.1 Recommendations

- In view of the study and experimental results of hybrid nanocomposites, the following recommendations are made:
- **Optimal Nanoparticle Content:** The concentration of nanoparticles should be carefully adjusted, typically between 0.5 and 1 weight percent, to provide the best mechanical and thermal performance. Excessive loading should be avoided as it leads to agglomeration and property degradation.
- **Improved Dispersion Methods:** Advanced dispersion methods such as chemical functionalization, mechanical stirring, or ultrasonication should be employed to ensure uniform nanoparticle distribution throughout the matrix.
- **Hybrid Fiber Design Optimization:** The fiber stacking sequence (such as the Kevlar–Basalt arrangement) should be modified to attain a balance between strength, stiffness, and toughness.
- **Surface Treatment of Fibers:** Chemical treatments or coatings can enhance mechanical properties and reduce delamination by boosting fiber–matrix adhesion.

Controlled Manufacturing Conditions: Curing temperature, pressure, and mixing ratios should all be carefully controlled to minimize defects such voids and uneven bonding.

Selecting the Right Nanofillers: Different nanoparticles (Al₂O₃, CNTs, and GNPs) should be selected based on the desired use, such as impact resistance, strength, or thermal stability.[42]

5.2 Future Scope of Work

- The current study provides a number of avenues for future investigation:
- **Multi-Nanoparticle Hybrid Reinforcement:** Future studies can study the combined effect of numerous nanofillers (e.g., CNT + GNP + Al₂O₃) to obtain synergistic increases in properties.
- **Advanced Manufacturing Techniques:** For improved quality and scalability, methods including automated fiber placement, 3D printing, and vacuum-assisted resin transfer molding (VARTM) can be studied.
- **Fatigue and Creep Analysis:** For practical applications, long-term performance studies covering fatigue behavior, creep resistance, and durability under cyclic loads should be carried out.
- **Environmental and Sustainability Studies:** To create eco-friendly and biodegradable composites, the utilization of natural fibers (jute, sisal) in conjunction with nanoparticles can be further investigated.
- **High-Temperature and Fire Resistance Studies:** Further testing in extremely hot environments can aid in determining suitability for defense and aerospace applications.

Quantitative Simulation and Modeling: To assess experimental data and predict mechanical behavior, ANSYS and other finite element analysis (FEA) software can be used.

Nano-Level Characterization: Advanced techniques such as Atomic Force Microscopy (AFM) and Transmission Electron Microscopy (TEM) can be used to examine nanoparticle dispersion and interface interactions at a deeper level.

Smart and Functional Composites: By including sensors or conductive nanoparticles, smart composites with self-sensing or damage-detection capabilities can be produced.

6. Reference

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