Enhancing Mechanical Characteristics and Cost-Efficiency of Composite Materials Through Hybridization and Nanoparticle Incorporation

G. Boopathy, G. Balaji, R. Bhoominathan, A. Bovas Herbert Bejaxhin, and N. Ramanan

Abstract

Lightweight materials are increasingly being used in engineering applications today. Composites are replacing traditional metallic materials in a variety of sectors, including aerospace, defence, and aircraft production, where there is a demand for structural materials with high strength-to-weight and stiffness-to-weight ratios. Natural fibre composites are also increasingly used in place of synthetic fibre composites in a variety of technical fields due to their affordability and environmental friendliness. In this particular study, Kevlar (Aramid fibres) is combined with other materials to improve the mechanical characteristics and impact resistance of composites. The only material that costs more than Kevlar is carbon fibres. The goal is to maximize mechanical qualities while utilizing the fewest amounts of pricey Kevlar fibres possible. The hand layup technique was used to create the hybrid composites, which included both natural and Aramid fibres. The performance of various mechanical properties was then assessed. In addition, a morphological examination was done to look at the interior structure of the composite materials that were examined. The results show that the hybrid composite, with or without the addition of nanoparticles, demonstrates great strength with little reliance on Kevlar fibres.

Keywords

Hybridization • Nanoparticle • Composites • Aramid fibre

1 Introduction

Extensive research has been conducted on the mechanical behaviour of unidirectional Kevlar/epoxy composites under tensile strength and various failure modes, with a particular emphasis on minimizing deviations (Asumani et al., 2012). By utilizing modified high-speed drill bits operating at operational speeds, the drilling capabilities of Kevlar composites were experimentally investigated. The study revealed that the application of liquid nitrogen at the drilling site significantly improved tool life, hole quality, and surface finish (Azmir & Ahsan, 2008). Experimental assessments have been carried out to examine the effects of treatment on Kevlar 29 fibre. The study focused on investigating the influence of temperature on the mechanical characteristics. The results indicated a decrease in mechanical parameters such as tensile strength and tensile strain as the treatment temperature increased. Furthermore, it was observed that vacuum treatment had no impact on Young's modulus and tensile strength (Azmir & Ahsan, 2009). The impact of using Kevlar fibre as reinforcement with bismaleimide, along with the effects of chemical treatments, was thoroughly examined. Two categories of bismaleimides were subjected to thermal analysis using techniques such as thermogravimetry, differential scanning calorimetry, and thermo mechanical analysis. The results demonstrated that interfacial strength was significantly improved through cholosulphuric acid

G. Boopathy (✉)
Aeronautical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India
e-mail: boopathyg81@gmail.com

G. Balaji
Aeronautical Engineering, Hindustan Institute of Technology and Science, Chennai, India

R. Bhoominathan
Aeronautical Engineering, Bharath Institute of Higher Education and Research, Chennai, India

A. B. H. Bejaxhin
Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, India

N. Ramanan
Mechanical Engineering, Sri Jayaram Institute of Engineering and Technology, Chennai, India

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treatment. Scanning electron microscopy was employed to investigate the fracture surface (Anuar & Zuraida, 2011).

Researchers investigating the filtration characteristics of ground kenaf core. A comparison was made between the constant pressure pre-coat filtration properties of kenaf and diatomaceous earth (DE). Three challenge solutions were specifically analysed in detail. The results demonstrated that both kenaf and DE were capable of efficiently removing silica particles from the solution without any degradation in flux during the filtration process. As a result, the study concluded that kenaf and DE displayed similar filtration characteristics (Akil et al., 2011). The characteristics of marble kerf were experimentally investigated in this study using abrasive water jet machining. Various input parameters, such as transverse speed, water pressure, and abrasive flow rate, were considered. The Taguchi method was employed to analyse the process parameters, and ANOVA was conducted to identify the significant factor affecting kerf characteristics. The findings revealed that the transverse speed had a substantial impact on both the kerf taper angle and kerf width (Bandaru, 2015; Boopathy et al., 2022).

Authors focus on conducting experimental investigations to assess the disparities in lignin content among three distinct varieties of kenaf, specifically Everglades (Ananth, 2011). The bast, inner bast, and core samples were prepared from four different positions for analysis The results indicated a decrease in lignin content with an increase in stem height. Furthermore, the disparities in lignin content between the core and bast samples were found to be more pronounced in Everglades and Aokawa varieties compared to Mesta (Azmir & Ahsan, 2011). Several experiments conducted on woven glass fibre reinforced polyester composites in three different orientations to assess their wear and friction coefficient. The characteristics were determined by varying loads and sliding speeds. Scanning electron microscopy was employed to observe changes in the composite laminate. The results revealed a significant improvement in both the friction coefficient and wear loss (Boopathy et al., 2017). Research projects investigated the use of kenaf non-wovens as substrates for laminated products, which have wide applications in wall coverings, upholstery covers, edge banding materials, and other laminates. The objective was to demonstrate the feasibility of utilizing non-woven kenaf fibres in the production of laminated products. The study involved blending kenaf fibres with polypropylene in an 80:20 ratio and preparing batts using a modified cotton card of standard widths. The batts were then processed through calendaring or needle punching and subsequently cured in an oven to create the substrate. These substrates were further laminated with various overlays, including polyester wood grain, phenolic resin, and decorative vinyl (Abbas et al., 2010; Al-Mosawi & Hatif, 2012; Boopathy et al., 2019).

Study focused on the full analysis of hybrid laminates created by mixing non-woven kenaf fibres with Kevlar epoxy, with an emphasis on both quasi-static penetration and ballistic characteristics. The laminates were subjected to high-velocity impacts from strong projectiles at a perpendicular angle, with a thickness spectrum spanning from 3.1 mm to 10.8 mm. The hand layup process was used to create these hybrid composites, which were then cured for 24 h under ambient conditions while carrying a static load. These hybrid composites were made up of three distinct arrangements comprising alternating layers of non-woven kenaf and Kevlar. Furthermore, for the sake of comparison, composite materials were created by combining Kevlar and epoxy, as well as kenaf and epoxy. A mechanical testing device with controlled displacement rates (1.27 mm/min and 2.54 mm/min) was used to perform quasi-static penetration tests. A powder cannon and a 9 mm full metal jacket bullet were used for ballistic testing to submit the laminates to various ballistic scenarios. Parallel to this study, another experiment was carried out to investigate the effects of fibre alignment and alkalization on the mechanical and thermal properties of stretched, randomly oriented kenaf and hemp fibres. The results of this investigation revealed a significant improvement in the mechanical properties of alkalized fibres when compared to their untreated counterparts. Morphological analysis techniques were used to investigate the interior structure of the composite laminate in order to fully appreciate the effects of fibre alignment and alkalization. The outcomes of this study emphasized that hemp polyester composites had enhanced fracture resistance, and treated hemp and kenaf fibres revealed a lack of surface pollutants that were present in untreated fibres (Arsath, 2014; AultrinK, 2016).

2 Material Selection and Manufacturing Process

2.1 Material Selection

Kevlar fibre is a remarkable synthetic material with many benefits over traditional materials, including decreased weight, cost effectiveness, and simplicity of manufacturing. Synthetic materials like Kevlar are essential in today's environment, where we constantly work to address the issues facing society and develop more durable and useful products. When compared by weight, the hard plastic material Kevlar is five times more powerful than steel. It is made using a polymerization method, which combines a large number of synthetic plastics to create long chain molecules. Its remarkable internal structure, in which the molecules are arranged in orderly, parallel lines, is responsible for its extraordinary properties. A strong material is made by firmly knitting these fibres together.

The Dupont Company is credited with developing and introducing Kevlar, a proprietary material with major technical significance. Stephen Kwolek is the man behind this breakthrough. Kevlar belongs to the class of synthetic aromatic polyamides, often known as Aramids. Kevlar and Nomex are two well-known examples of Aramids. Kevlar comes in a variety of compositions, including Kevlar 29 and Kevlar 49, each customized to a specific application.

Kevlar's unusual and durable molecular structure includes benzene-like rings, which are referred to as "aromatic" in this context. The term "polyamide" refers to long chains of these ring-shaped aromatic molecules that are coupled to form a bigger chemical framework. Kevlar is manufactured by spinning solid fibres from a liquid mixture. Poly para phenylene terephthalamide, a synthetic organic polymer, is used in this procedure. One of the hydrogen atoms in ammonia is substituted by amides generated from organic acids in this process. This substitution approach results in a super-strong structure with a reduced modulus and increased impact resistance. Kevlar's inherent qualities make it ideal for applications involving ballistic materials. The combination of ammonia and organic acid condensation produces a polymer with excellent strength and endurance. As a result, Kevlar is widely used in situations where its exceptional structural properties are critical.

2.2 Fabrication Method

A common method for creating hybrid composites is the hand layup process. This method is dependent on the operator's expertise, the composite's hardness, cost factors, production pace, and shape. The hand layup approach, which is simple and affordable, is used in this study endeavour to create the hybrid composites. The equipment needed to fabricate the composite is likewise reasonably priced. Twisted Kevlar fibres and glass reinforced polymer fibres are utilized to create the composite. To ensure a solid binding between the reinforcement and the medium, a thermosetting resin that has been combined with a hardener is used. The technique makes use of a frame and roller made of silica rubber. The hand layup technique is best suited for straightforward, low-volume production.

To make the laminate removal process simple, a releasing agent is first applied to the surface during manufacture. Following the application of a thin coat of resin, Aramid fibres are then spread across the surface. To remove any air bubbles, a weight of 5 kg is placed over the glass fibres. The composite is then left alone for about 3 h. The fibres are normally dried before the layup in order to reduce moisture. At the top and bottommost layers of the composite laminate, Aramid fibres are laid to produce a superior finish. Using the hand layup technique, three distinct categories and three samples were created. Every fibre is laid out in its usual direction. Before the fibres are added to the laminate framework, care is taken to keep them dry.

3 Experimental Analysis

3.1 Tensile Test

Tensile testing, a mechanical test, evaluates the tensile strength and characteristics of materials under tension. During the test, a sample is subjected to an increasing axial force until it either fractures or reaches its maximum deformation. Figure 1 illustrates the standard specimen utilized in the tensile test. The obtained tensile results for the aramid specimens, both with and without nanoparticles, are presented in Fig. 2 and Fig. 3, respectively, using a universal testing machine.

The tensile test results indicate a noticeable difference between the material with added nanoparticles and the material without nanoparticles. When nanoparticles were incorporated into the parent material, the ultimate load at which the material failed increased compared to the material without nanoparticles. Additionally, the yield point, which represents the onset of permanent deformation, also increased when nanoparticles were present. However, in the absence of nanoparticles, the ultimate load and yield point remained the same, indicating that the material could withstand the applied stress within the elastic limit without undergoing permanent deformation.

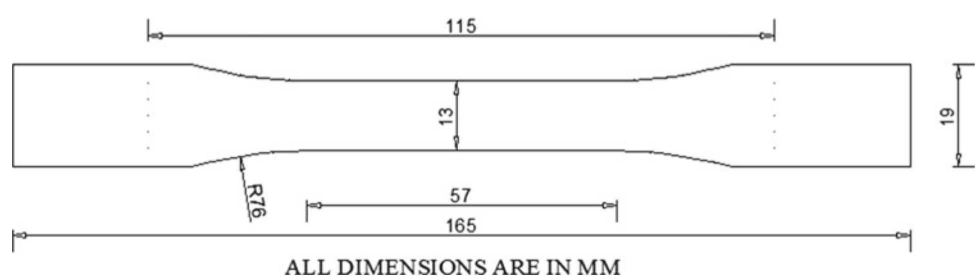

Fig. 1 ASTM D-638 standard for tensile specimen

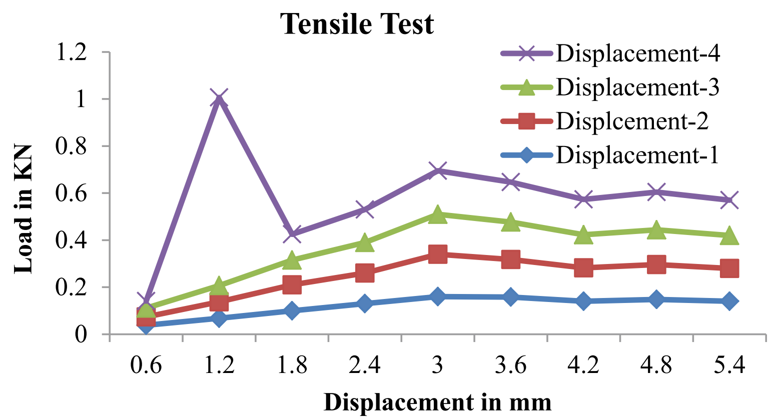

Fig. 2 Aramid fibre without nanoparticles

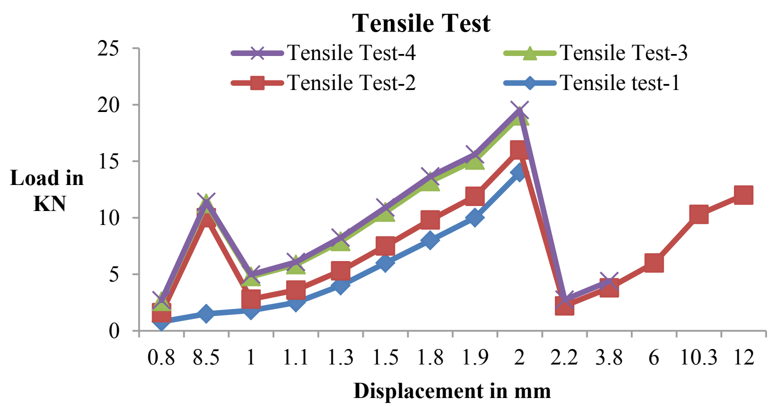

Fig. 3 Aramid fibre with nanoparticles

3.2 Flexural Test

The flexural test, also known as the bending test, is a common mechanical test employed to evaluate the stiffness and bending strength of materials. During this test, a specimen is secured at two points and subjected to a three-point bending configuration. Figure 4 illustrates the standard specimen used for the flexural test. The obtained flexural results for the aramid specimens, both with and without nanoparticles, are presented in Fig. 5 and Fig. 6, respectively, using a universal testing machine.

The flexural test results reveal a distinct difference between the material with added nanoparticles and the material without nanoparticles. When nanoparticles were incorporated into the parent material, the ultimate load, at which the material failed in bending, increased compared to the material without nanoparticles. Additionally, the yield point, which represents the onset of permanent deformation, also increased when nanoparticles were present.

However, in the absence of nanoparticles, the ultimate load and yield point remained the same, indicating that the material could withstand the applied stress within the elastic limit without undergoing permanent deformation.

3.3 Hardness Test

The hardness test is primarily conducted to evaluate the material's ability to absorb sudden shocks or resist indentation. The ASTM standard commonly employed for hardness testing is ASTM D2583.

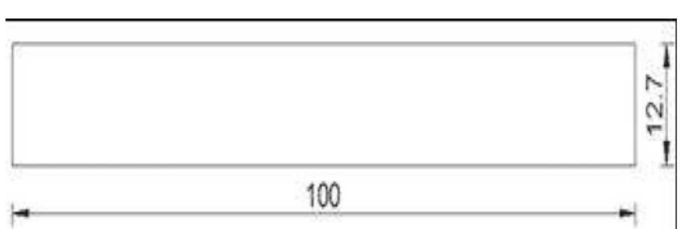

Fig. 4 Flexural test specimen-part diagram

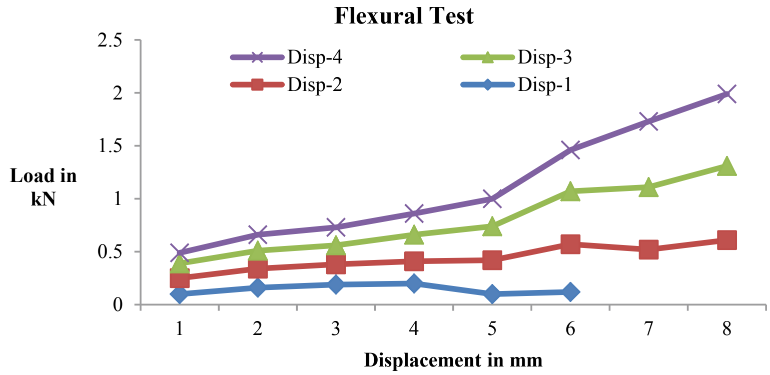

Fig. 5 .Aramid fibre without nanoparticles

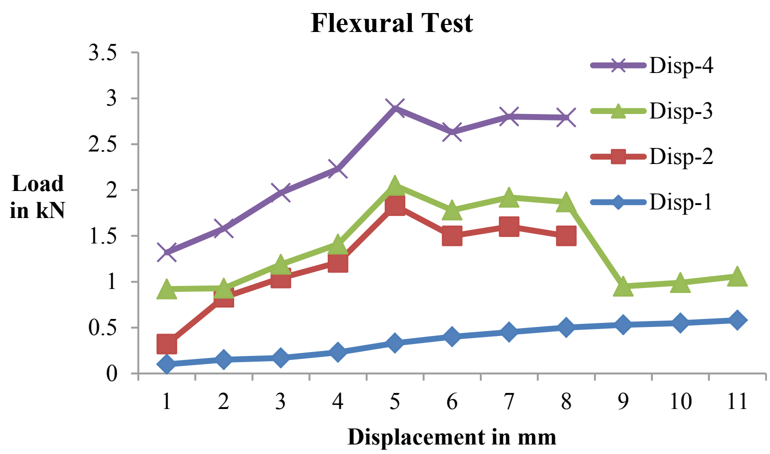

Fig. 6 Aramid fibre with nanoparticles

From Fig. 7, hardness test results indicate a noticeable difference between the material with added nanoparticles and the material without nanoparticles. When nanoparticles were introduced into the parent material, the hardness value increased compared to the material without nanoparticles. This suggests that the incorporation of nanoparticles enhanced the material's resistance to indentation or deformation.

4 Morphological Analysis Using SEM

A scanning electron microscope (SEM) is a type of electron microscope that produces high-resolution images of a sample by scanning it with a focused beam of electrons. This technique allows for the examination of the specimen's topography and morphology. When the electron beam

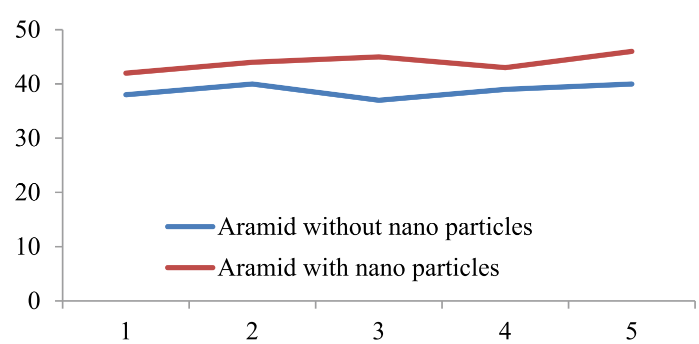

Fig. 7 Aramid particles without and with nanoparticles

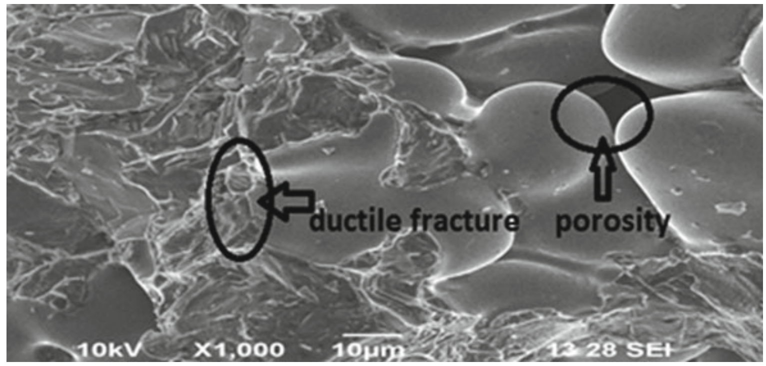

Fig. 8 Fracture surface of SEM images with nanoparticles

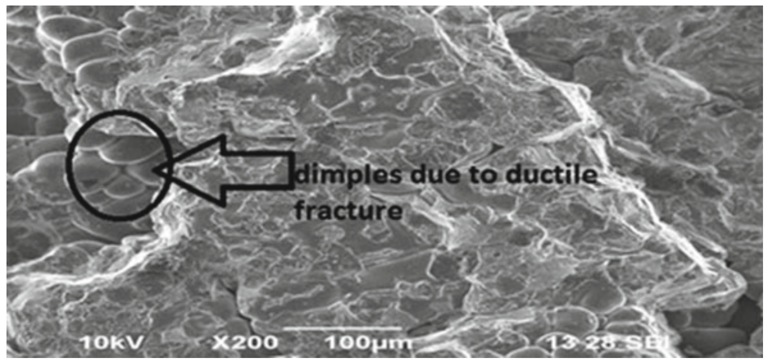

Fig. 9 Fracture Surface of SEM Images with Nanoparticles

interacts with the atoms in the sample, it generates signals that can be detected and provide valuable information about the surface's topography and composition.

SEM analysis is commonly employed to study fractured surfaces of impact test specimens. These samples are selected due to their significant variations in mechanical test results, as well as differences in composition and melting temperature. By using SEM, researchers can examine the microstructure and surface characteristics of these specimens, gaining insights into the nature of the fracture and understanding the material's response to the applied force. Fracture Surface of SEM Images with Nanoparticles is shown in Fig. 8.

The SEM images depicted in Fig. 9 offer significant insights into the particle distribution and fracture surface of the material. These images reveal the presence of black spots, representing the SiC particles, and provide valuable information about their distribution within the material. The presence of these particles indicates that the material has been reinforced with SiC, which can enhance its mechanical properties and improve its fracture resistance.

The SEM analysis provides insights into the nature of the fracture surface. If dimples are present, indicating ductile fracture, it suggests that the material can undergo plastic deformation prior to fracture, indicating high load-bearing capacity. This characteristic is advantageous for applications requiring strength and toughness. Additionally, the absence of porosity, as observed in the SEM image, signifies a sound and compact structure. Porosity can weaken the material and diminish its mechanical properties, making the lack of porosity a favourable attribute.

5 Conclusion

Numerous improvements in the material properties were found in the investigation on aramid matrix composites with and without nanoparticles. The tensile parameters of the aramid matrix composite, such as tensile strength and modulus, improved with the addition of nanoparticles. This shows that the nanoparticle addition improved the composite's total mechanical strength. The study also discovered that the composite's improved flexural properties were positively impacted by the composite's improved tensile capabilities. The aramid matrix's flexural strength and modulus gradually increased after the addition of nanoparticles. This implies that the composite displayed greater stiffness and bending resistance.

With the addition of nanoparticles, the aramid matrix composite's mechanical properties as well as hardness value improved. This suggests that the composite hardened and grew more indentation-resistant, which is advantageous for applications needing high wear resistance. Porosity and other defects were not present in the composite with nanoparticles, according to the microstructure examination. This shows that adding nanoparticles effectively filled any gaps and enhanced the composite's overall density and integrity. These results lead to the conclusion that the aramid matrix composite with nanoparticles is ideally suited for mechanical applications where enhanced hardness, high tensile and flexural strength, and a microstructure devoid of defects are needed.

Conflicts of Interest The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Data Availability The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

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