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Experimental Investigation on Mechanical and Microstructural Properties of Hybrid Composite Materials for Ballistic Armor Application

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Abstract

Recently the industries are in need for lightweight materials with high strength for specific applications. In this project are used three synthetic fibers which are Kevlar, carbon and glass fiber and fabricated two different sample laminates. The fibers are fabricated using hand lay-up process and among the two samples in one consists of EPE (Expanded polyethylene) foam which we included to increase the thickness and the other is without the EPE foam. The samples are fabricated in the sequence of fiber starting with kevlar then carbon which is followed by glass fiber, here in the sample with foam we used two EPE foam sheets and fabricated them in between two sequential layers of fibers. We used mechanical and microstructural characterization in which the tensile test, flexural test, DMA (Dynamic mechanical analysis) test, and SEM (Scanning electron microscope) analysis are performed and the results obtained for the same. The application of the fiber laminates prepared is for ballistic armor where the three fibers will be useful in ways like reducing the weight, increasing the strength and also performance of the armor while preventing a bullet from penetration into the human and saving the life in due process.

Keywords

Hybrid polymer composite materials, Tensile test, Flexural test, Dynamic mechanical analysis test, Microstructure analysis, Ballistic armor

Introduction

In recent years, there has been a growing demand for advanced materials that combine the beneficial properties of different constituents to achieve superior performance and versatility. One such class of materials that has gained significant attention is hybrid polymer composites. These innovative materials integrate two or more distinct components, typically polymers and reinforcing fillers, to create a synergistic blend that capitalizes on the strengths of each individual element [1]. Different interfaces divide these two phases. High specific strength and stiffness, good corrosion resistance, and good fatigue resistance are the most useful properties of composites. Advanced composite materials contain reinforcing fibers in resin matrix are used in transportation and defense industries. Because of excellent strength to weight ratio, laminated composite materials widely used in mechanical, marine, aeronautical, protective gear and automotive structures [2]. Engineers and researchers possess the capacity to customise composite materials to fulfil certain performance criteria by meticulously choosing and regulating the characteristics of nanofillers, such as their kind, size, and concentration. These tailored composite materials can exhibit a wide range of desired properties, including but not limited to flexibility, transparency, thermal stability, and flame

resistance. In conclusion, nanofillers play a paramount role in enhancing the performance and functionality of composite materials across various industries. Their intrinsic characteristics, such as the ability to improve structural integrity, facilitate thermal and electrical conduction, and customize material properties, make them indispensable in advancing sophisticated materials for fields like aerospace, automotive, electronics, and related domains. Nonetheless, the successful integration of nanofillers requires meticulous engineering and a thorough evaluation of safety factors, making this a captivating yet demanding domain in the field of materials science [3, 4].

Multilayered armor system

Hybrid polymer composites offer a wide range of remarkable characteristics, making them highly desirable in various industries, including aerospace, automotive, construction, electronics, and more. By combining different types of polymers, such as thermosetting and thermoplastic resins, along with diverse fillers like carbon fibers, glass fibers, nanoparticles, or natural reinforcements, manufacturers can tailor the composites to meet specific engineering requirements. The key advantage of hybrid polymer composites lies in their ability to overcome the limitations of individual materials. For instance, by blending a tough and flexible polymer with a stiff and strong reinforcing material, the resulting composite can exhibit enhanced mechanical properties, such as high tensile strength, improved impact resistance, and better fatigue performance. Moreover, hybrid composites can offer unique combinations of electrical, thermal, and chemical properties, enabling them to excel in multifunctional applications [5-7].

The front ceramic tile of a conventional multilayer armour system absorbs the vast majority of the impact energy, allowing it to stop the 7.62 mm fast bullet's perforating force. Not only does bullet spalling contribute to the dissipation of energy, but so does the breakage of brittle ceramics. Both the bullet and the ceramic will shatter with enough force to produce fatal injuries if they collide at high speed. So, another layer is added behind the primary ceramic to dampen the shock wave that follows a collision and the fragment explosion it causes. The second layer of a multilayered armor system configuration is often Kevlar, followed by a ductile material to stop projectiles from entering the body. The amount of energy absorbed by a multilayered armor system is dependent on the shock impedance at the layer contact. After projectile impact in the front layer, a compressive transverse wave travels through the ceramic, encountering several reflections on its way. What kind of waves are reflected back depends on the impedance of the interface. When the compressive component of a shock wave encounters a second layer with a lower density, like Kevlar™, the wave is reflected as a tensile wave, which helps efficiently break the ceramics. The more effectively energy is absorbed, the thinner the second layer can be [8-10].

Ballistic armor

In 1538, the concept of ballistic armor came into piture which comprised of steel plates. Ballistic armor is a type of barrier protection that is used to defend the human body against many types of sharp objects or projectiles. Bullet impact trauma has been mitigated by to advancements in body armor design and material selection, which have also increased energy absorption while decreasing weight. Two common types of body armor are hard body armor and soft body armor. Cetal, ceramic, or composite fibers are used to reinforce hard body armor. Military troops use them to defend themselves from high-speed projectiles during high-risk missions. On other hand multiple layers of high-performance fabrics are used for soft body armor which is used to protect torso and extremity regions. Absorption of the bullet or fragment's energy is the process through which ballistic protection is obtained. Because of their mass and projected velocity, these projectiles or pieces contain a lot of kinetic energy. In this paper, we will delve into the fascinating world of hybrid polymer composites, exploring their composition, manufacturing techniques, properties, and diverse applications. Additionally, we will discuss the latest advancements and ongoing research efforts in this field, highlighting the potential implications and future prospects of these innovative materials [11]. The novelty of this research is to develop hybrid polymer-reinforced composite materials and analysis the mechanical properties of hybrid composite. The integration of nanofillers into composite materials serves to enhance their mechanical properties. These materials frequently demonstrate improved stiffness, strength, and toughness. The incorporation of carbon nanotubes into a polymer matrix has been observed to yield a substantial enhancement in both the tensile strength and modulus of the resulting composite material. Several types of nanofillers, including carbon nanotubes and graphene, possess exceptional conductivity properties for both heat and electricity. When included into composite materials, they have the potential to significantly augment thermal and electrical conductivity, rendering these materials highly advantageous in various fields such as electronic devices and aeronautical components [12-14].

Materials and Method

Kevlar (para-aramid) is a strong and heat-resistant synthetic fiber. It is created by initiating a chemical reaction between an acid and a nitrogen and hydrogen-containing chemical solution. The molecules of Kevlar have a strong, ring-like structure, similar to that of benzene. The chemical nature of Kevlar causes it to spontaneously form in microscopic straight rods that pack tightly together. Long chains are formed when the ring-like aromatic molecules join. Because of its impact resistance, high strength, and low weight, Kevlar is the most commonly used cloth as armor against bullets used in hand weapons which make its excellent fabric for ballistic armor. Aerospace, road and marine transport, sports equipment's, used in prostheses, surgarey and X-ray equipment, implants, tendon/ligament repair. Glass fiber is a special synthetic fiber consisting of numerous fine fibers of glass. Glass fiber has a lesser stiffness than other reinforcing fibers, but it has the particular benefit of combining high strength with low density and, most importantly, a low cost. Used in food processing sector, chemical industries, sectors related to metals and mining aerospace and defense. Other name for Epoxy resins is polyepoxides which is reactive prepolymers in class and contains epoxide group. EPE foam is a foam made from expanded pellets (EPE bead) with using blowing agents then it is expended into mold in steam chest. The method is similar

to that of EPE foam production [15-17]. Figure 1 and figure 2 shows reinforcement materials.

One of the earliest and most used approaches to producing composites is the hand lay-up process. Fiber-reinforced plastic is made by impregnating layers of reinforcing fibers (often fiber glass, carbon fiber, or aramid) with a liquid resin matrix (typically epoxy, polyester, or vinyl ester) laid down by hand on a mold. Although time-consuming, this method is widely used because of its low cost, ease of implementation, and potential for creating elaborate composite structures. In most cases, these are the steps involved in a hand lay-up: Getting ready to mold: In order to create a composite component, the first step is to make a mold, which is a negative reproduction of the final design. To prevent the composite from adhering to the mold, it is often constructed of fiber glass or metal and treated with a releasing agent. Reinforcing fibers, often called "prepregs" or "fabric," are placed by hand in successive layers on the mould. The mechanical characteristics and strength of the finished composite can be tailored by adjusting the orientation and quantity of fiber layers. After the fibers have been laid down, the liquid resin is applied with brushes, rollers, or sprayers so that it covers the whole surface of the fiber stack. The resin permeates the fiber layers, creating a matrix that bonds and supports the composite [18-21]. Figure 3 and figure 4 shows hand lay-up process.

Consolidation: A consolidating tool, like a roller or squeegee, is used to press the layers together to ensure adequate compaction and to eliminate any trapped air or voids. This method aids in producing a composite with minimal flaws and consistent resin distribution. After the composite has been laid down, it must cure. Curing is the chemical reaction that causes the resin to crosslink and harden into a solid. The resin system and the desired qualities determine the curing time and temperature. Demolding and finishing occur once cure is complete and extreme care is used to remove the composite part from the mold. It's possible that further finishing like reducing the surplus and polishing the surface will be needed to get the appropriate proportions and quality. Applications where low to medium production numbers, customisation, and cost efficiency are paramount often employ the hand lay-up technique. It is important to note, however, that manual handling can cause discrepancies in the mechanical properties of the finished composite by introducing differences in fiber alignment and resin distribution. Since automated techniques like filament winding and automated tape laying allow for greater efficiency and accuracy in mass production, they are frequently favoured. The manual lay-up process is still frequently used in the composite manufacturing industry, particularly for prototypes, short-run production, and specialized applications.

Hand lay-up process

Hand lay-up is the most popular and least expensive open-molding method. Hand-placed fiber reinforcements in a mold, then resin is added with a brush or roller. Both huge and small products are made using this method. It's a straightforward approach for making composites. It is appropriate for parts made of fiber composite materials. Figure 4 shows the fabrication process.

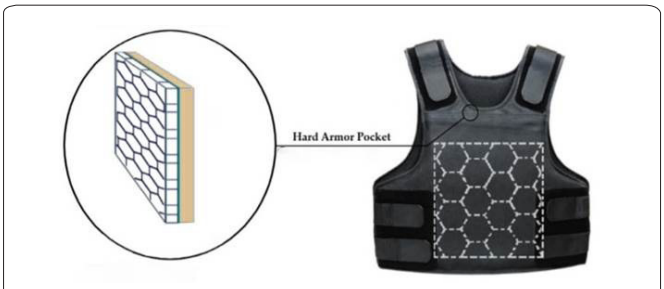


Figure 1: Multilayered armor.

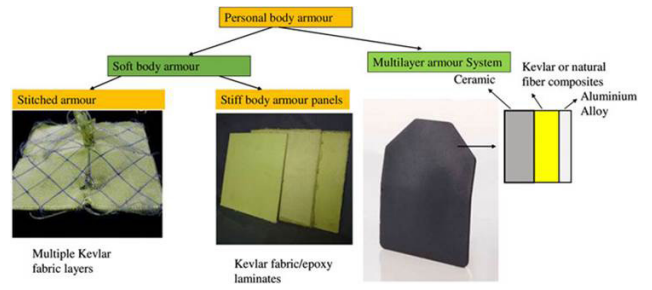


Figure 2: Types of armor.



Figure 3: Carbon, glass, Kevlar fibers, and EPE foam materials.



Figure 4: Hybrid composite laminates.

Fabrication process

We started by cutting the Kevlar, carbon, and glass fiber sheets into 18 x 30 by 30 cm sheets. Next, we took a 35 x 35cm wooden platform and placed a polymer sheet on top of it. We then used polyvinyl alcohol to clean the bedding. We made a resin with a total weight of 225 g, using 200 g of epoxy and 25 g of hardener. The resin was utilised to glue the composite laminate layers together. We lay the Kevlar fiber laminate sheet into the foundation and applied the resin carefully all over the fiber with a brush. We then used a roller to distribute the resin throughout the fiber sheet after applying it. The carbon fiber is then placed on the Kevalr fiber sheet, and the resin is applied again to the sheet and distributed throughout the sheet using a roller. We applied the third layer of glass fiber to the carbon laminate sheet in the same way. Finally, another composite layer was placed to the top. After that, we placed bricks on top of the laminate to allow it to cure. For

curing, we allowed the samples to air dry for three days. We made three laminae samples: one with all three fibers and EPE foam, another with three fibers but no foam, and a third with three fibers and steel plate. The hand lay-up approach was used to create all three examples. We removed the laminates from the hardwood basis after curing, and then used a power saw to cut the surplus section for the needed measurements from the laminates. After that, the completed laminates are polished to provide a superior finish. The finished laminates were 30 x 30 cm in size and came in three samples. The sample with all three fibers and EPE foam is the thickest, with a thickness of 9 mm. The thickness of the other sample without EPE foam is 7 mm, while the thickness of the steel laminate sample is 8 mm.

Results and Discussion

As a part of mechanical characterization, we carried out tensile test, flexural test, DMA. The test specimens were designed based on ASTM on the two sample laminates among which one sample is of all three fibers with foam included in it and the other sample has only all three fibers and no foam included in it. Table 1 shows mechanical properties of developed composites, the mechanical tests values for the two samples are taken separately and they are as follows: The tensile test comes under the mechanical characterization of the material. The tensile strength is important for a material as it has to have an ability to withstand the elongation and resist the load applied on it during the due process. Naturally, Kevlar fiber is a high-tensile material and is used in various applications across many industries. In figure 5 we have prepared a bar graph using the data of tensile strength for the two samples. One with EPE foam and the other without EPE foam, we can see the difference in the tensile strength parameter for both samples. On the Y-axis of the graph, we have tensile strength in MPa and on X-axis we have the two test samples with foam and without foam. The values obtained for the sample with foam is 4.65 MPa and without foam is 15.6 MPa. From the below graph we can observe that the tensile strength is more in the sample without foam in comparison to the sample consisting the foam. Figure 5 shows the DMA analysis of hybrid composites.

Table 1: Mechanical properties of developed hybrid composites.

Width (mm)	14.9	14.6
Thickness (mm)	2.6	2.7
Br load (KN)	6.1	6.1
Tensile strength (N/mm²)	15.7	14.5
Flexural strength (N/mm²)	26.144	13.768
Impact strength (Joule)	2	4
Hardness in shore 'D'	55	60

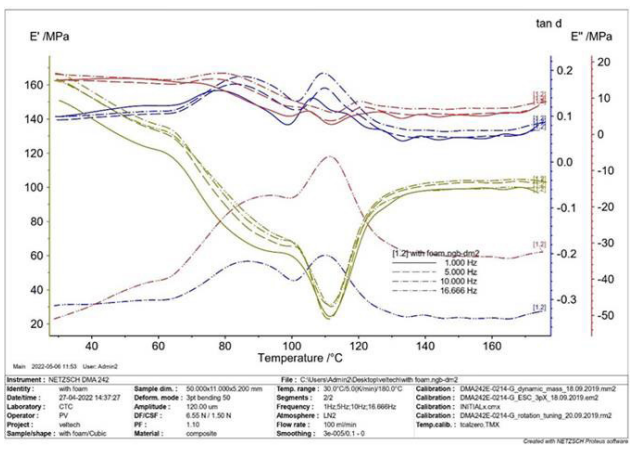


Figure 5: Dynamic mechanical analysis of fabricated hybrid composite.

DMA test is a powerful experimental technique used to characterize the viscoelastic properties of materials as a function of temperature, time, and frequency. It is widely employed in the study of polymers, composites, elastomers, and other viscoelastic materials to understand their mechanical behavior under varying conditions. DMA involves subjecting a material sample to an oscillatory mechanical force while simultaneously measuring its response. The sample is typically subjected to a sinusoidal deformation, and the resulting stress and strain are measured as a function of time or frequency. By applying a wide range of frequencies and temperatures, DMA can reveal critical insights into the material's mechanical properties, such as storage modulus (E'), loss modulus (E"), damping properties, and glass transition temperature (Tg).

A temperature sweep involves continuously measuring the sample's mechanical properties at a fixed frequency while the temperature is varied. This enables scientists to study phase shifts in materials, such as glass transitions and crystallisation. An important parameter determined by DMA is the glass transition temperature (Tg), which marks the change from a glassy to a rubbery or viscoelastic state. A frequency sweep is a method of measuring mechanical parameters in which the temperature of the sample remains constant while the frequency of the oscillatory deformation is changed. This reveals how the material behaves viscoelastically and how it reacts to various loading rates. For applications in the automotive, aerospace, and consumer goods industries, a thorough understanding of the viscoelastic characteristics of polymers and their behavior under varied situations is essential. DMA is widely employed for this purpose.

Microstructure analysis of hybrid composite plates

We have two different types of samples one is with foam and the other without the foam and there we can see the difference between the samples with the help of SEM and also seen the bonding between the fibers of Kevlar, glass, and carbon. The fractures caused by the cutting the materials. There are three images of each sample of with foam and without foam shows the different areas with various reasons behind the occurrences of voids and others. The first sample as seen by a SEM. While the epoxy resin cured, it attached perfectly to the fiber and matrix interface, as evidenced by the three visible sections of the matrix that clung to the fiber at various spots (see figure 6). As shown in figure 6 and figure 7, topographical features typical of a brittle fracture process are present, especially in glass fibers, and can be seen on surfaces with cohesive fractures in both the matrix and the fibers. Kevlar is extremely rigid for a material that appears to be fabric. Based

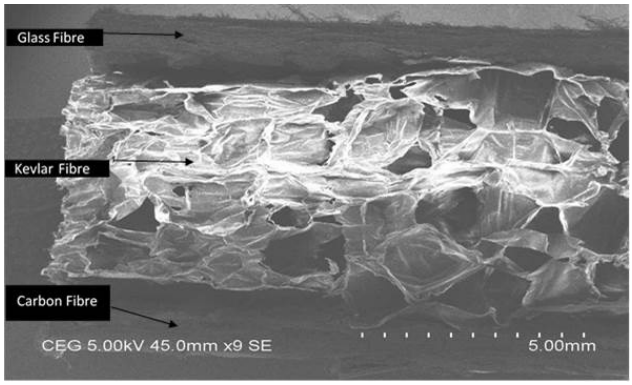


Figure 6: Microstructure of fabricated hybrid composite.

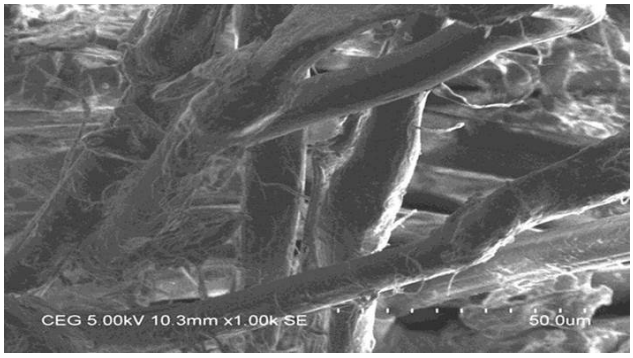


Figure 7: Microstructure of fractured hybrid composites.

on reviews of the relevant literature, it appears that attaching Kevlar to thermoset resins is different application of hybrid composite laminates for ballistic armor. We created and built an HPMC body armor as part of our project. The main goal of any ballistic armor is to protect the human body's vital organs, which in this case are the spinal column, heart, and kidneys. We divided the dough into 18 square sections, each measuring 30 x 30 cm. Fabrication of laminates with three combinations was done using the hand lay-up procedure. The material fails ductilely, and the distorted regions have no smooth surfaces. When a bullet hits the armour, it passes through the first layer of Kevlar before becoming impeded, causing the sharp point of the bullet to transform into a mushroom shape, preventing entry into the body. Because Kevlar is a woven material, it may be employed in a 0 - 90 orientation to get the maximum strength. Four impact angles (0°, 30°, 45°, and 60°) and impact velocities between 50 and 500 m/s were used to investigate the effect of oblique impact on the ballistic performance of laminated targets.

Researchers created large-scale composite pieces and used a water jet to chop them down to the desired dimensions. Each of the 95 carbon fiber/epoxy prepreg layers of the carbon fiber reinforced composite blocks was fabricated. A 14.5 mm 114 B32 API armor piercing bullet with a velocity of 911 m/s was used to fire high-velocity rounds against big and small panels. In the case of a perforation after the shot, an armor steel plate was installed below the test panels as a witness plate. The bullets pierced through the front armor steel block and entered the carbon fibers, but only to a depth of penetration right before the tiny panels' backing steel block.

Conclusion

The composite materials used in our project which are Kevlar, carbon, and glass fiber are good ballistic materials. The fabrication methodology selected was hand lay-up method, in which we fabricated the fiber laminates making three samples. Each sample has Kevlar, carbon, and glass fiber in common with a combination of EPE foam, without EPE foam. The purpose of adding EPE foam was to increase the thickness as well as the stiffness of laminate. The three samples were cut into test specimen as per ASTM standards and were tested for mechanical and microstructural characterization and the mechanical tests carried were a tensile test, flexural test, DMA test, and SEM analysis. The tensile strength for the foam sample received is 4.65 MPa and the without sample is 15.6 MPa. The flexural strength received is 19.95 MPa for the foam sample and without sample is 32.32 MPa. The samples were also tested for their viscous and elastic behavior against different temperatures and time and also the measure for physical properties were made to samples against the temperature and the microstructural properties were observed with the help of SEM images. The hybrid polymer matrix composite is useful for many applications across various industries. One such application where the usage of such polymers is made is the ballistic armors where these polymers are replaced with conventional metals due to their improved properties and performance. A bullet has its energy reduced as it tries to fight its way through.

Acknowledgements

None.

Conflict of Interest

None.

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