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Interlaminar shear strength of chemically treated Kevlar/Cucurbitaceae fiber metal laminated hybrid composites

Francis Xavier Joseph[1], Sudeshkumar Moranahali Ponnusamy[2], M. P. Natarajan[3], Jayabalakrishnan Duraivelu[4], Jayaseelan Veerasundaram[5], and Ramasamy Nallamuthu[5*]

[1]School of Mechanical Engineering, VIT Bhopal University, Bhopal, 466114, Madhya Pradesh, India
[2]Department of Mechanical Engineering, Shreenivasa Engineering College, Dharmapuri, 635301, Tamil Nadu, India
[3]Department of Mechanical Engineering, Bharath Institute of Higher Education and Research, Chennai-600073, India
[4]Department of Mechanical Engineering, Sriram Engineering College, Chennai, 602024, India
[5]Department of Mechanical Engineering, Prathyusha Engineering College, Chennai, 602025, India

*Corresponding author; E-mail: ramsnallamuthu@gmail.com

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Abstract

Many scientists and enterprises have shown their desire to develop novel materials with good mechanical capabilities and low-density equivalents to aluminium alloys in recent years. This is particularly noticeable in the aircraft and aerospace industries. Fiber Metal Laminates (FMLs) were newer composites, with the aramid aluminum laminate (ARALL) type laminates having aluminium and Aramid/epoxy composites. Furthermore, the Cucurbitaceae fiber has been utilized to test the interlaminar shear strength (ILSS) of fiber metal laminates. This paper introduces the FML made of aluminium and Kevlar/Cucurbitaceae/epoxy layers. In addition, the chemical treatment has been employed to change the surface of Kevlar and Cucurbitaceae fibers to develop polar components, resulting in improved inter-phase strength of FML composites. To examine the ILSS characteristics of FML composites, four laminate sequence combinations were chosen. When compared to other sequencing hybrid FML composites, the ILSS of hybrid FML composites improved by 41.76 percent. This sequence of reinforcing fibers influences the degree of the laminate structure, which can substantially impact the ability to construct laminates. The ability of the composite-metal bonding to give strong adhesive characteristics was an essential aspect impacting the laminate properties as a whole. A scanning electron microscope was used to examine the treated fibers.

Keywords: *chemical treatment; fiber metal laminates; interphase; sequencing layer; surface modification.*

1. Introduction

Synthetic fiber-reinforced composite materials have gained prominence in recent years. It has a wide range of uses when compared to other common metallic materials due to its higher mechanical properties, lighter weight, unique flexibility, corrosion resistance, ease of production, and so on (Singh & Samanta, 2015). Kevlar has a wide range of applications among synthetic fibers because of its unique mechanical properties, such as high strength-to-weight ratio and impact resistance (Hallad et al., 2018; Lokeshkumar, Ramasamy, & Bak, 2020). Due to its high crystallinity and smooth fiber surface, Kevlar fiber exhibits poor interfacial bond with a matrix. Surface treatment techniques have been utilized to augment the polar components of the fiber surface to improve the adhesion capabilities of Kevlar fiber (Ramasamy, Arumugam, & Rajkumar, 2019; Ramasamy, Arumugam, & Sureshkumar, 2021). Further, authors have noted that surface treatment is vital in enhancing polymer composites' mechanical properties. In particular, Epoxy ChloroPropane (ECP) grafting on fibers effectively promotes the adhesion mechanism between fiber and matrix (Ravi et al., 2021; Wu & Cheng, 2006).

Natural fibers have also been widely employed in several applications for decades due to their benefits: strong, lightweight, rigid, recyclable, biodegradable, good thermal insulation, abundant in nature, and low cost and density (Alhijazi et al., 2020). However, the hydrophilic nature of natural fibers causes swelling and the formation of voids at the interface between the matrix and the fiber, resulting in poor mechanical properties of composites prepared with these fibers. Also, authors have reported that fiber surface modification is attributed to reducing non-cellulosic components (i.e., hemicelluloses and lignin) in the natural fiber. This could improve the performance of natural fiber-reinforced composites (Gholampour & Ozbakkaloglu, 2019). As a result, after surface modification of the fiber, the thermochemical and physicomechanical properties of natural fiber reinforced polymer composites were improved (Mohammed, Ansari, Pua, Jawaid, & Islam et al.2015). Natural fiber characterization was influenced by fiber source, fiber age, and fiber extraction procedure (Lotfi, Li, Dao, & Prusty, 2019). In particular, due to their Polyporus structure, availability, low price, and surface structure, which can give good adhesion with the matrix, luffa fruit includes lightweight natural fibers that can be used in reinforcing lightweight composites (Hariprasad, Ravichandran, Jayaseelan, & Muthuramalingam, 2020). According to Ramakrishnan et al., alkali treatment of luffa fiber increased tensile modulus and tensile properties by 12.18 percent compared to untreated luffa fiber (Ramakrishnan & Sathishkumar, 2019).

The main advantage of hybrid laminates has a positive balance to mechanical properties, achieved through a sandwich laminate structure. Consequently, the various Kevlar hybrid configurations were the prominent factor to improve impact properties in the sandwiched Kevlar fiber composites (Bigdilou, Eslami-Farsani, Ebrahimnezhad-Khaljiri, & Mohammadi, 2020). The FML hybrid composites consist of a thin metal layer and the fiber-reinforced polymer layer. It provides good mechanical properties with less weight. Furthermore, the coefficient of variation (CoV) of flexural strength ranged from 5.5 to 7.3 percent for hybrid FML composites (Bellini, Di Cocco, Iacoviello, & Sorrentino, 2019). However, surface treatments, polymeric composite mechanical properties, metal type, metal/polymer interface adhesion strength, and fabrication parameters significantly influenced the mechanical properties of FML composites. In particular, the failure of FML composites were significantly dependent on interfacial adhesion strength between metal and fiber-reinforced polymer layers (Eslami-Farsani, Aghamohammadi, Khalili, Ebrahimnezhad-Khaljiri, & Jalali, 2020). Additionally, the researchers concentrated on failure features such as fracture growth behavior in aluminium and composite layers and delamination between layers during bending in a certain stress state, depending on the material state and bending conditions (Alves, Prado, & de Paiva, 2019). Researchers have examined Carbon-reinforced aluminium laminated hybrid FML composites. Delaminations in the carbon composites layer, at the metal-composite interface, and between the glass and carbon composite layers were the most common types of laminate damage (Bieniaś, Jakubczak, Droździel, & Surowska 2020). Further, Zareei et al. (2019) investigated various sequences of FML composites. The ILSS of hybrid FML composites was shown to be raised by approximately 61.84 percent when compared to natural fiber sandwich structures (Zareei, Geranmayeh, & Eslami-Farsani, 2019). Furthermore, the researchers stated that the short beam shear test is commonly employed to determine the ILSS. Slightly interlaminar shear and inelastic deformation were seen at the layer interfaces in Kevlar Fiber Reinforced Epoxy (KFRE) composite laminates. With the addition of about 10% SiC particle content in KFRE specimens, the ILSS reveals quite high values. (Alsaadi, Ugla, & Erklig, 2017). Moreover, the AA6063 aluminium alloy has been used in industrial applications and has desirable mechanical properties of composite materials (Vijay Ananth, Jayaseelan, & Kumar 2019; Vijay

Ananth et al., 2020). Only some investigations on Cucurbitaceae fiber and natural fiber laminated FML composites have been reported in the prior study. The polymer/metal interface is the most vulnerable site for FML composite failure. Relevantly, research work is needed to fill the gap of interfacial characteristics in FML composites.

In context, this research work fills the gap in the area of hybrid FML composites. The Kevlar fiber and Cucurbitaceae fiber have been used for preparing the FML composites. The Kevlar fiber and Cucurbitaceae fiber surface were chemically modified using epichlorohydrin (ECH) treatment after 15wt% phosphoric acid and NaOH treatment, respectively. Both fibers were chemically treated for increasing the interlaminar strength of FML composites. The aluminium (AA6063) sheet was used for hybridization with fibers. Moreover, the various sequence layers were involved in evaluating hybrid FML composites' interlaminar shear strength properties. Finally, the surface morphology of treated fiber was discussed.

2. Materials and methods

2.1 Materials

Kevlar-29 (E. I. Du Pont India Pvt ltd) was employed in this investigation for FMLs composites, with an areal weight of 440 g/m2. FMLs were created utilizing aluminum (AA6063) sheets with a thickness of 0.3 mm and Cucurbitaceae fiber. The matrix ingredients for composite fabrication were epoxy resin (LY556), i.e., diglycidyl ether of bisphenol-A (DGEBA) with hardener (HY 951) in a 10:1 ratio, which was acquired from Sakthi fiberglass (India). As the chemical material for exterior fiber surface modification, phosphoric acids (PA), NaOH, Epichlorohydrin (E0581) with a minimum purity of 98 percent, and Acetone (analytical reagent grade) were utilized. These chemicals were purchased from Sudagar Biological and Chemicals (India). The FMLs composites are made using the hand layup process. Table 1 shows how the various sequence layers were employed to create the four types of FMLs specimens. Where [K] denotes a single layer of Kevlar fibers, [Cu] denotes Cucurbitaceae fibers in FMLs, and [A] denotes an aluminum sheet. An epoxy matrix reinforced these layers. Mechanical abrasion has also been employed to generate a rougher surface in the aluminum sheet.

2.2 Surface pre-treatment

2.2.1 Kevlar treatment

The cleaned Kevlar fabric was treated with 15% PA at 40°C for 2 hours, then washed with distilled water and dried at room temperature for two days. This treatment might activate oxygen functional groups and introduce polar hydroxyl groups on the Kevlar surface (Ramasamy et al., 2019). Besides, the PA pre-treated Kevlar was treated by epichlorohydrin (ECH) treatment. A 1% KOH solution was immersed in the pre-treated Kevlar fiber for 2 hours at room temperature, then rinsed with distilled water and dried for 48 hours. It was used as an initiator for grafting with ECH. The amino bond was hydrolyzed, and –COOK groups were added to the Kevlar fiber surface, after which the Kevlar fiber was grafted in epichlorohydrin for 1hour at 70 degrees Celsius. To minimize a severe reaction, acetone was used with ECH during the surface modification process, washed with distilled water, and dried in a vacuum oven, as illustrated in Figure 1(a) (Ramasamy et al., 2021; Wu & Cheng, 2006).

2.2.2 Cucurbitaceae fiber extraction

Firstly, Cucurbitaceae fruit is harvested from Cucurbitaceae trees. Protective clothing while stapling because breaking down the starch content may irritate. Finally, soak the Cucurbitaceae stem for five days in water at room temperature. This procedure could be used to collect wastes from the stem as well as fiber that is freely extracted from the stem. After that, the fiber was soaked in a bucket of 20 litres of water and dried at room temperature for 48 hours. Figure 1 (b, c) shows how the metal brush removes undesirable particles, resulting in uniform fibers.

2.2.3 Cucurbitaceae fiber treatment

For 30 minutes at room temperature, the extracted Cucurbitaceae fiber was hydrolyzed in a 10% aqueous NaOH solution. Following that, the fibers were thoroughly rinsed with clean water and allowed to air dry for 24 hours at room temperature. The fibers were then dried in a vacuum oven at 110°C for 24 hours (Chatzi, Tidrick, & Koenig, 1988). Carboxylic groups may occur as a result of surface treatment. This could be related to the elimination of fiber lignin and hemicellulose.

2.3 Short beam testing

The interlaminar shear strength of FML composites was determined using a short beam test. The FML specimens and test equipment were prepared following ASTM D 2344 (Zhang, Huang, He, Wu, & Xu, 2008; Alsaadi et al., 2017) and had dimensions of 30x8x5 mm^3. Figure 2(a) depicts the testing procedure, with the specimen's span to thickness ratio and length to thickness ratio equal to 4 and 6, respectively. The short beam testing was performed on a UTM machine with a 2mm/min crosshead speed, as illustrated in Figure 2 (b). The specimen was prepared in five layers with different layer sequences utilizing Kevlar fabric, Cucurbitaceae fiber, and aluminium sheet, as indicated in Table 1. In each example, four samples were analyzed, and the average values were used to interpret the results. The ILSS was calculated using the empirical relationship shown in equation 1 (Lin, Wu, Lai, & Shyu, 2000).

$$ILSS \frac{0.75P_m}{bh} \qquad (1)$$

Where P_m represents the maximum amount of load obtained while b and h are the respective sample width and thickness.

Table 1 Samples sequence configurations

Sequence Configuration	Types of Samples	Volume percentage (%)			Thickness(mm)
		K	Cu	A	
(A/K/Cu/K/A)	S1	40	20	40	5.03
(Cu/K/A/K/Cu)	S2	40	40	20	5.17
(K/Cu/A/Cu/K)	S3	40	40	20	5.08
(Cu/Cu/A/K/K)	S4	40	40	20	5.14

Figure 1 (a) Virgin Kevlar fiber, (b) Before extracted Cucurbitaceae fiber, (c) Extracted Cucurbitaceae fiber

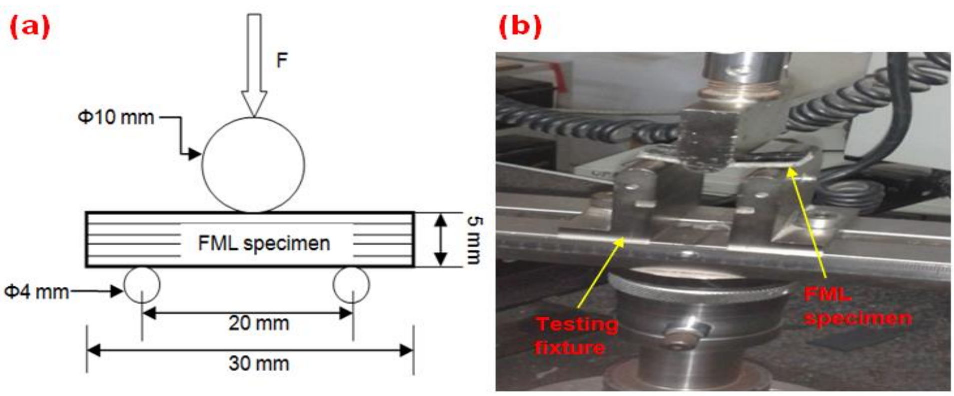

Figure 2 (a) Short beam testing configuration, (b) Experimental setup for Short Beam Shear Test

3. Results and discussion

3.1 Short beam testing

The load-displacement curve of FML hybrid composites is depicted in Figure 3. The S3 sample (K/Cu/A/Cu/K) demonstrated a higher load (2106 N) with a higher failure strain of 7.55mm. This could be due to the outer Kevlar fiber layer having greater load resisting strength, resulting in increased strain to failure (Alsaadi et al., 2017). Cucurbitaceae fiber was used as the outer layer in sample S2 (Cu/K/A/K/Cu), resulting in a lower strain to failure and flexural load (1987 N) due to the fiber's irregular surface and proclivity to absorb moisture. When compared to the other samples, sample S1 (A/K/Cu/K/A) had a higher load resistivity (2404.6 N). The outer layer of FML composite laminates can withstand more load than the interior layers. Aside from that, Kevlar fiber promotes considerable adhesion between aluminium and fiber layers (Zareei et al., 2019). In addition, the S4 (Cu/Cu/A/K/K) sample had a lower load (1663 N) than the other samples. This could be due to a lack of adhesion with the metal layer. As a result, the outer layer hybridization of Kevlar and Cucurbitaceae fiber promotes greater strain energy absorption than the S2 sample.

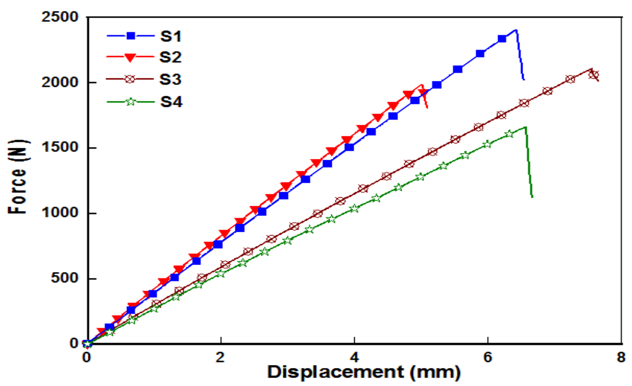

Figure 3 Load versus displacement curve

3.2 Interlaminar shear strength

The ultimate flexural load of FML composites is depicted in Figure 4(a). The ultimate loads of the S1, S2, S3, and S4 samples were 2404.6 N, 1987 N, 2106 N, and 1663 N, respectively. The S1 sequence sample outperformed the S3 and S2 sequence composites by 14.15 percent and 20.98 percent, respectively. This could be because Kevlar fiber has a stronger fiber/matrix contact than Cucurbitaceae fiber and aluminum layer. After all, Kevlar fiber has a special surface treatment that is entirely compatible with epoxy matrix (Alves et al., 2019). Figure 4(b) also showed the interlaminar shear strength of FML hybrid composites. S1, S2, S3, and S4 samples had ILSS of 45.08 MPa, 37.25 MPa, 39.49 MPa, and 31.8 MPa, respectively. The aluminum and Kevlar fiber outer layer in the FML composites was associated with greater ILSS across all sequencing composites. This could be because an interlaminar shear failure occurred less frequently at the interface between the layers (Alsaadi et al., 2017). Cucurbitaceae fiber outer layer has lower interlaminar shear strength. Additionally, it was discovered that a lack of diffusion resulted in the existence of empty gaps between the Cucurbitaceae fiber fibrils, which were the primary source of mechanical property degradation (Ramakrishnan & Sathishkumar, 2019). Additionally, each Cucurbitaceae fiber fibril and the epoxy may significantly affect the stress transfer from the matrix to the fibrils (Zareei et al., 2019). The S3 sample (K/Cu/A/Cu/K) has improved considerably in ILSS because the alkali-treated Cucurbitaceae fiber induces significant interfacial adhesion between the aluminum and Kevlar fiber layer.

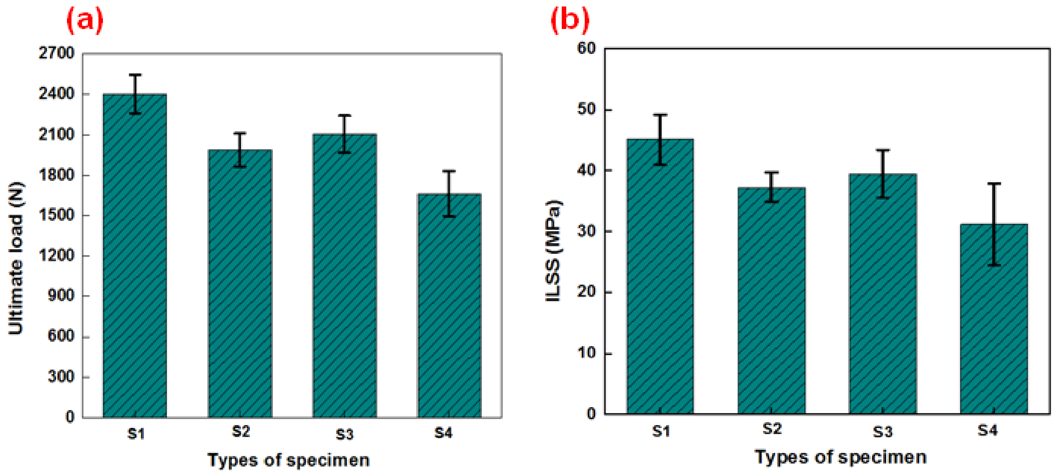

Figure 4 FML composites of (a) ultimate load (b) Interlaminar shear strength

3.3 Fiber surface morphology

The surface morphology of treated Kevlar fiber and Cucurbitaceae fiber was examined using a scanning electron microscope. The surface of treated Kevlar fiber is depicted in Figure 5(a). It was demonstrated that the surface treatment was responsible for boosting the rough surface to improve the adhesion mechanism between the matrix and fiber system. In addition, small microstructures were added to facilitate mechanical interaction with the matrix (Ramasamy et al., 2021). As a result, Figure 5(b) depicts the surface shape of Cucurbitaceae fibers. It was discovered that alkali treatment removed lignin and cellulose from raw extracted fiber, resulting in a rougher surface on the fiber surface. Furthermore, the fibrillated and flake structure of the fibers increased interfacial adhesion with the epoxy matrix (Alhijazi et al., 2020; Ramakrishnan & Sathishkumar, 2019).

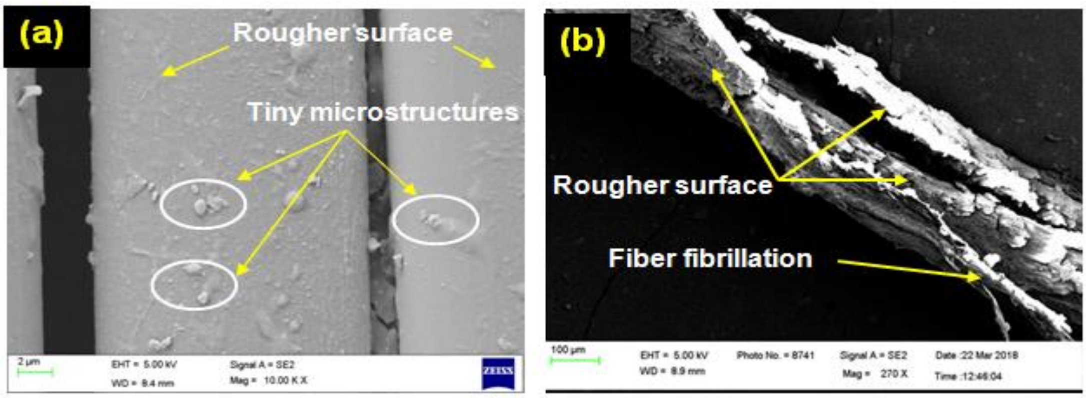

Figure 5 Surface morphology of treated (a) Kevlar fiber(b) Cucurbitaceae fiber

4. Conclusions

In the current work, a portion of Kevlar fiber is replaced by natural fiber in Kevlar Reinforced Aluminium Cucurbitaceae Laminate to lower the high cost of Kevlar and create a pollution-free environment, and its mechanical performance is examined. The interlaminar strength properties of FML hybrid composites have been observed. S1 (A/K/Cu/K/A) sample FML composites had 14.15 percent and 21.02 percent higher interlaminar shear strength than S3 (K/Cu/A/Cu/K) and S2 (Cu/K/A/K/Cu) sample FML composite laminates. Furthermore, fiber surface treatment has a significant role in improving the interphase of FML composites. Finally, the novelty of the current experiments revealed that surface modification of both Kevlar and Cucurbitaceae fibers promoted increased ILSS with optimum sequencing layers in FML composites.

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