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EXPERIMENTAL INVESTIGATION ON THE EFFECT OF GRAPHENE ADDITION ON MECHANICAL PROPERTIES OF Al8011-T6 BASED FIBER METAL LAMINATE

Abstract: In the present study, the tensile and flexural properties of lightweight fiber metal laminates composed of Al8011-T6 and carbon fiber/epoxy resin filled with varying weight percentages of graphene (0.0, 0.3, 0.6, 0.9, and 1.2 wt%) were examined under quasi-static loadings for automobile applications. Fibre-metal laminates having different stacking sequences of the same layer thickness are manufactured using the hand layup process. Surface treatment was performed on Al8011-T6 sheet in order to get good adhesion between aluminium and epoxy. With the optimum content of 0.6 and 0.9 wt% of graphene, the tensile and flexural strengths were improved by 15% and 25%, respectively, compared to aluminium fiber metal laminates without graphene for 0/0 fiber layup orientation.

Keywords: Fibre metal laminate; aluminium; Tensile strength; Flexural strength; Graphene; Carbon fibre

1. Introduction

Fibre-metal laminates are composed of a plies of fiber-reinforced prepregs and a thin layer of metal alloys [1-5]. They have outstanding properties such as lightweight, fatigue resistance, high specific strength, stiffness, and impact resistance at low velocity. FMLs are widely used in the automobile and aerospace industries, such as the fuselage structure of composite wings in the Airbus 320, Boeing's 737, Hercules C130 aircraft, the upper fuselage and tail leading edge of the Airbus 380, and the cargo door of McDonnel [6-9]. Different kinds of fiber-metal laminates have been developed depending on the constituents, such as fibers (aramid, carbon, and glass) and metals such as steel, titanium, aluminium and magnesium. During the fabrication of composites, graphene is used as a nanofiller in resin matrices for enhancing thermal conductivity, electrical conductivity, flexibility, stiffness, durability, UV resistance, fire resistance, and weight reduction. It also enhances toughness and impact resistance, eliminates microcracking defects in a composite laminate, and reduces interlaminar shear failure. It is reported that nanofillers are added to FMLs to enhance their functional and mechanical properties. The nanofillers could be metal nanoparticles, carbonaceous materials, or inorganic materials, i.e., Al, Cu, MWCNTs, graphite, graphene oxide, TiO_2, Al2O3, and SiO_2.

Bahari Sambran et al. [10] studied the effect of the addition of nanoclay on the mechanical properties of aluminium and basalt fibers in an epoxy metal laminate. Surface-modified nanoclays of different weight percentages (1, 3, and 5 wt%) were added to epoxy resin and mixed with a mechanical mixer and ultrasonic waves for adequate dispersion. A hand-layup process was used for the fabrication of fiber-metal laminate. Results indicated that impact strength was increased due to the enhancement of the interfacial properties of basalt fibers and epoxy and the formation of physical entanglement by the addition of surface-modified nanoclays. Fiber metal laminate consisting of 3 wt% nanoclay had higher absorption energy compared to 5 wt% nanoclay due to agglomeration and improper dispersion of nanoclay at higher concentrations. Zhang et al. [11] studied the effect of the addition of different weight percentages of MWCNTs (0.5, 1, and 2 wt%) on the enhancement of the flexural properties of glare fiber metal laminates. It was found that there was an enhancement of 40.3% in flexural strength when 0.5 wt% MWCNTs were added to Glare FMLs. The flexural performance of glare also increased by 1 wt% and 2 wt% in comparison to glare alone. The addition of a higher weight percentage of nanofillers results in the aggregation of the particles and contributes to the formation of enclosed air bubbles in the atmosphere. These aggregations act as stress concentrations that cause cracks in the nanocomposite laminate, which results in early failure [12-14]. Many researchers have

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reported that there is an enhancement of mechanical properties when 1 wt% of nanofillers are added to epoxy resin [15-19]. To the best of our knowledge, the mechanical overall performance of Al8011-T6 FMLs comprising graphene, focusing on tensile and flexural properties, has not been studied. Therefore, in this study, with the aim of enhancing the tensile and flexural properties of Al8011-T6 FMLs, graphene in 0.0, 0.3, 0.6, 0.9, and 1.2 wt% is added to epoxy resin.

2. Experimental work

2.1. Materials

Aluminium 8011 sheets having a thickness of 0.5 mm are used as metallic layers in fiber metal laminate. The composition of Aluminium 8011in mass percentages includes Fe-0.65, Si-0.70, Zn-0.10, Mn-0.20, Cu-0.10, Cr-0.05, Ti-0.08, Mg-0.05, and Al-98.07. Al8011 sheets were strengthened to the T6 state by solutionizing at 530°C for 1 hour, then quenching in ice, subsequently aging for 6 h at 175°C, and later cooling in air. Al8011-T6 has higher strength, better formability, excellent corrosion resistance, and stiffness, which are basically used in automobile applications. Unidirectional carbon fiber was used, having a weight of 600 GSM, a thickness of 0.33 mm, a Young's modulus of 2.32×10^5 MPa, and a Poisson's ratio of 0.22. The epoxy resin used in fiber metal laminate had a specific gravity of 1.16 g/cc, a viscosity of 650 mPa.s at 27°C, and a pot life of 1.5 hours. The nanofiller used is graphene, which has a bulk density of 0.01 g/cm^3, a thickness of 5-10 nm, a surface area of 60-200 m^2/g, and a number of layers of 1-5.

2.2. The surface treatment of aluminium 8011-T6 sheets

Surface treatment is performed on metallic layers after heat treatment in order to have excellent bonding between aluminium sheets and polymeric composite laminate. Initially, the surface of aluminium sheet was abraded by grit-size 200 abrasive sandpaper and cleaned using acetone and then distilled water. Further, the aluminium sheets were dipped in a volume of 10% HCL acid solution for 30 minutes to roughen the surface, soaked in 5 wt% NaOH solutions, and then cleaned in distilled water and dried in a heating oven.

2.3. Fabrication of Al8011-T6 based FML samples

The fabrication of Al8011-T6-based FMLs was performed after surface treatment by hand layup process. The resin to hardener ratio used in fabrication was 100:18 by weight, as recommended by the manufacturer. As the first step, graphene was mixed with epoxy resin at different weight percentages (0.0, 0.3, 0.6, 0.9, and 1.2 wt%) for 30 minutes at 2000 rpm to obtain an adequate dispersion with the hardener agent. The next lay-up process was used in accordance with the designed lay-up configuration (refer to TABLE 1) by stacking the 250 mm×250 mm layers of the Al8011-T6 sheets and plies of the unidirectional CF/E prepregs. A flat plate fixture with a dimension of 50×50 cm^2 was used for applying uniform pressure on FML plates. Specimens were pressed for 24 hours at 4 bars at room temperature to cure completely. Finally, manufactured Al8011-T6-based FMLs were cut by the abrasive water jet cutting technique.

2.4. Mechanical testing

2.4.1. Tensile testing

Standard tensile specimens of Aluminium 8011-T6 based fiber metal laminate, comprising different orientations of carbon fiber and graphene-filled epoxy resins, were tested in the electromechanical testing machine at a cross-head speed of 2 mm/min according to the ASTM E8M standard. Five specimens, each with a combination of dimensions of 250 mm×25 mm, were tested and the average values are reported.

$$\sigma_{ult} = \frac{P_{\max}}{bh} \tag{1}$$

σ_{ult} is the ultimate tensile strength, b and h refer to width and thickness of laminate.

2.4.2. Flexural testing

Specimens for flexural testing were tested according to the ASTM D2344-84 standard at a speed of 1mm/min in an electromechanical testing machine for Aluminium 8011-T6-based fiber metal laminate comprised of different orientations of carbon fiber and graphene-filled epoxy.

TABLE 1

Investigated types of Al8011(T6)-CF FMLs

Al8011(T6)-CF FML		Metal layer	Fibre layer		
Specimen type	Notation	Thickness per metal layer (mm)	Notation	Number of UD CF/E prepreg plies	UD CF/E prepreg lay-up orientation
1	Al8011(T6)-CF 0.5/2P	0.5	CF/E 2P	2	0°/0°
2	Al8011(T6)-CF 0.5/2Q	0.5	CF/E 2Q	2	90°/90°
3	Al8011(T6)-CF 0.5/2R	0.5	CF/E 2R	2	0°/90°
4	Al8011(T6)-CF 0.5/3S	0.5	CF/E 3S	3	0°/90°/0°

Five specimens of dimension 150 mm×20 mm from each combination were tested for the determination of flexural strength and average values were reported.

The flexural strength of tested composites is determined according to the equation

$$\sigma_B = \frac{3Pl}{2bh^2} \tag{2}$$

Where, L represents support span length and P is maximum flexural load.

3. Results and discussion

The tensile strength of samples containing 0.6 wt% graphene in cases of 0°/0°, 90°/90°, 0°/90° and 0°/90°/0° fiber layup orientations is enhanced by 15%, 17.5%, 18%, and 17.8%, respectively, in comparison to similar samples without graphene content, as shown in Figs. 1(a) to 1(d). Therefore, it is concluded that the incorporation of graphene in enhancing the load transfer mechanism and interface characteristics from matrix to fiber is important.

According to Figs. 1(a) to 1(d), the tensile strength of all samples containing 1.2 wt% graphene has decreased in comparison with the similar samples containing 0.3, 0.6, and 0.9 wt%. This is due to the agglomeration and improper distribution of graphene in high concentrations. A graphene agglomeration causes the formation of stress concentration points and leads to failure at the interface of the fiber matrix. Further, increasing the concentration of graphene in the resin leads to the formation of air bubbles in the mixture, which cause defects and finally deteriorate composite properties [20-21]. Fig. 2 depicts the average ultimate tensile strength values of Aluminium fiber metal laminates with different wt% of graphene and various fiber lay-up orientations. The highest tensile strength was obtained by adding 0.6 wt% graphene powder to the composite laminate for different fiber lay-up orientations. Fig. 3 shows the damage mechanisms in Aluminium fiber metal laminates with varying wt% graphene content subjected to tensile loading. Delamination and separation between metal layers and composite laminates were observed in samples without graphene content. Delamination is due to weak bonding between carbon fiber/epoxy composite and Al8011-T6 sheets. However, the addition of 0.6 wt% graphene content enhances the bonding between Al8011-T6 sheets and composite laminate in comparison to samples containing 0.3, 0.9, and 1.2 wt% graphene content. The failure occurred due to carbon fiber breakage without debonding between composite laminate and Al8011-T6 sheets. These results are consistent with the Megahed et al. [22] study.

Fig. 4 shows the SEM of tensile fractured surfaces of composite laminates filled with and without different wt% of graphene. As shown in Fig. 4a, in the unreinforced sample, fiber pullout and debonding between carbon fibers and matrix exist, which indicates poor adhesion between carbon fibers and epoxy resin. Whereas, as can be seen in Figs. 4b-c, in the samples filled with graphene, the epoxy matrix is perfectly bonded to the carbon fibers, indicating improved adhesion between the matrix and carbon fibers compared to the unreinforced samples, resulting in increased strength. Poor adhesion between carbon fiber and epoxy resin is shown in Fig. 4d, which is filled with 1.2 wt% graphene is due to the agglomeration of graphene, resulting in decreased strength of composite laminates. This phenomenon

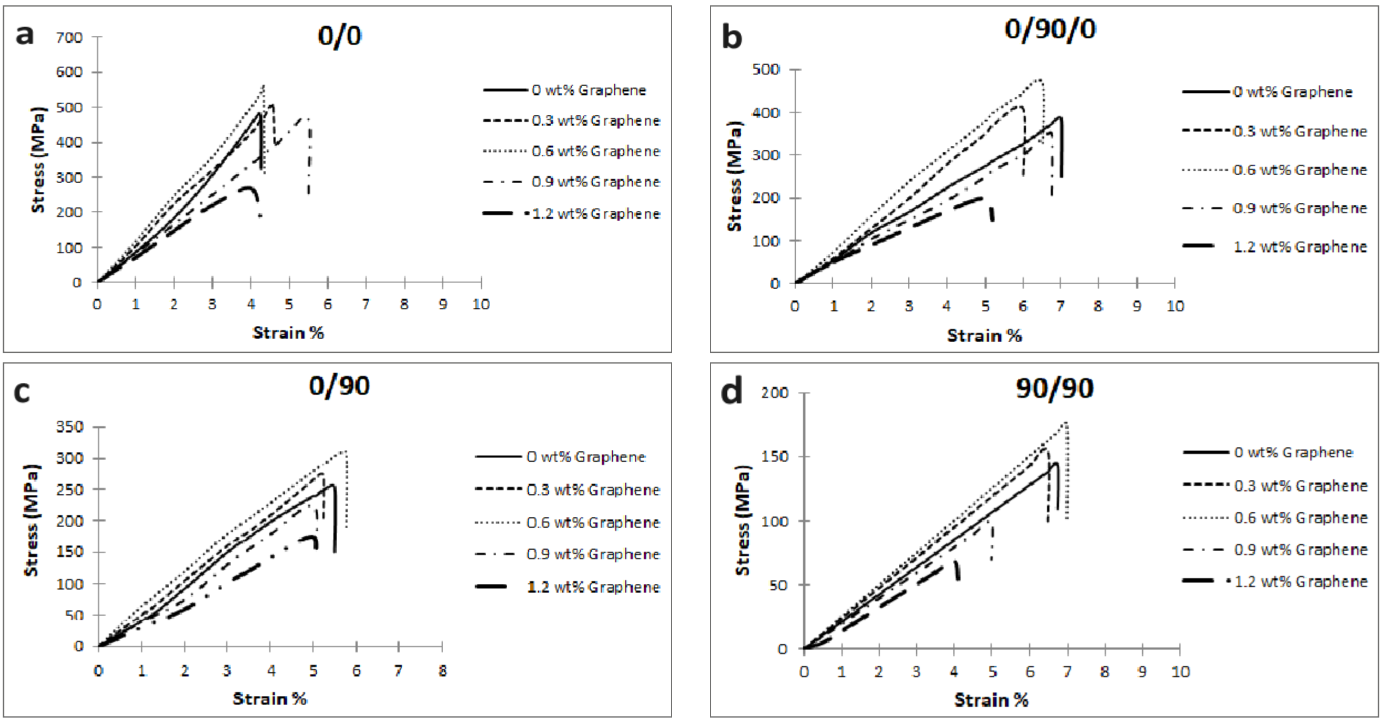

Fig. 1. Stress strain curve of Aluminium fiber metal laminates with different wt% of Graphene (a) 0/0, (b) 0/90/0, (c) 0/90, d) 90/90 fiber layup orientations

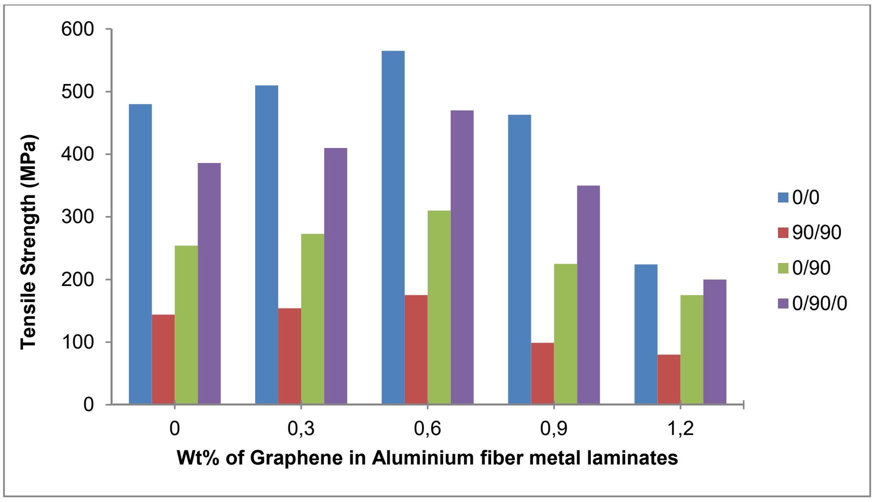

Fig. 2. Ultimate tensile strength of Aluminium fiber metal laminates with different wt% of Graphene

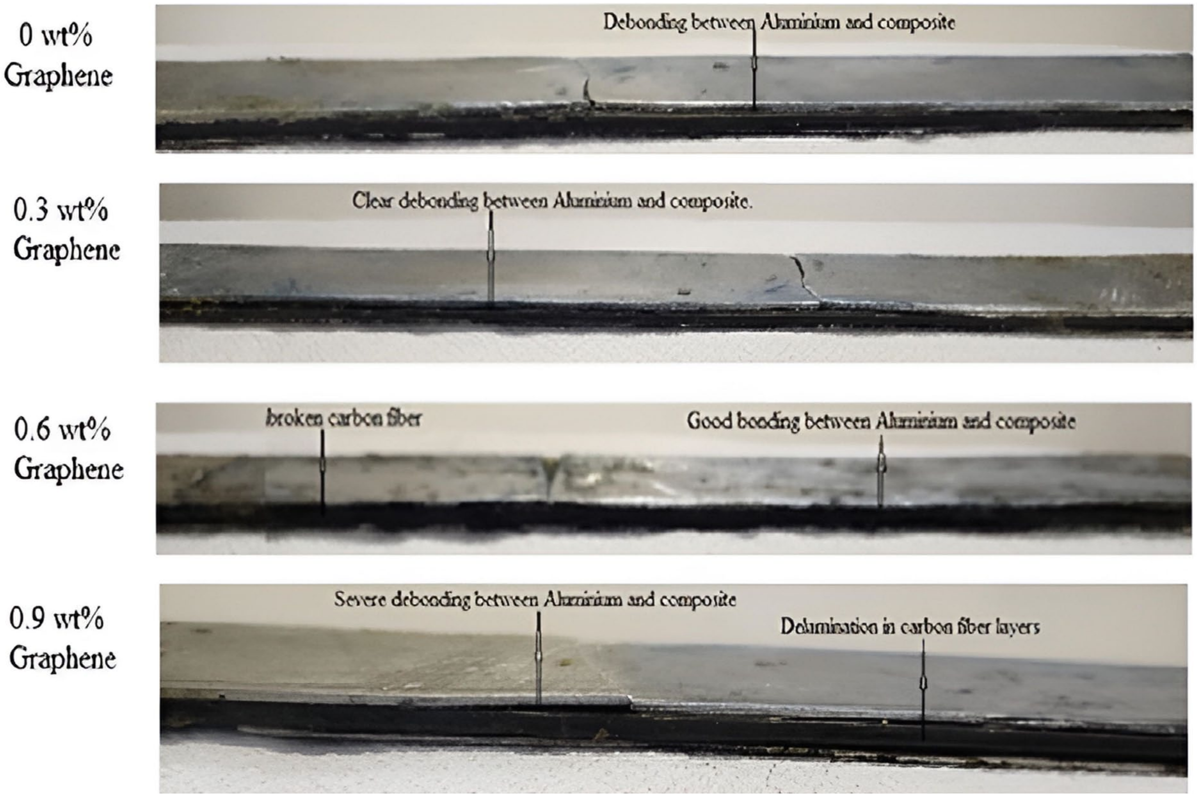

Fig. 3. The damage mechanism of Aluminium fiber metal laminates with different wt% of Graphene subjected to tensile loading

was also observed by Afshin et al. [23]. They studied the reinforcement of nanoclay in fiber-metal laminates. Nanoclay was reinforced in different weight percentages (0, 0.5, 1, 2, 4 wt%) in the composite fiber metal laminates. They found that the fracture toughness of FML with 0.5 wt% of nanoclay increased double-fold compared to the fracture toughness of FML without nanoclay. However, further addition of nanoclay results in a reduction of fracture toughness due to the agglomeration of nanoclay particles.

The flexural strength of samples containing 0.9 wt% graphene in cases of 0°/0°, 90°/90°, 0°/90° and 0°/90°/0° fiber layup orientations is enhanced by 25%, 33%, 24%, and 18%, respectively, in comparison to similar samples without graphene content, as shown in Figs. 5(a) to 5(d). Hence inclusion of optimal nanoparticles in fiber metal laminates, contributes to light weight, high performance, low fuel consumption, reduced manufacturing cost and enhanced safety in the automotive industry [24]. Fig. 6 depicts the average flexural strength values of Aluminium fiber metal laminates with different wt% of graphene and various fiber lay-up orientations. The highest flexural strength was achieved with the incorporation of 0.9 wt% graphene powder in the composite laminate of FMLs for different fiber lay-up orientations. Fig. 7 shows the damage mechanisms in Aluminium fiber metal laminates with varying wt% graphene content subjected

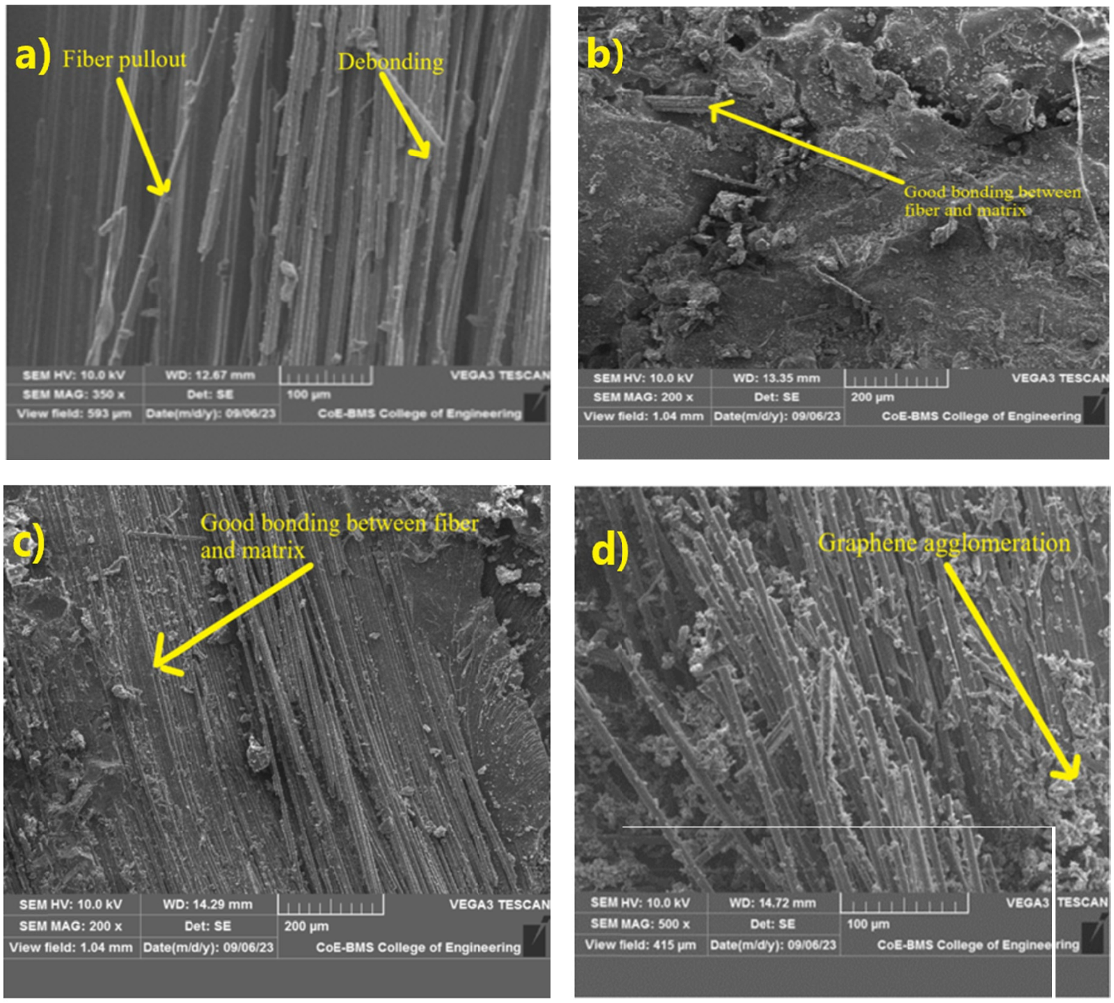

Fig. 4. SEM images of tensile fracture surface of carbon fibers/epoxy a) without Graphene b) 0.3 wt% Graphene c) 0.6 wt% Graphene d) 1.2 wt% Graphene

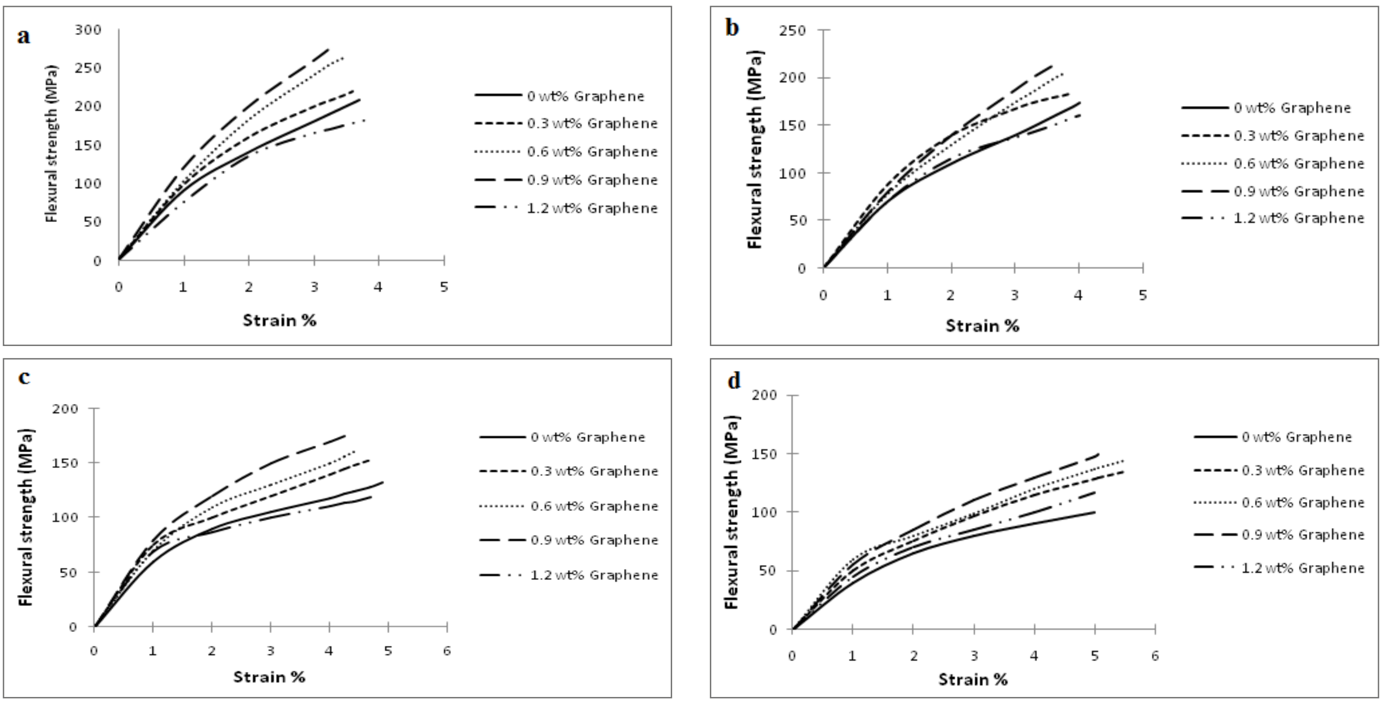

Fig. 5. Flexural behaviour of Aluminium fiber metal laminates with different wt% of Graphene (a) 0/0, (b) 0/90/0, (c) 0/90, d) 90/90 fiber layup orientations

to flexural loading. Debonding between the composite laminate and outer Al8011-T6 sheets is observed in samples without graphene content, indicating poor adhesion. Whereas, in samples containing 0.9 wt% graphene content, the composite laminate is perfectly bonded to Al8011-T6 layers in comparison to samples containing 0.3,0.6, and 1.2 wt% graphene content. These results are consistent with the Sadegh et al. [25] study.

Fig. 8 shows the SEM of flexural fractured surfaces of composite laminates filled with and without different wt% of graphene. As shown in Fig. 8a, in the unreinforced sample, fiber breakage and debonding exist between carbon fibers and matrix, which indicates poor adhesion between carbon fibers and epoxy resin. Whereas, as can be seen in Figs. 8b-c, in the samples filled with graphene, better mechanical interlocking between the carbon fibers and matrix exists, resulting in enhanced strength of the composite in comparison to the unreinforced sample. Graphene agglomeration is observed in Fig. 8d, which is filled with 1.2 wt% graphene, resulting in weak interfacial strength between carbon fiber and epoxy matrix. These phenomena were also observed by Farzad et al. [26]. They studied the role of MWCNTs and the mechanical properties of the adhesive joints between glass fibers, polyvinyl chloride matrix, and aluminium 1050. They reinforced 0, 0.5, 1, and 1.5 weight percentages of MWCNTs in the composite laminate. They found that the tensile and flexural strengths of the MWCNT-reinforced specimens increased by adding up to 1 wt% of MWCNTs. Further addition of MWCNTs resulted in

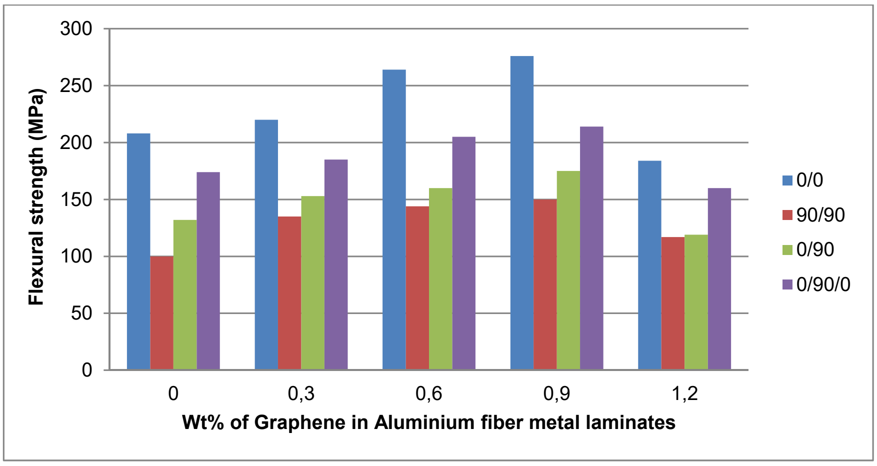

Fig. 6. Flexural strength of Aluminium fiber metal laminates with different wt% of Graphene

Fig. 7. The damage mechanism of Aluminium fiber metal laminates with different wt% of Graphene subjected to flexural loading

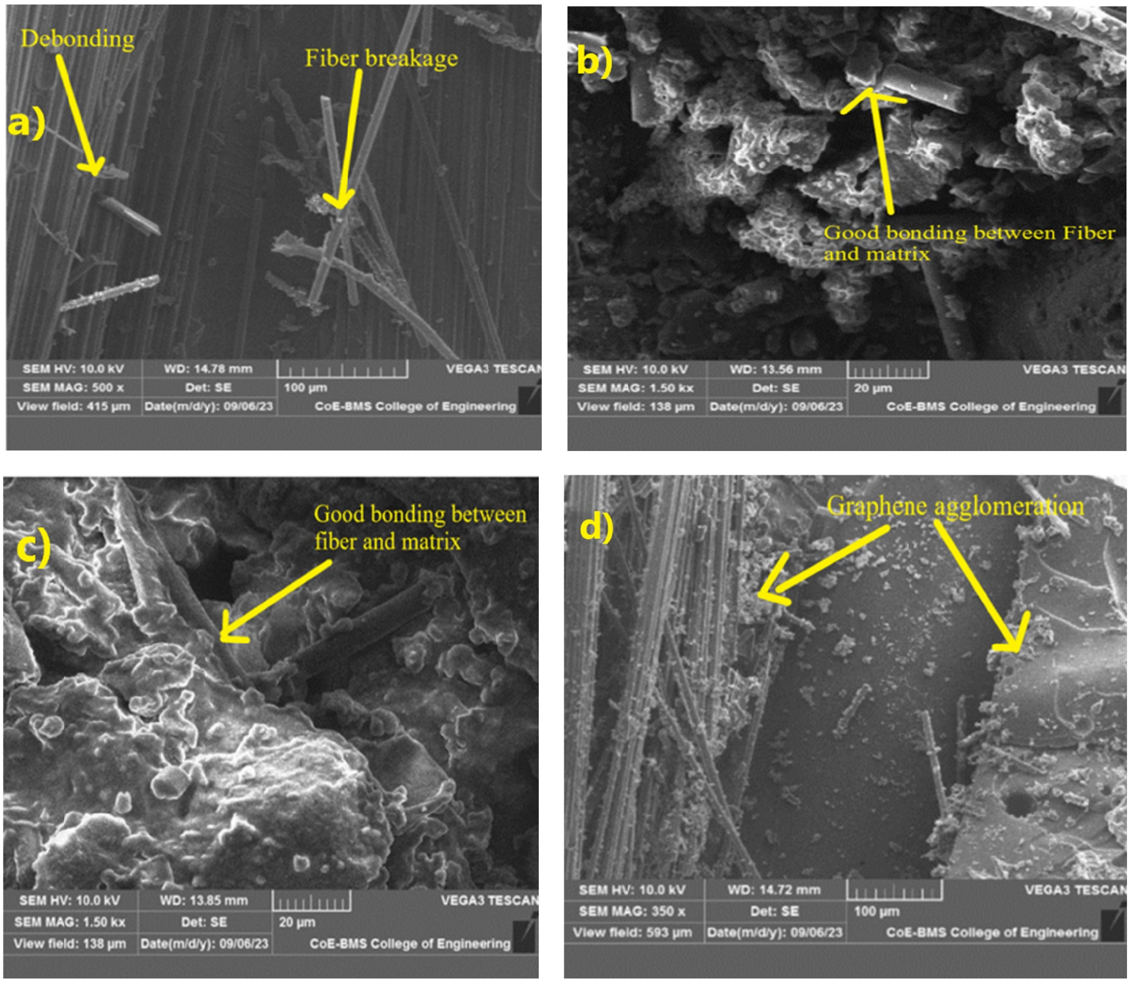

Fig. 8. SEM images of flexural fracture surface of carbon Fibers/epoxy a) without Graphene b) 0.6 wt% Graphene c) 0.9 wt% Graphene d) 1.2 wt% Graphene

the agglomeration of MWCNTs so that the tensile and flexural strengths were reduced in comparison to unreinforced specimens.

4. Conclusion

In this study, the effect of adding graphene content on the mechanical behavior of Al8011-T6/carbon fiber/epoxy laminates with different fiber layup orientations was investigated. The tensile strength of samples containing 0.6 wt% graphene in cases of 0°/0°, 90°/90°, 0°/90° and 0°/90°/0° fiber layup orientations is enhanced by 15%, 17.5%, 18%, and 17.8%, respectively, in comparison to similar samples without graphene content. The flexural strength of samples containing 0.9 wt% graphene in cases of 0°/0°, 90°/90°, 0°/90° and 0°/90°/0° fiber layup orientations is enhanced by 25%, 33%, 24%, and 18%, respectively, in comparison to similar samples without graphene content. Hence, 0.6 wt% graphene is suitable for best ultimate tensile strength and bonding properties with most favorable layup orientation is 0/0°. Damage mechanisms observed in samples subjected to tensile loading include delamination, fiber breakage, and separation between metal layers and composites. However, the addition of 0.6 wt% graphene content enhances the bonding between Al8011-T6 sheets and composite laminates. Damage to samples caused by flexural loading is seen as debonding and delamination between composite layers. However, the addition of 0.9 wt% graphene content enhanced the bonding between the metal layers and the composite. Further research is required for increasing the bonding between Al8011-T6 and carbon fiber by using different surface treatment techniques, innovative nanoparticles, and the different properties of Al8011-T6/carbon fiber/epoxy composites should be analyzed using different equipment such as atomic force microscopy, x-ray photoelectron spectroscopy, fragmentation tests, and zeta potential measurements.

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