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Investigating the Phenomenon of Flutter as well as the Mechanical and Microstructural Properties of Layered Composite of Aluminum Sheet with An Epoxy Matrix Reinforced with Carbon Fibers

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ABSTRACT

Flutter is an example of an aero-elastic phenomena that involves analyzing the interaction between elastic and aerodynamic forces, both static and dynamic. This study examined the effects of the stacking of polymer and aluminum layers on the modal frequency, drop weight impact, and tensile characteristics of polymeric composites and Fiber Metal Laminates (FMLs) incorporating carbon fibers. In this study, Carbon Fiber Reinforced Plastic (CFRP) laminates were used in the FML composite specimen. Based on a hand-lay-up method, 20 layers of carbon fiber prepregs were used to fabricate the specimen, i.e., Al/4CFRP/Al (Al2C1) and then, Al/4CFRP/Al/4CFRP/Al (Al3C2) fiber metal laminates with two stacking arrangements were made. The surfaces of the aluminum sheets were treated through an anodizing method to improve the adhesion between aluminum and polymer layers. The fracture surface of the specimen was investigated using Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). The mechanical properties along with the vibration behavior of specimen were also studied accordingly. The results showed that Al3C2 had the greatest values of the required frequency for vibration and lowest stress brought on by vibration, with 0.0008 MPa for the initial state. Additionally, the FML sample demonstrated a higher frequency and less stress from vibration than the CFRP specimen with the same thickness. According to the findings of the impact tests, CFRP and Al3C2 had the lowest (210 KJm^{-2}) and the highest (960 KJm^{-2}) values, respectively. However, due to the lower weight of Al2C1 than that of Al3C2, the specific absorbed energy value of the former was higher (4.7 Jm^2kg^{-1}) than that of the latter (2.3 Jm^2kg^{-1}). In tensile testing, Al3C2 was characterized by the best tensile properties (i.e., yield strength of 580 MPa and ultimate tensile strength of 897 MPa) compared to other samples. The current study demonstrated that compared to other specimen, Al3C2 possessed the least potential to flutter occurrence in a possible real situation.

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1. INTRODUCTION

Aerospace, shipbuilding, and automobile industries all utilize polymer-based composites which are a significant form of composites in general. In recent years, metal sheets have been replaced by polymer composites due to

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their great mechanical strength, low cost, and outstanding corrosion and chemical resistance [1]. Fiber Metal Laminates (FMLs) composites are a new kind of polymer-based composites made of sheet metal and fiber-reinforced polymer composites. Various types of FML have been developed to date to reduce the weight of products so as to replace aluminum alloys with the FML composites in automotive and other relative applications [2]. FML composites have facilitated the production of materials with acceptable mechanical and physical properties thanks to their strong impact resistance, convenient repair conditions, high fatigue resistance, low density, and reaso nably excellent stiffness [3]. Aluminum, titanium, magnesium, and steel alloys are suitable candidates for the metal layer in FML [3,4]. In addition to its affordable costs in comparison to other choices, aluminum also has good mechanical and chemical qualities [5]. FML composites employ many aluminum alloy grades including 2024 and 7075. The excellent mechanical qualities of these types of alloys such as their high fracture toughness, strong strength, and inexpensive cost have made them a popular and interesting option in a wide range of applications in FML composites [4,6]. To ensure the greatest functioning of the finished components, a strong mechanical link between these layers must be maintained. The mechanical characteristics of the finished composites are improved by a higher degree of adhesion between the layers of the composite and metal sheet.

A number of techniques can be used to improve the adhesion among the composite layers such as providing the mechanical connections (such as bolts and nuts) and using the bonding agents (such as binders), to name a few. It should be noted that the surface modification of aluminum (as metal sheet) is also necessary sometimes and in this regard, surface modification techniques using chemicals, electrochemistry, and mechanics can be useful [2]. Abdullah et al. [7] investigated the composites consisting of woven fibers of glass and polypropylene resin and aluminum sheets under high-speed impact experiments. Based on the test results and an analytical method, they concluded that the energy required to break the specimen in GLARE was higher than that needed for a multi-layer aluminum sheet.

Sadighi et al. [8] investigated the effect of the number and arrangement of fibers and aluminum layers on the FML composite properties. They discovered that the samples with more layers of aluminum exhibited higher impact resistance than those with more layers of polymer. They further evaluated the impact resistance of the multilayer fiber-metal composites made of different metals with various thickness values under low-speed impacts. They discovered that increasing the thickness of the aluminum layer improved the performance of the composite under impact and increased the mass of the layer. Therefore, it can be suitably used in cases that do not require lightweight components only. In the current work, FML composites with various configurations of aluminum sheets and polymer composites were used to evaluate their vibration, tensile, and impact characteristics and factors controlling these qualities. Another noteworthy advantage of the FMLs is that their mechanical characteristics can be easily modified to meet some particular requirements by altering the direction, thickness, and number of layers in the composite. The components that make up FML each have unique qualities that interact to produce a complicated pattern of the mechanical failure behavior (metal layers are pliable while the composite layers are brittle). Iaccarino et al. [9] found that the bending properties of Carbon Fiber Reinforced Aluminum Laminates (CARALLs) were dependent on the bond between the composite sheet and aluminum layers while the tensile properties were not affected. Poor bonding can reduce the interlayer shear strength by about 10 times.

They also discovered that despite a minor reduction in the strong bonded specimen, the bond strength had no effect on the residual strength of a slit specimen. In order to determine the stress-strain curve, residual strain in relation to a particular stress level, and stress-shear curve, they did some experiments on the FMLs. Based on a comparison between the numerical data and experimental results, they proposed a modified classical lamination model. Although the results did not match their predictions in all cases of failure, they were successful in developing a reasonable model overall.

Dhaliwal and Newaz [10] studied the effect of the position of the metal layers on the stacking materials and then, they produced and tested some CARALL specimens using carbon fiber laminates as the outer layers. The regular CARALL, which featured aluminum laminates as the outer layers, was compared to their laminates and the bending behavior they exhibited, and it was discovered that the former had more strength than the latter.

The impact behavior of the fiber metal sheets has been thoroughly studied in recent years. Abdullah and Cantwell [7] studied the impact behavior of the glass fiber-reinforced polypropylene FML and found that FML offered excellent impact resistance under low-to-high velocity loads. Their findings showed that the FMLs absorbed energy through plastic deformation in aluminum and micro-cracks in composite layers [11].

The improved mechanical characteristics are provided by manufacturing the aluminum-reinforced epoxy composites using the compression molding process. FMLs are hybrid concepts for wind turbines, boats, and marine components in addition to the aerospace sector. Bonding of thin metal sheets to the fiber-reinforced polymer composites without adhesive layers or other adhesive layers forms the basis of the FMLs mainly because the fracture toughness of the metal/composite joint surface increases followed by preparation of a suitable metal surface, such as anodizing and priming with a corrosion inhibitor. The unique characteristics of the FMLs include fatigue, corrosion, and impact resistance [12]. Layering on the metal or composite surface, however, is crucial that has a detrimental impact on the strength characteristics. The weakest feature of the FMLs is the fracture toughness of a metal/composite contact. The impact and fatigue are two common external stress events that make the metal/composite contact break in the FMLs.

Nazari et al. [13] compared the vibrational properties of the cylindrical FML specimens containing glass fibers and aluminum sheets with epoxy and polymer composites containing glass fibers numerically and experimentally. According to their observations, the amount of natural frequency in all frequency numbers for the FML sample is higher than that of the polymer composite, which is in line with the results obtained in this study.

Khalili et al. [14] carried out torsional vibration test on two samples of polymer composite and FML at different temperatures. They found that the frequency required to vibrate the FML sample at different temperatures was higher than that needed for the polymer composite. They also reported that as the temperature increased, the frequency of both the polymer and FML composite samples increased as well.

The current study aims to investigate the effect of the anodized aluminum sheet on the mechanical properties of the manufactured FML composite specimen. In addition to the mechanical performance, the vibrational behavior of the specimen was studied in order to determine whether or not they were prone to flutter phenomena.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, in order to manufacture the desired FML composites, a particular type of CFRP was used (RC200-carbon pre-impregnated with epoxy resin), with each layer 25 mm thick. Table1 lists the physical and mechanical properties of carbon precoated fabric with epoxy resin.

TABLE 1. Properties of carbon pre-coated fabric with epoxy resin [15]

Properties	Quantity
Coefficient of Thermal Expansion (10^{-6} K^{-1})	2.1
Density (g/cm^3)	1.6
Compressive Strength (MPa)	570
Shear Strength (MPa)	90
Shear Modulus (GPa)	5
Young’s Modulus (GPa)	70
Ultimate Tensile Strain (%)	0.85
Ultimate Compressive Strain (%)	0.8

In order to prepare the FML composite metal sheet [16], aluminum sheets with the thickness of 2 mm were used. Then, XRF chemical analysis was done to evaluate the accuracy of the purchased aluminum sheet. Table 2 shows the chemical composition of the purchased aluminum sheets using XRF.

TABLE 2. Chemical composition of aluminum sheets 2024-T3

Element	wt. %
Al	93.954
Cu	3.546
Mg	1.696
Mn	0.437
Si	0.203
Cr	0.119
Ti	0.024
V	0.021

Table 3 shows the physical and mechanical properties of 2024-T3 aluminum. Epoxy resin provides excellent chemical resistance to corrosion against a wide range of organic and inorganic acids [17], alkalis, oxidizing chemicals, and salts and offers good mechanical properties.

TABLE 3. Physical and mechanical properties of 2024-T3 aluminum [18]

Properties	Quantity
Coefficient of Thermal Expansion (10^{-6} K^{-1})	22.6
Density (g/cm^3)	2.78
Thickness (mm)	2
Tensile Strength (MPa)	469
Young’s Moduls (GPa)	73.1
Ultimate Tensile Strain (GPa)	0.2

2.2. Electrochemical Preparation of 2024-T3 Aluminum Surface

In the anodizing method, the surface was first placed in a 5.1 % by weight solution of sodium hydroxide at 60 °C for two minutes to remove the weak oxide layer and possible scratches. Then, in order to deoxidize the surface, the sample was placed in an aqueous solution containing a few drops of 66 % by weight nitric acid for five minutes. After preparing the aluminum sheet, the sample was anodized in 3.0 % by weight solution at 55 °C with a constant flow of 7.0 A/dm^2 for 45 minutes.

2.3. Fabrication of Polymer Composite and FML

In order to determine how the arrangement of the polymer composite and the aluminum sheet would affect the vibration, impact, and tensile characteristics of these composites, the samples were created in accordance with Table 4.

First, a manual layering technique was employed to make all three samples of CFRP, Al2C1, and Al3C2 and create the composites. The samples were then placed in a specific mold under 2 kPa of pressure and heated up to 200 °C for baking operations and generating a strong connection between the layers for 40 minutes in order to bake and reach maximum strength.

TABLE 4. Properties of polymer and FML composite samples

Sample Code	Al2024 Layers	CFRP Layers	Lamination
CFRP	0	1	20 layers of carbon fiber pre-impregnated as a polymer composite
Al2C1	2	1	4 layers of carbon fibers with a thickness of 1 mm as a polymer composite in the middle of 2 aluminum sheets with a thickness of 2 mm
Al3C2	3	2	2 layers of the polymer composite containing 4 layers of carbon fiber with the thickness of 1 mm among 3 layers of aluminum sheet with the thickness of 2 mm

2.4. Mechanical Testing

Dynamic vibration, impact, and static tensile tests with the reliability coefficient of 3 for each sample were done as the related mechanical tests in this study. A changing excitation point and an accelerometer were taken into consideration on a fixed location during the vibration test. Signals for stimulation and reaction were measured and delivered to the two channels installed on the analyzer. The frequency response function was determined by eye examination in accordance with the resonance peaks in the frequency response on the analyzer monitor. Based on the Hounsfield H25KS traction device and the 3039D standard, the tensile behavior of the samples was examined. A force-displacement diagram was obtained as a result of the tensile test, which was carried out at the loading speed of 5 mm/min.

The impact device (manufactured by Iran University of Science and Technology) and the standard 7136ASTM D were utilized to investigate the impact properties of the manufactured samples. The square-shaped specimen as the target was 10×10 cm^2 in size, which was hit by a steel sphere with the mass of 5.9 kg and a tip which was hemispherical in shape with the diameter of 1 cm falling from a height of 47 cm at the speed of 3 m/s. Another set of samples were subjected to a single shear stress test using a Hansfield H25KS machine and the ASTM D 1002-01 [13] standard. The samples were loaded at the strain rate of 2 mm/min. Shear-displacement data was recorded on a computer connected to the test device, and the force was divided by the initial area of the joint to calculate the shear stress. It should be mentioned that each test was carried out on the comparable samples at least three times in order to demonstrate the repeatability of the results, and the final results are an average of the output data.

2.5. Microscopic Studies

Meiji Techno IM 7200 light microscope was used to investigate the joint chapter as well as the failure interface of the composite samples and study the failure mechanism. Scanning Electron Microscopy (SEM) of VEGA\TESCAN-LMU model was also used to study the surface of the modified aluminum and fracture interface of the samples.

3. RESULTS AND DISSCUSSION

3.1. Assessing the Aluminum Sheet's Surface Condition

In order to assess the effect of surface treatment, a SEM microscope was utilized. The microscopic pictures of the aluminum surface before (a) and after (b) surface modification are shown in Figure 1.

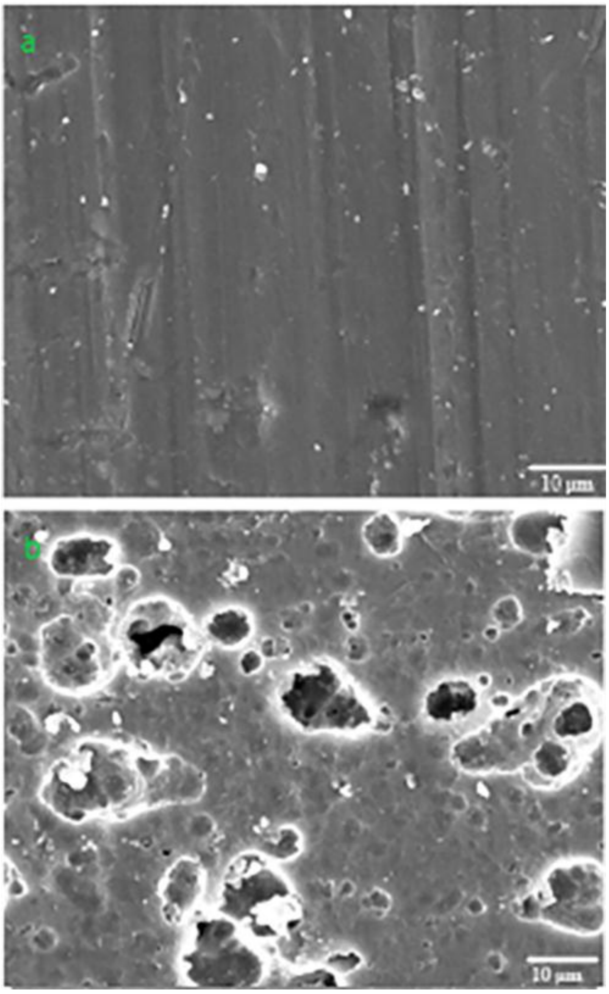

Figure 1. Microscopic image of a) the unmodified aluminum surface and b) anodized aluminum surface

Surface modification increases the specific contact surface between the aluminum and polymer, creates cavities on the aluminum surface where the polymer easily penetrates, makes a mechanical bonding between the composite of aluminum and polymer, and enhances the adhesion of the epoxy layer to the aluminum surface. The mechanical qualities would probably be better owing to the improvement in the load transmission between the layers.

3.2. Vibration Test Results

Vibration tests were carried out on all three samples CFRP, Al2C1, and Al3C2, and the first five natural frequencies were recorded by the device. Tables 5 and 6 show the frequencies obtained by the vibration test and the stresses obtained from these frequencies for all three samples, respectively.

All three samples, CFRP, Al2C1, and Al3C2, underwent vibration testing, and a device was used to capture the first five natural frequencies. Tables 5 and 6 list the frequencies for each of the three samples that were determined through the vibration test and the stresses determined from these frequencies. In Table 6, the initial frequency of the Al3C2 sample is 257 Hz, which is 110 % and 233 % higher than the frequencies of the Al2C1 and CFRP samples, respectively. The frequency of the Al2C1 sample was 122 Hz at the same frequency, which is 58 % higher than the frequency of the CFRP sample. As a result, less vibration occurs in the desired portion when FML composites are used instead of polymer composites. Additionally, a significant increase in the natural frequency is observed in the Al2C1 sample, compared to the Al3C2 sample. In this regard, the improvement in the vibrational properties can be attributed to an increase in the number of hybrid composite layers.

TABLE 5. The first five frequencies of polymer composite and FML (in Hz, with a telorance of ± 5 %)

Samples	Mod1	Mod2	Mod3	Mod4	Mod5
CFRP	77	129	154	188	272
Al2C1	122	157	189	249	341
Al3C2	257	322	378	394	443

TABLE 6. Maximum amount of stress equivalent to Von misses in the first five frequencies (in MPa, with a telorance of ± 5 %)

Samples	Mod1	Mod2	Mod3	Mod4	Mod5
CFRP	0.2245	0.1112	1.12	0.1132	0.0201
Al2C1	0.002	0.0074	0.0014	0.0012	0.0009
Al3C2	0.0008	0.0006	0.0002	0.00009	0.00004

The percentage difference between the fifth frequency of the Al3C2 sample (443 Hz) and the fifth frequencies of the Al2C1 sample and the CFRP sample, respectively, diminishes as the frequencies increased. In general, it can be concluded that the Al3C2 sample has a higher frequency for all five desirable states than the other two samples, which ultimately lowers the vibration.

According to Table 5, the highest stress from the first frequency for the Al3C2 sample is around 0.0008 MPa, which is 100 % and 60 % lower than the values for the CFRP and Al2C1 samples, respectively. Low stresses lengthen the useful life of the part and boost the number of fatigue cycles, hence less worries about the flutter phenomena in components made from FML composites. It seems that the reduction in the frequency stress results from adding more FML composite layers. Additionally, using FML composites instead of polymer composites reduces the likelihood of fatigue failure because the maximum stress of Al2C1 (0.002 MPa) is nearly 99 % lower than that of CFRP.

Contrary to frequency, the level of stress rises as the number of frequencies grows. The frequency differences between the samples cause an increase in the maximum stress differential. For instance, the Al3C2 sample has a maximum stress of 0.00004 MPa at the fifth frequency, which is 101 and 95 % lower than the maximum stresses of the CFRP and Al2C1 samples, respectively.

3.3. Impact Test Results

The impact test results for the CFRP, Al2C1, and Al3C2 samples are shown in Figure 2. The energy absorption rate for the CFRP sample is 210 KJ/m^2, which is 300 % less than the 850 KJ/m^2 for the Al2C1 sample and 350 % less than the 960 KJ/m^2 for the Al3C2 sample. This might be justified by the metal layers of the Al2C1 and Al3C2 samples. The existence of an additional aluminum layer and its impact on strengthening the entire system account for the difference between the two Al2C1 and Al3C2 samples.

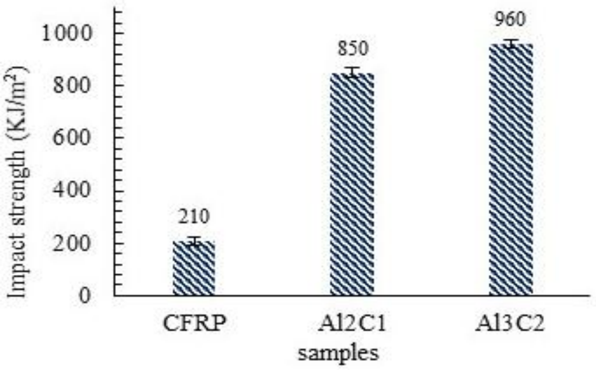

Figure 2. Adsorbed energy in the impact test

The interface of fiber breakdown in the CFRP and Al2C1 samples is depicted in Figure 3. As seen in Figure 3a, debonding of the fibers from the resin results from the failure brought on by impact on the composite sample. Additionally, Optical Microscope images were taken which are shown in Figure 4. As illustrated in Figure 4a, CFRP sample demonstrated a significant distortion in layers after the impact. Due to the absence of a rigid layer, the structure endured a significant amount of strain prior to failure but showed little delamination. Figure 4b shows debonding of Al2C1 sample after the impact. The force concentration on bonding surface is high, consequently, delamination occurs.

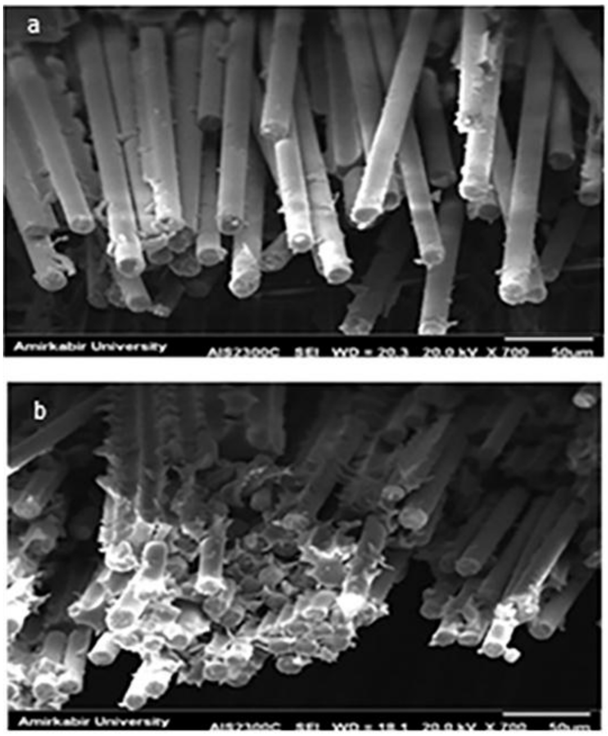

Figure 3. SEM images of the fiber breakdown surface of a) CFRP and b) Al2C1

However, in Figure 3b, the epoxy resin sustains less damage than the CFRP specimen due to the relatively even distribution of the applied load throughout the FML layers. Therefore, the absorbed energy during the impact test is greater for the Al2C1 sample.

Moreover, the FML composites can have an increased amount of plastic deformation prior to any failure. This in turn increases the energy absorption during the impact test. The SEM image (figure 3a) and impact strength diagram (figure 2) demonstrate that the CFRP samples, compared to their Al2C1 and Al3C2 counterparts, have a substantial potential to fail catastrophic. The FML specimen enjoy an improved and effective bonding between the layers of the polymer composite and aluminum sheets. Since the enhanced surface microstructure of aluminum sheet (Figure 1b), the porosity of surface facilitates improved bonding strength between layers in the FML composite.

The reason for the little discrepancy in the quantity of energy absorbed by the Al2C1 and Al3C2 samples was examined using the force-time diagram. The force-time diagram for the impact test for the Al3C2 and Al2C1 samples is shown in Figure 5. Similar behavior is observed in the diagram up until the A-zone, where it reaches its maximum value. The Al3C2 composite has a maximum applied force of 5840 N, which is 840 N more than the maximum applied force on Al2C1 sample. In contrast to Al2C1, Al3C2 requires more force to reach the maximum zone (A-zone).

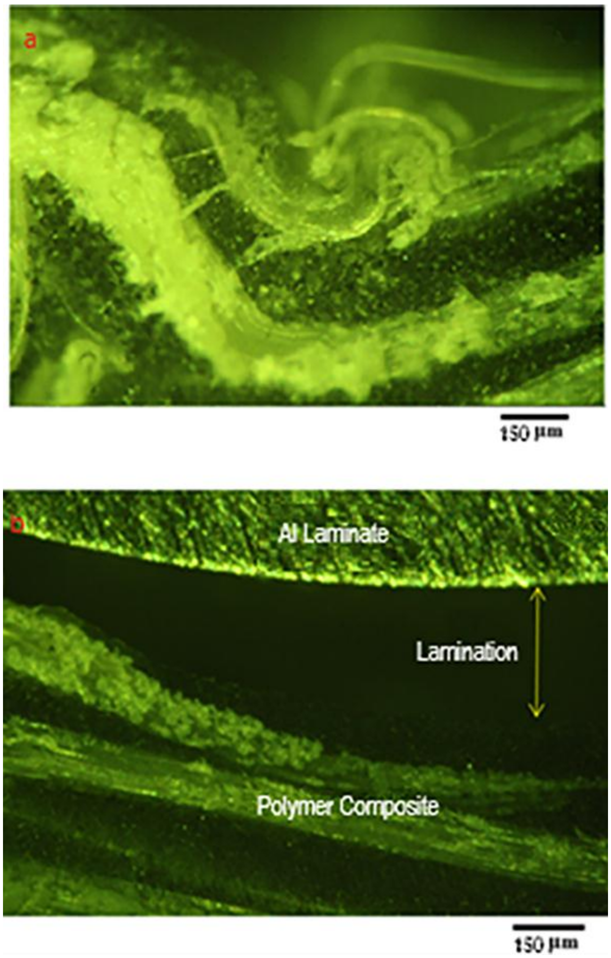

Figure 4. Optical microscope images from side view a) CFRP sample and b) Al2C1 sample after impact test

The graphs climb again to the local maximum value (C-zone) after reaching their maximum value, and this section of the graph (AC) shows how much impact strength is still present in FML. After a significant amount of time, the graph gradually reaches its minimum at the D-zone.

Fan et al. [19] studied the absorbed energy from low velocity impact in three different types of FML composite laminates and three types of polymer composite laminates. They noticed that the sample FMLs had a higher rate of refractive energy absorption than polymer composites and that the perforation energy increased as the layer thickness increased. Additionally, increasing the composite layer thickness enhanced the impact resistance, which is consistent with the findings of the current study.

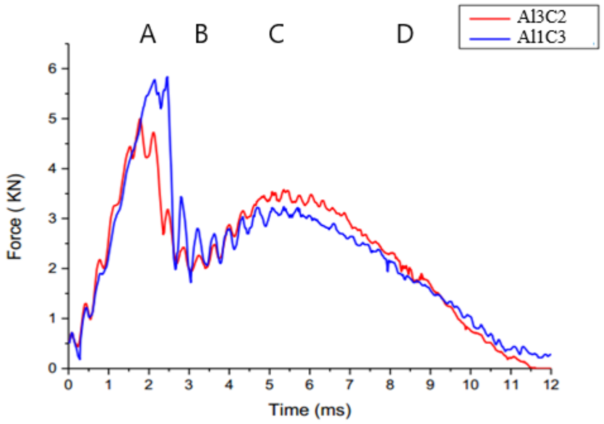

Figure 5. Force-Time diagram of Al3C2 and Al2C1 layered composites.

They further discovered that as the number of layers in the FML samples increased, the rate of refractive energy absorption decreased, primarily as a result of the growing sample weight.

The specific energy absorption quantity is calculated by dividing the weight unit by the energy per unit area. As a result, the composite samples can absorb more energy when their weight and thickness increase. The quantity of specific absorbed energy for the CFRP, Al2C1, and Al3C2 samples is shown in Figure 6.

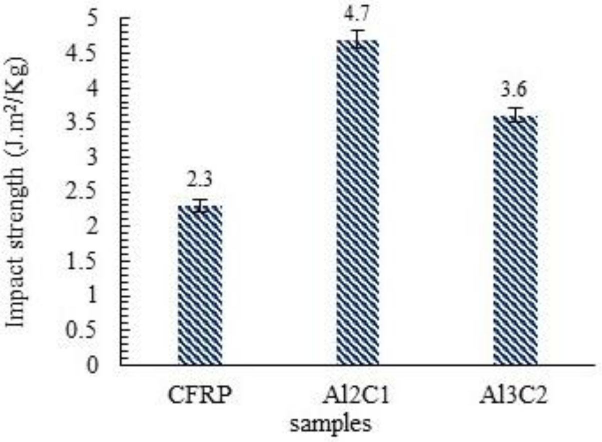

Figure 6. Specific adsorbed energy for 3 samples

According to Figure 6, FML samples have a greater specific energy absorption rate than the polymer composite samples. However, the specific energy absorption (Jm^2/kg) of the Al3C2 sample is about 30 % lower than that of the Al2C1 sample. Therefore, it can be concluded that as the overall weight of the FML composite increases, the amount of specific energy absorbed decreases while increasing the number of layers.

3.4. Tensile Test Results

Table 7 and Figure 7 show the effect of aluminum and polymer composite arrangement on the tensile properties of CFRP, Al2C1, and Al3C2 samples. The yield and final strength values of the Al3C2 sample are 580 and 897 MPa, respectively (Table 7) which is 110 and 150 % greater than those of the CFRP sample (274 and 357 MPa). Additionally, the tensile and yield strength values of the Al2C1 sample are 427 and 653 MPa, respectively, which are 55 and 83 percent higher than those of the CFRP polymer sample. The tensile modulus value of the CFRP sample is 31 GPa, which is 62 % and 71 % lower than those of the Al2C1 (50 GPa) and Al3C2 (53 GPa) samples, respectively.

TABLE 7. Tensile properties of polymer and FML composites (±5 MPa).

Samples	Yield Strength (Mpa)	UltimateTensile Strength (MPa)	Young's Modulus (GPa)
CFRP	274	357	31
Al2C1	427	653	50
Al3C2	580	897	53

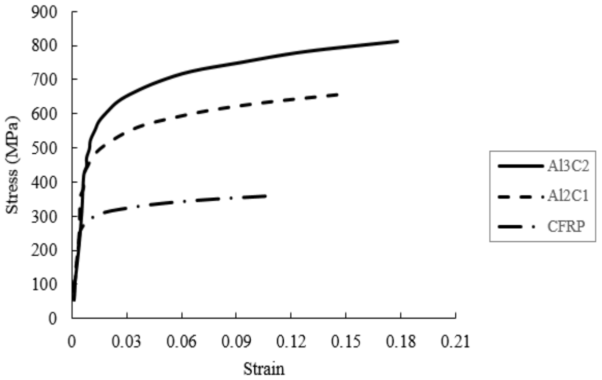

Figure 7. Stress-strain diagram of the tensile test of CFRP, Al2C1, and Al3C2 samples

Increasing the number of aluminum sheets in the FML composite rises the yield strength value from 427 up to 580 MPa in the Al2C1 and Al3C2 samples, respectively. The ultimate tensile strength follows the same pattern and increases from 653 up to 897 MPa in Al2C1 and Al3C2, respectively. Young's modulus, however, does not follow the previous pattern since the materials are identical in type, hence little difference in the Young's modulus of the Al2C1 and Al3C2 specimen.

The findings of the tensile test demonstrate that the tensile properties are improved when the polymer composite is converted to the FML version with the same thickness. Additionally, the amount of tensile properties increases upon increasing the thickness or the number of layers of the FML composite.

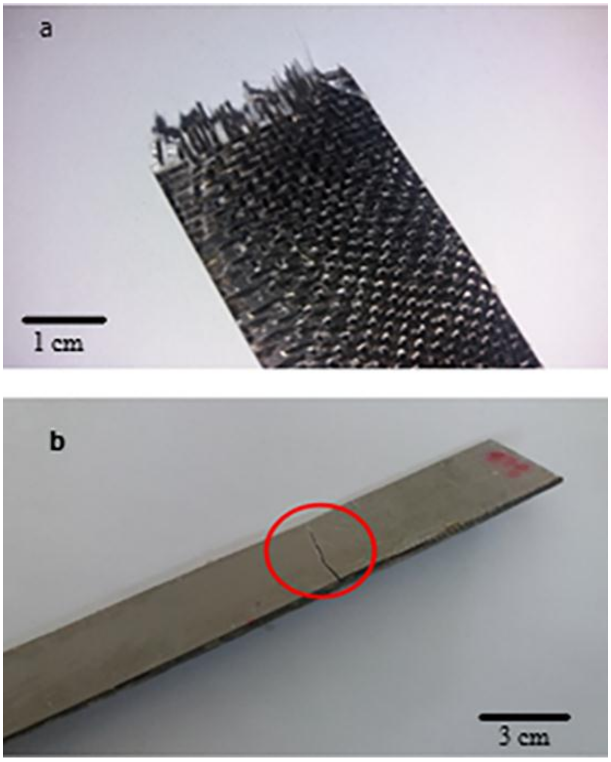

Figure 8. Overall view of fractured sample a) CFRP and b) Al1C2 after tensile test

4. CONCLUSIONS

This study evaluated the effects of 2024-T3 aluminum sheets and carbon fiber-reinforced epoxy composite on the vibration (free vibration), impact, and tensile properties of polymer composite laminates combining the two materials. The following remarks are the final findings of this research:

1. The mechanical properties of the FML composite increased upon increasing the bonding strength between the components of the FML composite as well as the porosity of the surface modification of aluminum sheet through an electrochemical technique (i.e., anodizing).
2. According to the results from the vibration tests, the FML samples required a greater frequency to produce vibration than the polymer composite samples. With an increase in the number of polymer and aluminum layers, the needed frequency and maximum stress in the FML increased due to a decrease in the natural vibration of the samples.
3. Inclusion of the metal layers in the composite may be the reason why the FML samples absorb more energy than polymer composite samples. The absorbed energy would increase with an increase in the polymer and aluminum layers. The energy absorption rate for the CFRP sample was obtained as 210 KJ/m^2, 300 % and 350 % less than that of the Al2C1 (850 KJ/m^2) and Al3C2 (960 KJ/m^2) samples, respectively. Although the specificity of the FML samples is greater than that of the polymer composite samples, the specific energy absorption of the Al3C2 samples (3.6 Jm^2kg^{-1}) was about 30 % lower than that of the Al2C1 samples (4.7 Jm^2kg^{-1}), hence more layers. The FML composite materials lowered the amount of specific energy absorbed while causing weight growth.
4. Compared to the raw polymer components, making FML composite boosts all tensile parameters including yield and final strength, modulus, and tensile strain. In a similar vein, adding more layers improved the tensile properties of the FML composite. According to the data, the yield and final strength values of the Al3C2 sample were calculated as 580 and 897 MPa, respectively, which are 110 and 150 % greater than those of the CFRP sample (274 and 357 MPa). Finally, the yield and tensile strength values of the Al2C1 sample were 427 and 653 MPa, respectively, 55 % and 83 % greater than those of the sample made of CFRP polymer.

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