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The Effects of Stacking Sequence and Thermal Cycling on the Flexural Properties of Laminate Composites of Aluminium- Epoxy/Basalt- Glass Fibres

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Abstract

The current study aimed at investigating the effects of different stacking sequences and thermal cycling on the flexural properties of fibre metal laminates (FMLs). FMLs were composed of two aluminium alloy 2024-T3 sheets and epoxy polymer-matrix composites that have four layers of basalt and/or glass fibres with five different stacking sequences. For FML samples the thermal cycle time was about 6 min for temperature cycles from 25 °C to 115 °C. Flexural properties of samples evaluated after 55 thermal cycles and compared to non-exposed samples. Surface modification of aluminium performed by electrochemical treatment (anodizing) method and aluminium surfaces have been examined by scanning electron microscopy (SEM). Also, the flexural failure mechanisms investigated by the optical microscope study of fractured surfaces. SEM images indicated that the porosity of the aluminium surface increased after anodizing process. The findings of the present study showed that flexural modulus were maximum for basalt fibres based FML, minimum for glass fibres based FML while basalt/ glass fibres based FML lies between them. Due to change in the failure mechanism of basalt/ glass fibres based FMLs that have glass fibres at outer layer of the polymer composite, the flexural strength of this FML is lower than glass and basalt fibres based FML. After thermal cycling, due to the good thermal properties of basalt fibres, flexural properties of basalt fibres based FML structures decreased less than other composites.

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Keywords: Fibre-metal laminate, Stacking sequence, Thermal cycling, Basalt fibres, Flexural properties

List of Abbreviations

Abbreviation	Full Meaning
FML	Fibre Metal Laminate
FRP	Fibre Reinforced Polymer
GLARE	Glass Laminate Aluminum Reinforced Epoxy
CFP	Carbon Fibre-reinforced Polymer
BFP	Basalt Fibre-reinforced Polymer
BCFP	Basalt/ Carbon Fibres hybrid Phenolic
T_g	Transition Glass temperature
G	Glass fibres
B	Basalt fibres
Al	Aluminium sheet
C	Thermal cycling
GB1	Al/B/B/B/B/Al
GB2	Al/B/G/G/B/Al
GB3	Al/B/G/B/G/Al
GB4	Al/G/B/B/G/Al

1. Introduction

Fibre metal laminates (FMLs) are composites that are composed of metal sheets and fibres reinforced polymers. FML is developed for decreasing product's weight and replacing it with aluminium alloys in the aircraft industry. For example GLARE (Glass Fibre Metal Laminate) has been successful on manufacturing commercial aircraft like the airbus 380. High fatigue resistance, high strength, high facture toughness and high impact resistance are mechanical advantages of FMLs. Furthermore low density of these composites is a weight saving point

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compared to other materials [1].

Aluminium alloy, titanium alloy, magnesium alloy, and steel can be used in metal based FMLs. Compared to some other alloys, low density, improved electromagnetic shielding capability and superior corrosion resistance are the advantages of magnesium alloy [2, 3]. However, magnesium alloys based FMLs have low static and fatigue properties than other metal alloys based FMLs [3]. Titanium might be the next hybrid FML to be introduced in the market. High stiffness, high yield strength, good fatigue and good impact properties at room and elevated temperatures are the advantages of magnesium alloy over some other alloys. As a result of the low ductility of the high-strength, high density, and expensive Ti-alloy, its usage becomes limited [2]. Al 2024-T3 and Al 7075-T6 (or 7475-T6) are aluminium alloys that are commonly used in the FMLs. Al 2024-T3 has high fracture toughness and Al 7075-T6 has high stiffness and strength. Generally aluminium alloys offer good mechanical properties in the FMLs properties compared to other metal alloys based FMLs [3, 4].

Basalt fibres have of good physical and chemical properties, and also good adhesion to metals, epoxies and glues [5]. These natural fibres can be used in high temperature and chemical environment since they have high thermal and chemical stability. Basalt fibres are now being popular choices for the material scientist for the replacement of steel [6].

Adhesion between metal sheet and fibre reinforced polymer (FRP) is certainly important. Because of weak adhesive between these layers in thermal cycling, or without thermal cycling, separation problem arises between metal sheet and FRP. In order to overcome this problem, there are different methods for aluminium alloy. For example, putting a thermoplastic interlayer between FRP layer and aluminium alloy, etching or anodizing treatment aluminium sheet, mechanical treatment aluminium sheet are amongst the most common ones. Thermoplastic interlayer can offer good adhesive between metal sheet and FRP. However, the

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mechanical experimental results revealed that the interlayer results in the reduction of stiffness and the fatigue strength of FMLs. Sulphuric acid anodizing is good for corrosion resistance, material strength, and environmental protection, however it's not effective as chromic acid anodizing for the corrosion protection of aluminium alloy. Even so due to environmental problems, the use of chromates compounds has been limited. Recently, new chromate-free surface treatment technologies are available for aluminium. Anodizing method offers surface with more porous [7].

Thermal cycling causes damage of the resin matrix, fibres and fibre/resin matrix interface. In the process of thermal cycling, chain scission, and cross -linking and micro- cracking cause degradation of resin matrix. The difference of thermal expansion coefficient between components is the reason for the separation of components. Thermal expansion coefficient is one of the most important thermal properties. The thermal expansion coefficient is defined as the degree of expansion divided by the change of temperature. When the material warms up, different thermal expansions of composite components results in different volume changes; this fact results in the separation of composite layers [8, 9].

Subagia et al. [10] examined the effect of stacking sequence on the flexural properties of hybrid composites. They used basalt and carbon fibres as reinforcement. They observed higher flexural strength, and modulus was obtained when carbon fibres layer was stacked at the outer layer.

Amico et al. [11] studied the influence of the stacking sequence on the mechanical properties of glass/sisal hybrid composites. They found that when glass fibres are on the outer flexural, strength is more than other composites.

Bozkurt et al. [12] examined the hybridization effects on mechanical properties of aramid/ basalt fibre reinforced epoxy composites. Their experiments showed that the mechanical

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properties (tensile and flexural) of hybrid composite laminates can be tailored by the employment of basalt fibres for partial replacement of aramid ones, and considerable improvement in mechanical properties can be obtained through the proper design of hybrid composite laminates.

According to the study carried out by Najafi et al. CFP composite possesses the highest value of bending modulus and lowest strain value among composites. This is when; BFP has the lowest bending modulus and highest strain. The BCFP composites present properties in between those of CFP and BFP. They found out that by an increase in the weight percent of basalt fibres, the extent of flexibility of CFP composites increases. The obtained results showed that an increase in the amount of basalt fibers- in addition to the fact that basalt by itself increases the extent of energy absorption- causes its fracture process in the composite which includes fracture and separation of fiber from the matrix and results in an increase in the impact energy absorption [13].

Costa et al. [14] studied the effect of thermal cycles on the mechanical properties of GLARE and they compared mechanical properties of samples with different cycle number. They used thermoplastic for increasing adhesion between FRP layer and aluminium alloy sheet. They observed that the thermal-shock cycles did not result in significant micro- structural changes of the FML. Similarly they reported no appreciable effect on the mechanical properties.

Eslami-Farsani et al. [15] carried out an experimental research on effect of thermal cycling on the mechanical properties of polymer composites reinforced by basalt and carbon fibres. Hardness of specimens decreased after thermal cycling, while the hardness of the carbon fibre-reinforced polymer (CFP) was reduced more than basalt fibre-reinforced polymer (BFP) specimens. They found that the mean charpy impact energy of the BFP specimens is higher

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than CFP at all thermal cycles. Hybrid composites consist of basalt and carbon fibres showed stability of various thermal cycles more than CFP.

Mahdavi et al. have studied the effect of thermal cycles on interlamellar shear strength and glass-transition temperature of Thermoset composites reinforced by carbon fibres. Different numbers of thermal cycles between -196 ºC and 140 ºC were carried out. Shear strength decreased with increase in the number of thermal cycles; and, after 200 thermal cycles, shear strength decreased by an amount of 10% compared to the composite without thermals cycles. The reason is the occurrence of microcracks after thermal cycles. Added to this; by an increase in the temperature, secondary curing factor causes in an increase in T_g. Afterwards, the occurrence of microcracks results in its decrease [16].

Segerström et al. [17] studied the effect of thermal cycling on flexural properties of carbon–graphite fibre-reinforced polymer. They found that increased percentage of fibre decreases flexural strength. For example, flexural strength does not decrease after hydrothermal cycling for the carbon–graphite fibre-reinforced polymers of 24 and 36 wt.% fibre loading. While flexural strength decreases for fibre loadings of 47 and 58 wt.%.

Timmerman et al. [18] examined the effect of matrix and fibres on the cryogenic micro - cracking of carbon fibre/ epoxy composites. They found that the high glass transition temperatures of the laminates decreased the micro- cracking propensity of these laminates. It was also found that composites containing fibres that they have higher modulus and linear coefficients of thermal expansion are more prone to micro-cracking.

In line with previous research, the aim of the present work was to develop and characterize laminate hybrid composite of aluminium- epoxy/basalt- glass fibres under thermal cycling. The results can help to the increased use of the FML structures for various applications in the different temperature conditions.

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2. Experiments

2.1. Materials

Epoxy resin (Epon 828), TETA amine hardener and the E-glass roving fibres and two-dimensional plain weave E-glass fibres with surface density of 200 g/m^2 supplied by Asfoonshimi engineering materials company, Iran. Basalt woven fibres (BAS 350.1270.A) prepared at Basaltex company, Belgium, aluminium alloy 2024-T3 were used as layers of sheet metals. Properties of fibres, resin, and metal used in this work are presented in Table 1.

Table 1. Mechanical and physical properties of fibres, resin, and metal used in this work

Properties	Al 2024-T3 [31]	Basalt fibres [6]	Glass fibres [6]	Epoxy resin (Epon 828) [19, 30]
Thickness (mm)	0.5	0.5	0.2	-------
Density (g/m^3)	2.78	2.67	2.54	1.16
Tensile strength (MPa)	469	3000-4840	3100-3800	-------
Tensile modulus (GPa)	73.1	79.3-93.1	72.5-75.5	-------
Elongation at break (%)	20	3.1	5.3	0.8
Thermal expansion coefficient (ppm/℃)	22.6	8.0	5.4	62.0
Temperature Withstand (℃)	-------	-250 … 550	-50 … 300	Up to 115
Viscosity (p)	-------	-------	-------	110-150

2.2. Surface preparation Al 2024-T3

To create a porous of aluminium for good adhesive between the resin and metal layer, the aluminium etched with NaOH 4 wt.% at 50 °C for 2 min and cleaned oxidized surface of aluminium with immersion in HNO_3 solution. Afterward these aluminium sheets were anodized in H_2CrO_3 0.3 wt.% at 55 °C with current density 0.7 A/dm^2 for 45 min.

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2.3. Composite preparation

To fabricate FML, the composites contained of four layers of fibres with different layouts of glass and basalt fibres and two aluminium's sheets have been used. First, resin and hardner mixed with ratio 100:10 by weight [19] and polymer composites were made by hand lay-up technique and then it was placed between two aluminium's sheets. Then samples in dimensions 150 mm × 25 mm placed under pressure 5 bar at 25 °C for 18 hours. For curing and reaching good mechanical properties in samples, thermal cycling done after 3 weeks of fabricating stage is needed. The FML specimens' codes, stacking sequence, sample thickness, and the content of composite components are shown in Table 2. Also Fig. 1 shows different stacking sequences of aluminium, glass and basalt fibres.

Table 2. Information of FMLs

Specimen's codes	Stacking sequence*	Sample's thickness (mm)	Content of composite components (wt.%)			
			Glass fibres	Basalt fibres	Epon 828	Al 2024-T3
GB1	Al/B/B/B/B/Al	1.85	0	25	12	63
GB2	Al/B/G/G/B/Al	1.80	10	16	13	63
GB3	Al/B/G/B/G/Al	1.82	10	16	14	63
GB4	Al/G/B/B/G/Al	1.80	10	16	13	63
GB5	Al/G/G/G/G/Al	1.78	23	0	14	63

* "Al", "B" and "G" show aluminium sheet, basalt fibres and glass fibres, respectively.

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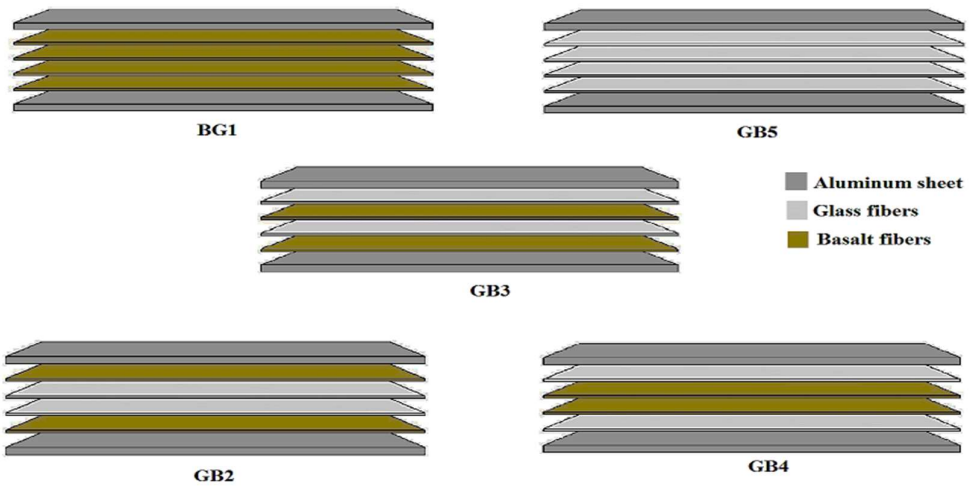

Fig. 1. Different stacking sequences of aluminium (Al), glass fibres (G) and basalt fibres (B) plies.

2.4. Thermal cycling

To study the effect of thermal cycling, the specimens were put into a furnace of thermal cycling (model ATM 7004-37, Sarmayesh, Iran). The thermocouple (model USB-4718, Advantage, U.S.A) was used to accurate measurement of temperature changes. Specimens were exposed to 115 °C for 2 min and then the temperature with cooling rate 1.5 °C/s reached 25 °C and exposed to this temperature for 2 min. The thermal cycling was repeated for 55 cycles. Fig. 2 shows general temperature profile applied on the FML specimens.

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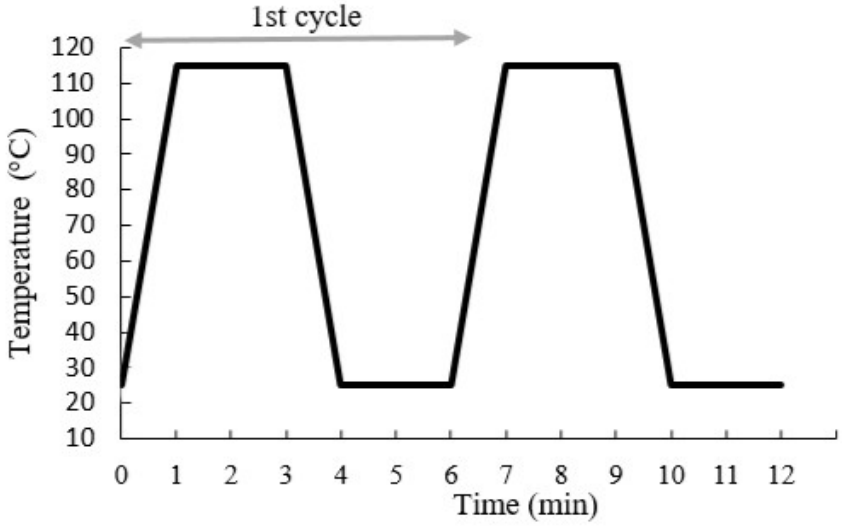

Fig. 2. Representative temperature profile for thermal cycle test conditions of FML specimens.

2.5. Flexural testing

Three-point flexural bend test was run at ambient temperature along with ASTM D790. Hounsfield H25KS testing machine was employed to conduct the test. Cross-head speed for flexural tests were 3 mm/min. For flexural test, support span length set at 59 mm. Three specimens of each category were tested and the average value was reported. Flexural Cross-head speed (R), flexural strength (σ_f), and flexural modulus (E_B) calculated from the formula [20]:

$$R = ZL^2/6d \quad (1)$$

$$\sigma_f = 3Pl/2bd^2 \quad (2)$$

$$E_B = L^3m/4bd^3 \quad (3)$$

where R is the rate of crosshead motion (mm/min), Z is the rate of straining of the outer fibre (mm/mm/min) and would be equal 0.01, L is the span length (60 mm), d is depth or thickness of tested beam (mm), b is width of test beam (mm), P is the applied load (N) at the highest

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point of load-deflection curve, and m is slope of the tangent to the initial straight-line portion of the load-deflection curve (N/mm).

3. Results and discussion

3.1. The study of the surface treatment of Al 2024-T3

As shown in Fig. 3-a, the porosity after etching stage is very low. Fig. 3-b shows that the porosity of the aluminium surface increased after the anodizing process. Typically, chemical treatment, i.e., acid-etching, is an intermediate production step between degreasing, alkaline cleaning, and electrochemical treatment. Thus, this step should be compatible with post treatments, i.e., an anodizing process [21]. Anodizing produces a thin oxide film, again with a high degree of micro-roughness and an oxide form which is highly resistant to hydration [22].

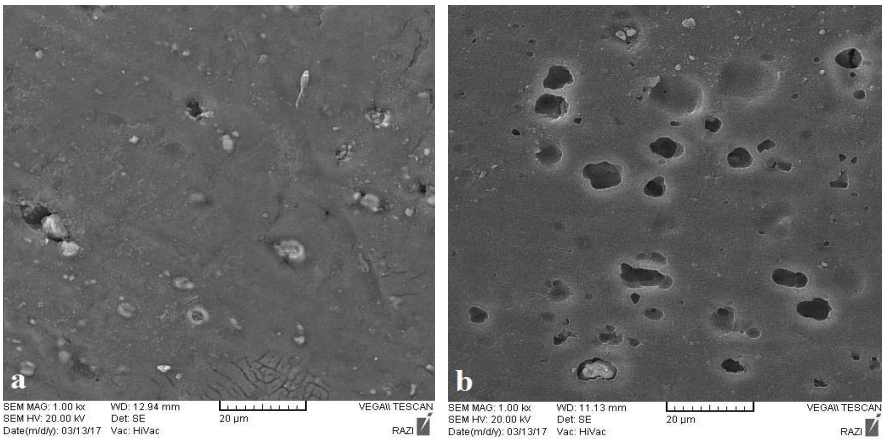

Fig. 3. SEM images of (a) etched aluminium surface, (b) anodized aluminium surface.

Fig. 4 shows the difference between the joint surface of composite and aluminium in the FMLs with etched aluminium and composite with anodized aluminium. The mechanical interlocking of the polymer composite with aluminium in the FMLs with anodized aluminium is more than FMLs with etched aluminium.

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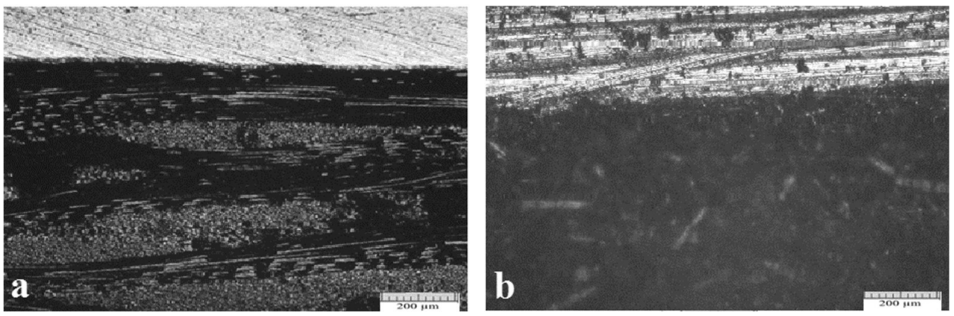

Fig. 4. Optical microscopy images of cross-section of FML (a) composite with etched aluminium, (b) composite with anodized aluminium.

3.2. Effect of stacking sequences on the flexural properties

The calculated mechanical properties of the FML specimens with thermal cycling and nonexposed are summarized in Table 3. According to Figs. 5 and 6, the flexural strength and modulus of GB1-0C composite are 665 MPa and 57.7 GPa, respectively that they were found to be 4.7% and 6.2% greater than the pure glass fibres based FML (GB5-0C), respectively. The GB1-0C composite showed a higher flexural strength and modulus than other composites. That might be due to the high flexural modulus and strength of basalt fibres [23, 24], their good wettability [6] and excellent interfacial adhesion [23] compared to glass fibres. According to Table 3, GB1-0C shows respectively 3.9% and 2.4% of flexural strength and modulus more than that of GB2-0C. GB2-0C and GB4-0C show flexural strength and modulus of 640 MPa, 56.3 GPa and 624 MPa, 55 GPa, respectively. That flexural strength and modulus for GB2-0C are 2.5% and 2.3% greater than GB4-0C. In flexural test, the upper and lower surfaces of the specimens are more likely to be deformed than the mid-plane.

Hence, flexural stiffness and strength are indeed dependent on the properties of the surface layers [10]. So if basalt fibres are on the outer layers in the polymer composite and they are adhered to aluminium, FML would show high flexural properties. That might be due to the

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high flexural properties [23, 24] and good adhesion to metal [5] of basalt fibres compared to glass fibres. The lowest value of flexural modulus is obtained when individually glass fibres are used for the preparation of composites. But the lowest value of the flexural strength is obtained for GB4-0C, as a result of difference in the failure mechanism. In fact, regions of weakened interfacial adhesive contact on the interfaces of the components of the structure have an important effect on the property of local failure of composite materials [25].

Table 3. Results of three- point bending test of FMLs

Specimen codes**	Flexural strength (MPa)	Flexural modulus (GPa)	Energy absorption ($J/mm^{3)}$
GB1-0C	665	57.7	170.6
GB1-55C	642 (-3.3%)*	56.8 (-1.6%)*	169.1 (-0.8%)*
GB2-0C	640	56.3	169
GB2-55C	614 (-4%)*	55.3(-1.7%)*	160 (-5.3%)*
GB3-0C	631.5	56	162
GB3-55C	610.3(-3.5)*	54.7 (-2.3%)*	132.5 (-19.5%)*
GB4-0C	624	55	161
GB4-55C	596 (-4.4%)*	53.7 (-2.3%)*	120.7 (-25%)*
GB5-0C	635	54.3	163
GB5-55C	587 (-7.5%)*	53 (-2.4%)*	148 (-9.5%)*

* The percentage reduction in the flexural properties relative to the 0 thermal cycle.
** The numbers used in the specimen codes represent the thermal cycle numbers and "C" symbol represent the thermal cycling.

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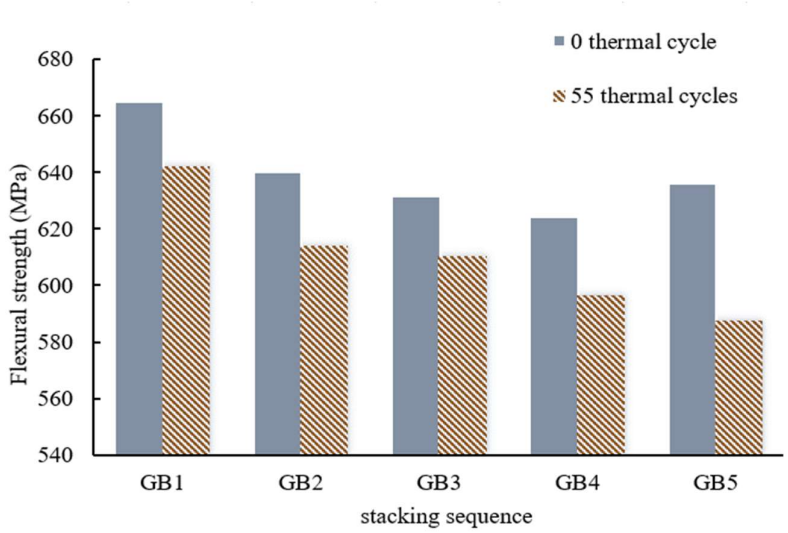

Fig. 5. The effect of stacking sequence and thermal cycling on the flexural strength of FMLs.

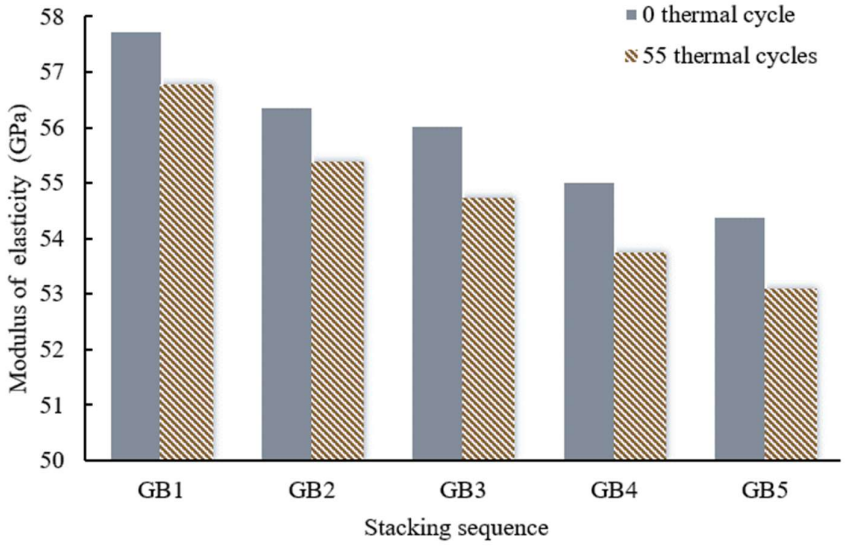

Fig. 6. The effect of stacking sequence and thermal cycling on the flexural modulus of FMLs.

Fig. 7 shows the difference in the mechanism of failure in the GB4-0C and GB3-0C composites with other composites. In Fig. 7-a, first, aluminium was broken (black arrow) then delamination in the basalt fibres and/ or glass fibres layers was occurred (white arrow). But as shown in Fig. 7-b, the GB4-0C and GB3-0C composites fail for a premature local delamination in the glass fibres layer, aluminium sheet (white arrow) and basalt fibres layer (black arrow).

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Fig. 8 shows the effect of stacking sequence and thermal cycling on the energy absorption of FML specimens. According to the Fig. 8 and Table 3, energy absorption of the GB1-0C is 170.6 J/mm^3 that 4.7% greater than glass fibres based FML (GB5-0C). GB2-0C and GB3-0C show energy absorption of 169 and 162 J/mm^3, respectively. Due to the changes in the failure mechanism, the GB4-0C shows the least of energy absorption (161 J/mm^3) compared to other FMLs. From Figs. 5 and 8 and Table 3, it can be deduced that the abortion energy of the samples are relatively similar to their flexural strength.

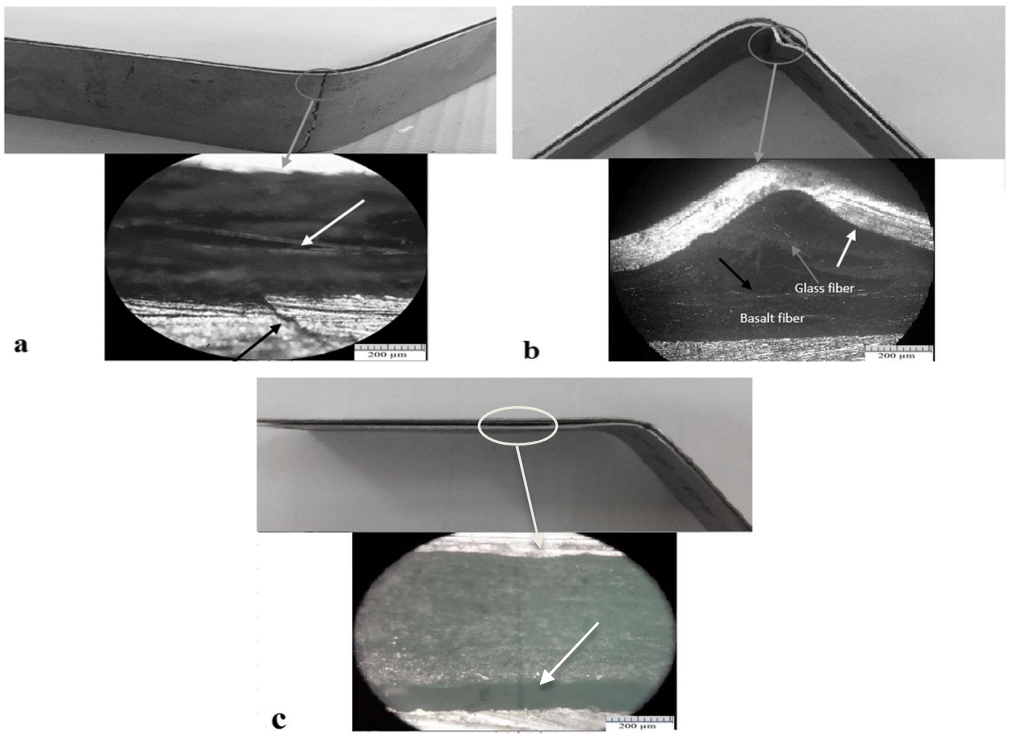

Fig. 7. Different types of failure modes of failed flexural FML specimens, (a) aluminium breakage and delamination of fibres layers, (b) the local delamination of the glass fibres layer aluminium sheet and basalt fibres layer in the GB3-0C and GB4-0C composites, (c) the

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delamination of the glass fibres layer and aluminium sheet after thermal cycling in the GB3-55C and GB4-55C.

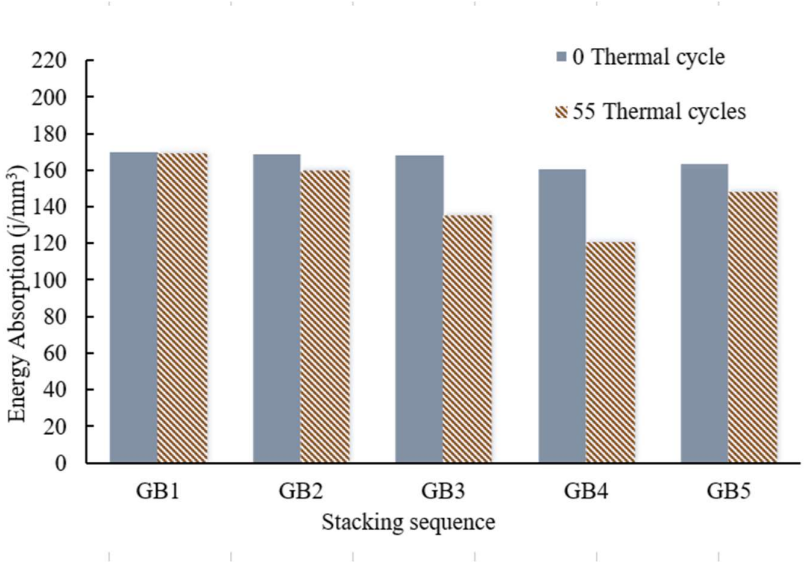

Fig. 8. The effect of stacking sequence and thermal cycling on the energy absorption of FMLs.

3.3. The Effect of thermal cycling on the flexural properties

Figs. 5 and 6 show the effect of thermal cycling on flexural strength and modulus of FMLs. This thermal conditioning had different effects on the basalt fibres, glass fibres, and basalt/ glass fibres based FMLs. The flexural strength and modulus of the basalt fibres based FML (GB1-55C) are 642 MPa and 56.8 GPa, respectively that were found as 3.3% and 1.6% lesser than GB1-0C. While considering the GB5 combinations, the flexural strength and modulus of the glass fibres based FML (GB5-55C) are 587 MPa and 53 GPa, respectively that are 7.5% and 2.4% lesser than the GB5-0C. Thermal stability of basalt fibres are higher than the glass fibres [6, 26]. Also thermal expansion coefficient of basalt fibres is nearer to aluminium and epoxy than glass fibres [6]. So the flexural strength and modulus of the GB1-55C decreases lesser than BG5-55C. Because the flexural modulus of the composites are independent of failure mechanism, the flexural modulus sensitivity to thermal cycling is lower than the flexural

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strength and decreases lower rate. Since the glass fibres has lower thermal stability compared to basalt fibres [6], the GB5-55c composite shows the greatest decrease of flexural modulus.

In the basalt/ glass fibres based FMLs, the flexural strength and modulus of the GB2-55C are 614 MPa and 56.3 GPa, respectively that are 4% and 1.7% lesser than GB2-0C. Comparing the GB4-55C with GB4-0C, the flexural strength and modulus of the GB4-55C are 596 MPa and 53.7 GPa, respectively that decrease 4.4% and 2.3% compared to GB4-0C. The flexural strength of GB4-55C composite are more susceptible to be damaged by thermal cycling, compared to the others basalt/ glass fibres based FML. Based on the fact that the flexural properties of the polymeric composites are dependent to their surface layers, main reason for remarkable decrement in the flexural strength of the GB4-55C was de-bonding of the glass fibres and the aluminium sheet. Finally comparing the combinations of GB3-55C with GB3-0C shows that the flexural strength and modulus of the GB3-55C decrease 3.5% and 2.3%, respectively compared to GB3-0C. As shown in the Fig 7-c, that's due to premature separation of glass fibres layer from aluminium sheet (white arrow).

The energy absorption of GB1-55C and GB5-55C are 169.1 J/mm^3 and 148 J/mm^3, respectively that are decreased to 0.8% and 9.5% compared to GB1-0C and GB5-0C. In the basalt/ glass fibres based FMLs, the GB2-55C and GB4-55C show the energy absorption of 160 J/mm^3 and 120.7 J/mm^3, respectively that were found as 5.3% and 25% lesser than GB2-0C and GB5-55C. The energy absorption such as flexural strength depends on the failure mechanism. Then according to Fig. 8, due to the premature delamination in the glass fibres layer and aluminium sheet, the energy absorption of the GB4-55C and GB3-55C are decreased with more intensity compared to other composites.

In general, post curing and deboning between components are the major occurrences during the thermal cycles of FMLs. Temperature rise can induce post-curing to some extent

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and causes the improvement of cross linking degrees of the resin matrix [27], which in turn may improve some physical and mechanical properties. In contrast, the differences between thermal expansion coefficients of glass fibres, basalt fibres, aluminium sheet and polymer matrix, lead to the high interfacial strains during a thermal cycling process. The stresses caused by strains can lead to failure of the interfacial adhesion between composite components and thereby decreasing the flexural properties of composite. Therefore, it can be said that there should be a comparative mechanism between post curing and deboning between components.

Results showed that the effect of thermal cycles on the flexural properties of basalt fibres based FMLs is insignificant. While the flexural properties of glass fibres based FMLs and basalt/ glass fibres based FMLs decreased more quickly with decreasing thermal cycles. Therefore, it can be conclude that the type of fibres have significant effect on the mechanical behaviour of FMLs, after thermal cycling. In consistent with these findings, Dutta et al. [28] studied the effect of cryogenic cycling on the young's modulus of polymer composites. They found that the type of fibres plays a major role on the mentioned mechanism and consequently on the mechanical behaviour of FMLs. Similar results were also observed by khalili et al. [29]. They combined carbon and basalt fibres at different sequences and concluded that thermal cycling caused to decreasing the ultimate tensile strength and modulus in carbon/basalt fibres reinforced polymer and basalt fibres reinforced polymer.

4. Conclusion

The effect of stacking sequence and thermal cycling on the flexural properties of the laminate composite of aluminium alloy 2024-T3 epoxy/basalt- glass fibres has been evaluated. The results are as follows:

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- It was observed that the porosity obtained on the aluminium alloy 2024-T3 surface by chromic acid anodizing was higher than the sodium hydroxide-based etching.
- The flexural strength, modulus and energy absorption are highest for the basalt fibres based FML. In the basalt/ glass fibres based FMLs, when glass fibres layer be put on out layers in the polymer composite, the flexural strength and energy absorption are lower than other composites and the glass fibres based FML has lowest modulus strength.
- When the basalt fibres are outer layers and are adhered to aluminium, basalt/ glass fibres based FMLs show the greatest value of the flexural strength and modulus.
- After 55 thermal cycles, flexural strength and modulus and energy absorption decrease for basalt fibres based FML 3.3%, 1.8% and 0.8%, and for glass fibres based FML 7.5%, 2.4% and 9.5% compared to specimens without thermal cycling. Then the thermal cycling results in severe degradation effects in the flexural properties for the glass fibres based FML.
- The reduction of the flexural strength after thermal cycling was less than 4.5% compared to specimens without thermal cycling for basalt fibres based FML and basalt/ glass fibres based FML. The flexural strength of the glass fibres based FML was reduced to more than 7.5% of the specimens without thermal cycling values. In addition, the reduction of flexural modulus after thermal cycling was for glass fibres based FML compared to the specimens without thermal cycling more than basalt fibres based FML and basalt/ glass fibres based FML.
- Applying high numbers of thermal cycles on the FML composites, or changing the time, electrical current, and solution temperature while inducing surface modifications by electrochemical method, and investigating its influence on adhesion between metal and polymer composite in FML, are potential future studies in this field.

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