Development and Properties of Fiber Metal Laminate Used in Aircraft Wing by Using Epoxy-Novolac

Ahmed Mohammad Kadhum 1, Saad Theeyab Faris 1, Ali Adwan Al-katawy 2
1 Department of Mechanical Engineering, College of Engineering, Daiyla University, Baquba, Iraq 32001, Daiyla governorate, Iraq.
2 Department of Materials Engineering, College of Engineering, Daiyla University, Baquba, Iraq 32001, Daiyla governorate.

Abstract. The purpose of this study is to reduce weight and to improve the mechanical properties of aircraft wing by using fiber metal laminates (FMLs). They are layered materials based on stacked arrangements of aluminum alloy layers and fiber reinforced plastic (FRP) layers. They have benefits over both aluminum and fiber reinforced composites. In this study, seven layers consist of 2024-T3 aluminum alloy reinforced by carbon and glass fibers bonded using blend of epoxy-novolac as adhesion, were used to produce the Carbon Glass Reinforced Aluminum Laminates (CAGRALLs) as FMLs. The mechanical properties (tensile, flexural, impact and fatigue) of CAGRALLs are experimentally investigated. The results revealed that CAGRALLs give good mechanical properties because of increasing in tensile strength, yield strength, elastic modulus, elongation at fracture, flexural modulus and impact toughness except flexural strength comparing than Carbon with Glass Reinforced Aluminum (CACAGRALLs) and Carbon with Jute Reinforced Aluminum (CAJURALLs) using epoxy. The increasing in layers led to weaken adhesion between layers of FMLs that led to decrease almost mechanical properties. The fabricated CAGRALLs showed higher fatigue strength than Aramid Reinforced Aluminum Laminates (ARALL) and lower density than aluminum alloy 2024-T3 and steel that used in manufacturing of aircraft wing.

1. Introduction
In the past decades, the composite structures are the more popular materials used for different applications. They are widely used in lightweight structures since they have several advantages like strength and stiffness to weight ratio, fatigue characteristics and corrosion resistance. The materials that have the potential to meet the durability and safety of the structures are FMLs [1]. Hybrid composite materials are designed based on beneficial of different properties of the fibers employed. For example, the mixing of glass fiber with carbon fiber embedded within a polymer matrix gives inexpensive composite because the glass fiber have the low cost but with mechanical properties enhanced by the excellent stiffness of carbon [2]. A fiber metal laminates (FMLs) are one of class of metallic materials consisting of laminate of thin metal layers, which bonded with composite layers as shown in figure 1. They have better damage tolerance to fatigue crack growth and impact damage owing for aircraft applications. The bonding of the metallic layer and fiber reinforced laminate is done by classical techniques, i.e. mechanically and adhesively. The fabrication of FMLs method infusing liquid resin into dry fabric layers solely by vacuum pressure to produce high quality materials has proven to be more cost effective process for preparation composites. It is consisted of...
layers of aluminum and carbon fiber bonded together by compression moulding process along with epoxy as hardener [3]. The FMLs were originally development at Delft University of technology, Netherlands. They are good choice for advanced aerospace structural applications because of their high specific mechanical properties especially fatigue resistance. The most important factor in manufacturing of these laminates is adhesion force between metals and fabrics. Aerospace industries are very interested in FMLs because of their good fatigue loads as well as lower density comparison with traditional metals like aluminum alloys(e.g. 2024T3) [4]. In modern aircraft design, skin materials were increased use of FMLs due to beneficial characteristics in the fatigue and fire resistance in aircraft constructions [5]. The weight saving is one of the important factors for improving structure design. The composite materials such as fiber-reinforced composites give desirable stiffness by optimizing orientations with low density [6]. Phenolic materials are both acid (novolac) and base (resole) catalyzed used in production of composites. They have low fire, smoke and toxicity properties [7]. Production of novolac can be achieved by the reaction of formaldehyde with phenol or phenol derivative under acidic catalyst like sulfuric, phosphoric and oxalic. The mixture ratio of phenol to formaldehyde is used between 1.49 and 1.72 [8]. The phenolic resin was used in molding parts, industrial sheeting, insulating varies and coating in 1900's. Later it was used as adhesion in woods and fiber to make composites. It is high performance polymeric, which has high stable nature and has ultimate mechanical strength during curing process so that it used in electronics and aerospace. It is as thermo-structural materials that used in transportation and aerospace industry because of having resistance to heat, flam and chemicals [9]. Chlupová et al studied the fatigue crack growth of the Glass Reinforced Aluminum Laminates (GLARE) [10]. Vasumathi et al studied the mechanical properties of Carbon Jute Reinforced Aluminum Laminates (CJRAL). The tensile strength was increased with increased number of layers and the decreased with increasing number of layers. The young's modulus, flexural strength, flexural modulus and impact toughness were decreased with increasing number of layers. [11]. Qaiser et al studied the mechanical properties of Aramid Reinforced Aluminum Laminates (ARALL) [12]. Rajkumar et al studied the tensile and flexural of FMLs. The Aluminum and Carbon Fiber Reinforced Plastics had better bonding that lead to arrest the crack in the flexural test [13]. Harichandan et al studied the tensile behavior of Carbon Jute Aluminum Laminates (CAJALL) [14].

In the present study, the mechanical properties (tensile, flexural, impact and fatigue) of CAGRALLs have studied that used in aircraft wings. The CAGRALLs made of aluminum sheets reinforced by carbon and glass fibers have bonded by using epoxy-novolac.

![Figure 1. Schematic presentation of FMLs](image)
2. Methodology

2.1. Materials used for fabrication of FMLs

In this study, the carbon and glass fiber have been used for the fabrication of composite materials. The blend of epoxy-resole has been used as matrix. The aluminum sheets have been used as FMLs plate. The CAGRALLs as FMLs have been made of three sheets of Aluminum alloy 2024-T3 (0.5 mm thick) reinforced by the carbon fiber SikaWrap-301C and E-Glass fiber EWR450 and used epoxy Sikadur 52 resin with its hardener and resole resin as adhesion force between layers. Properties of resins were used in this work, which showed in table 1 and 2. These fibers have been purchased from local market and their properties can be presented in table 3. The properties and chemical composition of Aluminum sheets can be shown in table 4 and 5 respectively. The fabrication of FMLs has been done by using Hand lay-up technique at room temperature. The fibers and aluminum sheets have cut according to the desired size and held in the mould. The pressing by roller has applied to the skins. The applied pressure compresses the prepreg for improving the bonding between the fibers and aluminum sheets. The time must be enough for been suitable bonding. The mixing ratio is 90% of epoxy with 10% novolac resin. The weight friction is 0.2 wt for reinforcement that has been used in this work. The specimens 1, 2 and 3 have the same conditions that consist of seven layers (Al/C90/G45/Al/ G45/C90/Al) which used in this work. The specimen has made to the size (300 mm x 300 mm x 3 mm). The CNC water jet machine is the cutting machines, which have used for cutting the hard materials by water jetting. It is used to cut specimens according to ASTM for each test. At least three specimens were used in each test.

| Table 1. Properties of polyprime-EP epoxy [16]. |
|-----------------------------------------------|
| Color                          | Amber |
| Solid content                  | 100%  |
| Density                        | 1.05  g/cm² |
| Application life               | 30 minutes |
| Application temperature        | 5-35 °C |
| Water resistance               | Very good |

| Table 2. Properties of novolac used in this study [17]. |
|--------------------------------------------------------|
| Chemical formula          | (C₆H₆O. CH₂O)ₓ |
| Molar mass                | Variable      |
| Appearance                | Brown solid   |
| Density                   | 1.33 g/cm³    |
| Thermal conductivity      | 0.2 (W/m.K)   |
| Reflective index          | 1.63          |
| Specific heat capacity    | 0.92 (kJ/kg. K) |
Table 3. Properties of fibers used in this study [18, 19].

| Property            | EWR 450            | Slikawrap301 C          |
|---------------------|--------------------|-------------------------|
| Material            | E-glass fiber      | Carbon fiber            |
| Color               | white              | black                   |
| Orientation         | 45° (Woven Roving) | 0° (unidirectional)    |
| Density (g/cm³)     | 1.88               | 1.8                     |
| Thickness (mm)      | 0.3                | 0.17                    |
| Tensile strength (MPa) | 331             | 4900                    |
| Elastic modulus (GPa) | 25.86            | 230                     |
| Elongation at break (%) | 3.4             | 2.1                     |

Table 4. Mechanical properties of aluminum alloy 2024-T3 [20].

| Property         | Value            |
|------------------|------------------|
| Density          | 2.78 g/cm³       |
| Tensile strength | 435 MPa          |
| Yield strength   | 290 MPa          |
| Elongation       | 10-15 %          |
| Endurance limit  | 138 Mpa          |
| Elastic modulus  | 73.1 GPa         |
| Poisson's ratio  | 0.33             |

Table 5. Chemical composition of AL 2024-T3 [20].

| Component | Wt. % |
|-----------|-------|
| Cr        | 0.1   |
| Cu        | 3.8-4.9 |
| Fe        | 0.5   |
| Mg        | 1.2-1.8 |
| Mn        | 0.3-0.9 |
| Si        | 0.5   |
| Ti        | 0.15  |
| Zn        | 0.25  |
| Other each| 0.05  |
| Other total| 0.15  |
| AL        | Reminder |
2.2. Mechanical tests
The tensile test specimen is prepared according to the standard ASTM D-638. The tensile test is done for two specimens in the University of Technology/ Materials Engineering/in the materials strengths lab. The shape of the tensile test specimens is as a dog bone, as shown in figure 2a. The flexural test specimen is prepared according to the standard ASTM D790. The three points flexural test is used in this work which is widely used in composite materials. The flexural test is done for three specimens in the University of Technology /Applied Science Department / the strength of materials lab. The tensile and flexural tests were carried out with crosshead speed 3 mm/min. The charpy impact test with V-notched with (300-Joule) pendulum is used. The specimen for this test is prepared according to the standard ISO 179. The impact test is done for two specimens in the General Company for Engineering Inspection and Rehabilitation. The fatigue test is done by using a rotating cantilever load at the end. The specimen is prepared according to standard HSM 19 Rotating fatigue Machine. The fatigue test is done in the Al-Nahrain University / college of Engineering/mechanical department in the applied lab. These tests are carried out at room temperature. Figure 2 shows dimensions and shape of samples for each test.

3. Results and Discussion
In the present research, Aluminum reinforced by carbon and glass fibers bonded with using the blend of epoxy-novolac matrix. The results presented and discussed as follows:
Figure 3 showed that sample before and after tensile test. The stress-strain can be showed in figure 4. The figure indicates that tensile load carry capacity increased up to certain extend and after that, there is a sudden fall at load later. Rajkumar et al [13], used four sheets from aluminum reinforced by four carbon and two glass fibers bonded with epoxy (CACAGRALLs) and obtained that tensile strength (200 MPa) is lower to CAGRALLs (262 MPa) because of increasing in layers in FMLs led to decrease the tensile strength. Harichandan et al [14], used eight layers from aluminum reinforced by carbon and jute fibers bonded using epoxy (CAJURALLs). They obtained that elastic modulus (2.37 GPa) is lower to CAGRALLs (4 GPa) because of increasing in layers led to decrease the elastic modulus and using carbon with jute fibers led to have the low elastic modulus by comparing with using carbon and glass fibers as shown in figure 5. Rajkumar et al [13], obtained that elongation at fracture (8.5%) is lower than CAGRALLs (20%). We note that CAGRALLs using epoxy-novolac have higher by comparing with CACAGRALLs using epoxy.
Figure 3. Tensile test sample

(a) Sample before tensile test
(b) Sample after tensile test

Figure 4. Stress-strain curve for CAGRALLs
Figure 5. Elastic modulus values for FMLs

Figure 6 showed that sample before and after flexural test. Figure 7 shows the flexural strength for FMLs. Rajkumar et al [13], obtained the flexural strength (320 MPa) is higher than CAGRALLs (300 MPa) because of increasing in layers led to increase the flexural strength. It indicates that epoxy-novolac adhesion is better than epoxy. Figure 8 shows the flexural modulus for FMLs. Vasumathi et al [11], obtained the flexural modulus (1.71 GPa) is lower than CAGRALLs (1.95 GPa) in this study because of increasing in layers led to decrease the flexural modulus. The flexural test is applied to the combined stresses: the pressure stress is in the outer surface and the shear stress occurred in inner surface [21]. Figure 9 shows the shear strength for CAGRALLs. The figure indicates that the shear strength is varied for three specimens. The figure is indicated that the shear strength is varied from 18.3 to 26.7 MPa.

(a) Sample before flexural test  (b) Sample after flexural test

Figure 6. Flexural test sample
Figure 7. Flexural strength values for FMLs

Figure 8. Flexural modulus values for FMLs

Figure 9. Shear strength values for CAGRALLs

Figure 10 showed that sample before and after Impact test. It has used for finding the impact energy absorbed per volume of sample by CAGRALLs. Figure 11 shows the impact toughness for CAGRALLs. Vasumathi et al [11], obtained the impact toughness $\left(23.24 \times 10^{-4} \text{ J/mm}^3\right)$ is lower than CAGRALLs $\left(31.85 \times 10^{-4} \text{ J/mm}^3\right)$ in this study because of increasing in layers for FMLs causing decreasing in impact toughness and using
carbon with jute fibers led to have the low impact toughness by comparing with using carbon with glass fibers.

Figure 10. Impact test sample

Figure 11. Impact toughness values for FMLs

Figure 12 showed that sample before and after fatigue test. Figure 13 shows the number of life (N) for CAGRALLs under the fluctuating loadings that lead to failure. In this work, it has used range of stresses (R = -1). Reversed stress levels from 100 to 300 MPa were used. At reversed stress (100 MPa); the number of life was obtained 3.1482 x 10⁴ cycles for CAGRALLs. At reversed stress (200 MPa), the number of life was obtained 6.266 x 10³ cycles for CAGRALLs. Chulpova et al [10], used The GLARE 3/2 lay-up has unidirectional fiber. The range of stress (R = 0.04) was used. The number of life for GLARE under stresses applied that lead to failure can be showed in figure 6 [10]. The GLARE has high number of cycles with using epoxy by comparing with FMLs with using blend of epoxy-novolac because this blend has more cracks that
led to reduce number of cycles. Qaiser et al [12], used aluminum sheet reinforced by Kevlar 49 fiber cloth bonded by epoxy with range of stress (R= 5) and obtained that the number of cycles (3000 cycles) is lower to CAGRALLs because of carbon fiber have excellent fatigue resistance by comparing with other fibers. The Kevlar fiber was considered hinder for any crack propagation. Typically, the range of stresses is lower than zero (R< 0 ) caused low fatigue life for composite materials [22].

(a) Sample before fatigue test                   (b) Sample after fatigue test

Figure 12. Fatigue test sample

Figure 13. S-N curve for CAGRALLs
The design of wing must be caused decreasing in its weight so that aluminum used more than metals like steel. The density of aluminum is 2.78 g/cm³ and steel is 7.86 g/cm³ [20]. The density is achieved from fabrication of CAGRALLs (1.951 g/cm³). It indicated that the density of CAGRALLs is lower comparing to aluminum and steel. These CAGRALLs caused reduction 29.82% of aircraft wing weight by comparing with aluminum alloys 2024-T3, which is used in manufacturing in this part.

4. Conclusion
This study was the first attempt to know and study the changes and improvement of mechanical properties for CAGRALLs, which used in manufacturing of aircraft wing. The tensile strength has increased up to certain limit and ten fails due to the variation of metal-fiber laminate. The flexural strength also shows the same trend due to three different materials such as fibers and aluminum. The impact damage and fatigue resistance are good with using hybrid FMLs. The CAGRALLs has high tensile strength, elastic modulus, elongation at fracture and flexural modulus except flexural strength comparing with CACAGRALLs. The CAGRALLs has high elongation comparing to aluminum. The CAGRALLs has high impact toughness comparing with CAJURALLs. The CAGRALLs has the low density comparing to aluminum alloy 2024-T3.

5. References
[1] Surowska B, Majerski K and Bienias J 2014 Mechanical behaviour of hygrothermal conditioned fibre metal laminates. In 16th European conference on composite materials, Seville, Spain, 22-26.
[2] Matthews FL, Davies GAO, Hitchings D, and Soutis C 2000 Finite element modelling of composite materials and structures. Elsevier. Published by Woodhead Publishing Limited, Abington Hall, Abington Cambridge CB1 6AH, England.
[3] Hariharan E., and Santhanakrishan R 2016 Experimental Analysis Of Fiber Metal Laminate With Aluminium Alloy For Aircraft Structures, International Journal Of Engineering Sciences & Research Technology, 5(5).
[4] Ardakani MA, Khatibi A A and Ghazavi S.A 2008 A study on the manufacturing of Glass-Fiber-Reinforced Aluminum Laminates and the effect of interfacial adhesive bonding on the impact behavior. In Proceedings of the XI International Congress and Exposition, Orlando, Florida USA.
[5] Linde P, Pleitner J, de Boer H and Carmone C 2004 Modelling and simulation of fibre metal laminates. In ABAQUS Users’ conference (pp. 421-439).
[6] Li D and Guo S 2013 Optimization of Composite Wing Structure for a Flying Wing Aircraft Subject to Multi Constraints. In 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (p. 1934).
[7] Shafizadeh JE and Seferis JC 2000 Characterization of phenolic resins for composite honeycomb applications. Society of Manufacturing Engineers, Seattle, Washington, United States of America, p.1285.
[8] Ratna D 2009 Handbook of thermoset resins. Shawbury, UK: ISmithers.
[9] Ibrahim AM, Mubarak TH , Adwan AA. and Hussian WA 2017 Study of Adding Cement to Hardened Powdered Novolac Resin Matrix for Manufacturing Novel Concrete in the Presence of Heat and Pressure, Diyala Journal For Sciences 13(3).
[10] Chlupová A and Kozák V 2012 Fatigue Crack Growth And Delamination In Fiber Metal Laminate (Glare) During Loading With Positive Mean Stress. 18th International Conference Engineering Mechanics, 300, pp. 531–536.
[11] Vasumathi M and Murali V 2013 Effect of alternate metals for use in natural fibre reinforced fibre metal laminates under bending, impact and axial loadings. International Conference On Design And Manufacturing. Procedia Engineering, 64, p.562-570
[12] Qaiser MH, Umar S and Nauman S. 2014 Development and characterization of fatigue resistant Aramid reinforced aluminium laminates (ARALL) for fatigue Critical aircraft components. *In IOP Conference Series: Materials Science and Engineering* Vol. 60, No. 1, p. 012050.

[13] Rajkumar GR, Krishna M, Narasimhamurthy HN, Keshavamurthy YC and Nataraj JR. 2014 Investigation of tensile and bending behavior of aluminum based hybrid fiber metal laminates. *International Conference on Advances in Manufacturing and Materials Engineering (AMME)*, Procedia Materials Science, 5, 60-68.

[14] Harichandan A and Kumar KRV. 2016 Study on tensile behaviour of carbon jute aluminum-fiber metal laminates. *International journal of mechanical and production engineering*, ISSN, 2320-2092.

[15] Emberey C L, Milton NR, Berends JPTJ, Van Tooren, M.J.L, Van der Elst SWG and Vermeulen B 2007 Application of knowledge engineering methodologies to support engineering design application development in aerospace. In 7th AIAA ATIO Conf, 2nd CEIAT Int'l Conf on Innov and Integr in Aero Sciences, 17th LTA Systems Tech Conf; followed by 2nd TEOS Forum (p. 7708).

[16] Gharkan, MR 2017 Improvement the Mechanical and Physical Properties of Epoxy–Polyurethane Matrix Resin by Using Kevlar Fiber and ZnO Particles. *Engineering and Technology Journal*, 35(3), p.261-266.

[17] Husien WAK, Mubarak TH and Ibrahim A. M 2016 *Mechanical and Insulation Properties of Light Weight Concrete Produced by Phenolic Resin (Novolac)*, Diyala University, college of science, Diyala, Iraq.

[18] Astrom B 1997 *Manufacturing of Polymer Composites Chapman & Hall*. (pp. 1-175).

[19] Al-Mutairee HM, and Al-Hamdan HA 2017 Flexure Behavior of Hybrid Continuous Deep Beam Strengthened by Carbon Fiber Reinforced Polymer. *Journal of University of Babylon*, 25(5), 1580-1592.

[20] American Society for Metals. 1990 *Metals handbook. 2. Properties and selection: nonferrous alloys and special-purpose materials*. American Society for Metals: pp 48-188.

[21] Rijab MA, Kader EI, Hamod AA ,and Hameed AH I 2017 Mechanical properties of silica, graphite and carbon fiber reinforced composites, *International Journal of Engineering and Technology (IJET)*, 9 (5) 2319-8613.

[22] Tomblin J and Seneviratne W 2011 Determining the fatigue life of composite aircraft structures using life and load-enhancement factors. *Final report, Air Traffic Organization, Washington DC, USA*.

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