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COMPOSITES THEORY AND PRACTICE

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THE MECHANICAL PROPERTIES AND FAILURE ANALYSIS OF SELECTED FIBER METAL LAMINATES

Composite materials have developed in recent years. Fiber reinforced polymer composites (laminates) and aluminum alloys currently constitute the most dominant materials applied in the aerospace industry. The paper presents the tensile properties of selected fiber metal laminates regarding the content of structural components. Additionally, the failure characteristics of the tested specimens were determined. The hybrid systems (Fiber Metal Laminates) in this study were based on the 2024-T3 aluminum alloy and glass and carbon fibers reinforced polymers. The tensile properties were determined according to ASTM D 3039. The strain gauge Vishay CEA-06-125UT-350 was employed to measure the strain. The results have shown that the tensile properties of both tested types of laminates depend on the metal volume fraction factor. The investigated specimens showed a bilinear character in the stress-strain curves. The findings imply that the tensile properties of fiber metal laminates depend on the type of composite reinforcement, metal volume contribution and fibers orientation. It can be noted that with a decrease in the metal volume fraction and a layer orientation change from 0 by 0/90 up to 45 results in a decrease in the Young's modulus of the tested laminates. Several fracture modes were identified depending on the lay-up configuration and type of reinforcing fibers. Use of the metal volume fraction approach in predicting the mechanical properties is appropriate for both carbon and glass fiber reinforced fiber metal laminates.

Keywords: Fiber Metal Laminates, tensile properties, failure analysis

WYBRANE WŁAŚCIWOŚCI MECHANICZNE ORAZ ANALIZA ZNISZCZENIA LAMINATÓW METALOWO-WŁÓKNISTYCH

Kompozyty polimerowe wzmacniane włóknami są od kilku dekad stosowane z powodzeniem jako materiały konstrukcyjne w przemyśle lotniczym. Nową generację materiałów o dużym potencjale rozwoju stanowią laminaty metalowo-włókniste. Laminaty tego typu poprzez swoją hybrydową konstrukcję łączą korzystne właściwości polimerowych laminatów kompozytowych wzmacnianych włóknami oraz lekkich stopów aluminium tradycyjnie stosowanych w przemyśle lotniczym. W pracy przedstawiono wyniki badań wytrzymałości na rozciąganie laminatów metalowo-włóknistych zawierających warstwy kompozytowe wzmacniane włóknami węglowymi oraz szklanymi w układzie jednokierunkowym. Badane były laminaty z różną orientacją warstw kompozytowych. Testy wytrzymałościowe przeprowadzono zgodnie z normą ASTM D 3039 na prostopadłościennych próbkach o długości 180 mm i szerokości 15 mm dla włókien ułożonych w kierunku (0) i 20 mm dla włókien ułożonych w kierunku (0/90 i ±45) w warstwie kompozytowej laminatu. Dla badanych materiałów uzyskano bilinearne charakterystyki naprężeniowo-odkształceniowe oraz silną zależność pomiędzy kierunkiem ułożenia włókien w warstwie kompozytowej a wartością wytrzymałości na rozciąganie oraz sztywności. Wykazano liniową zależność pomiędzy objętościową zawartością metalu a wytrzymałością na rozciąganie i sztywnością dla laminatów wzmacnianych zarówno włóknami szklanymi, jak i węglowymi. Dodatkowo dokonano analizy zniszczenia badanych próbek w mezoskali z użyciem mikroskopu optycznego (Nikon SMZ1500). Zaobserwowano istotne różnice w charakterach zniszczenia warstw kompozytowych wzmacnianych włóknami węglowymi oraz szklanymi, co jednak nie wpływa znacząco na opisane powyżej zależności i przewidywanie właściwości mechanicznych.

Słowa kluczowe: laminaty metalowo-włókniste, właściwości wytrzymałościowe, analiza zniszczenia

INTRODUCTION

Fibre reinforced polymer composites and aluminum alloys currently are advanced engineering materials having a wide range of applications in aerospace [1]. In fact, Fiber Metal Laminates (FML) are a new generation of composites possessing superior properties of both metals and fibrous composite materials. Generally, FMLs have both low weight and good mechanical properties [2-4]. This combination produces a material which has significant improvements in some or all properties including high strength-to-weight and stiffness-to-weight ratios, fatigue, impact resistance, low density, corrosion and fire resistance [3-6].

Currently, due to their excellent properties, FML laminates have been used by a number of aircraft manufacturers in the design of primary aircraft components e.g. the fuselage of Airbus A380, and also applied in the leading edges of the vertical and horizontal tail planes of the A380 [4].

Because hybrid laminates are a relativity new material technology, the material properties still need to be characterized. Moreover, there is limited and insufficient information available about the mechanical behavior of FML in the published literature and some areas still remain to be further verified by more detailed testing and analysis. The metal volume fraction (MVF) also called the *metal layer contribution* assumes a linear relationship between the relative contribution of the aluminum layers and the mechanical properties in Glare laminates [5-7]. The Metal Volume Fraction is defined as the ratio of the sum of the thickness of the individual aluminium layers and the total thickness of the laminate [5]. That approach is very similar to the rule of mixtures used for composites [8]. The MVF approach is utilized to predict approximate values of tensile strength, compression strength, shear strength, bearing strength, and blunt notch strength in the range of 0.45 < MVF < 0.85 [5, 9, 10].

This paper presents the results of tensile strength tests of fiber metal laminates conducted to validate the feasibility of using the relationship of mechanical properties and metal volume fraction for glass and carbon reinforced fiber metal laminates.

MATERIALS AND METHODS

The hybrid laminate systems examined in this study were prepared by stacking alternating layers of 2024-T3 aluminum alloy and glass (Al/G) and carbon fibers (Al/C) reinforced polymer. Two types of composite reinforcement were used: unidirectional (0.25 mm thick) R-glass and AS7-carbon (thickness of 0.131 mm) high strength fibers/epoxy prepregs (Hexcel, USA). The nominal fibres content was about 60 vol. Different fibre orientations (0, 0/90, ±45) for FML configurations were considered.

The lay-up schemes of the FML were 3/2 and 2/1 (for example, 3/2 represents three layers of aluminum sheet and two layers of fibre reinforced polymer). Two standard aluminum alloy sheet thicknesses, 0.3 and 0.5, were used to control the desired metal volume fraction. The total thickness of each composite layer in the laminates was constant (0.5 mm) respectively 4 layers of CFRP and 2 layers of GFRP.

The FMLs were produced by the autoclave technique (Scholz, Germany) with the following parameters: heating and cooling rate of 2°C/min, curing temperature of 135°C, pressure of 450 kPa and vacuum of 80 kPa.

Tensile tests were carried out on rectangular specimens with a total length of 180 mm, a width of 15 mm for (0) fibre orientation and 20 mm for (0/90, 45), and total thickness dependent on the laminate configurations. The tensile properties were conducted with the use of a universal servo-hydraulic testing machine (MTS 322) at room temperature. Fractographic analysis of the laminates was studied using an optic microscope (Nikon SMZ 1500, Japan).

RESULTS AND DISCUSSION

Typical stress/strain curves for the tested FMLs are presented in Figure 1 a) and b). Generally, laminates exhibit complex behavior under tension due to the plasticity of the aluminum layers. The stress/strain curves of the tested materials consist of the initial part up to the aluminum layers and a post-yield linear part that only depends on the stiffness of fiber reinforced polymer composites. On reaching the maximum stress, the composite layers fractured in a brittle manner and similar results were obtained in [5].

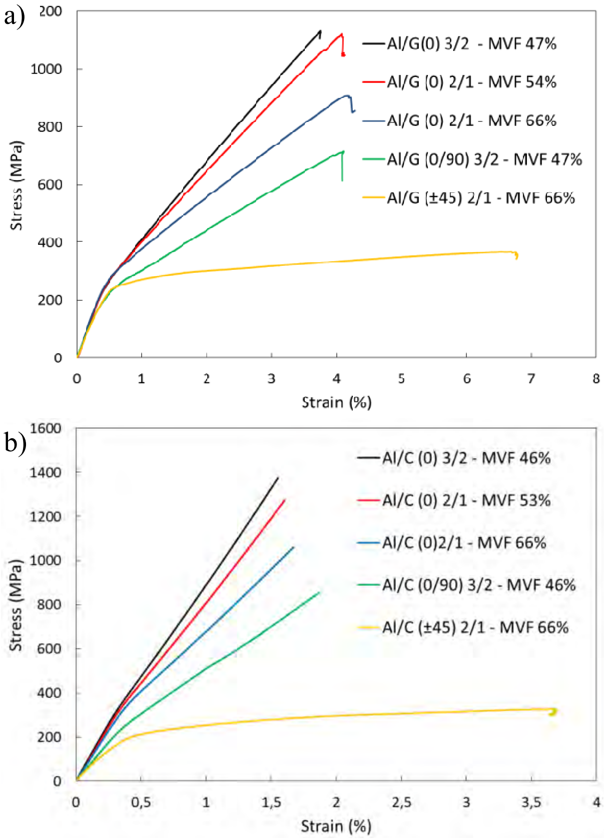

Fig. 1. Typical stress/strain curves for: a) Al/G, b) Al/C laminates with different fiber orientations

Rys. 1. Typowa krzywa naprężenie/odkształcenie dla laminatów: a) Al/G, b) Al/C z różną orientacją włókien w warstwach kompozytowych

The results of the tensile properties tests of the studied materials are listed in Table 1. Analysis of the tensile properties revealed that there were significant differences overall among the strength parameters for FMLs with a different type and stacking sequence of polymeric composites. The specific hybrid laminate structure consisting of metal and composite layers results in a higher tensile strength of the laminates compared to the monolithic aluminum alloy. From Table 1, it can be concluded that the tensile values of the Al/C laminates are higher than that of Al/G (by 16÷22%). Moreover, significantly higher tensile properties of the studied FMLs with carbon fibers were observed when compared with the glass fibers. Nevertheless, for the laminates with fiber orientations in the (45) direction, the tensile properties are similar for both the reinforcement fibers.

Comparison of the tensile modulus shows decreases in Al/G with respect to the monolithic aluminum alloy (by 17÷45%). However, the tensile modulus of the Al/C laminates is much higher due the high stiffness of the carbon fibers.

TABLE 1. **Tensile properties of tested Fibre Metal Laminates**
TABELA 1. **Właściwości wytrzymałościowe badanych laminatów metalowo-włóknistych**

Laminate	Metal volume friction MVF [%]	Young's modulus E [GPa]	Poisson ratio ν	Ultimate tensile strength σ_{ult} [MPa]	Tensile strain ε [%]
Al/G 3/2 [0]	47	60.60 (±0.87)	0.37 (±0.01)	1137.56 (±35.05)	3.72 (±0.07)
Al/G 2/1 [0]	54	60.06 (±2.51)	0.32 (±0.01)	1 080.98 (±114.89)	3.96 (±0.26)
Al/G 2/1 [0]	66	62.87 (±0.57)	0.31 (±0.02)	918.80 (±24.21)	4.23 (±0.12)
Al/G 3/2 [0/90]	47	50.44 (±0.36)	0.31 (±0.01)	705.34 (±11.45)	4.12 (±0.15)
Al/G 2/1 [±45]	66	52.26 (±0.71)	0.36 (±0.01)	365.62 (±2.49)	6.62 (±0.05)
Al/C 3/2 [0]	46	104.78 (±1.62)	0.37 (±0.02)	1 375.91 (±55.83)	1.54 (±0.05)
Al/C 2/1 [0]	53	100.55 (±0.36)	0.30 (±0.01)	1294.80 (±33.71)	1.63 (±0.02)
Al/C 2/1 [0]	66	91.38 (±0.61)	0.31 (±0.02)	1071.01 (±39.62)	1.7 (±0.04)
Al/C 3/2 [0/90]	46	69.35 (±0.88)	0.23 (±0,02)	865.72 (±31.98)	1.84 (±0.04)
Al/C 2/1 [±45]	66	52.99 (±1.28)	- -	327.01 (±1.28)	3.57 (±0.13)
2024 T3*	100	73.1	0.33	490	18

* ASM Metals Reference Book, Third edition, Michael Bauccio, Ed. ASM International, Materials Park, OH, 1993.

To examine the influence of the metal volume fraction, it can be concluded that a decrease in MVF increases the tensile strength of FMLs (Fig. 2). The beneficial effect is caused by increasing the amount of high strength glass and carbon/epoxy composites. For Al/G and Al/C laminates, the tensile strength is 87÷232% and 218÷280% higher than the aluminium alloy, respectively. Moreover, greater tensile strength of the Al/C laminates was observed when compared with the Al/G (by 17÷21%). Incorporation in the quantity of carbon/epoxy composites into FML systems offers a rise in tensile modulus. However, in the case of Al/G laminates, a similar level of tensile modulus with volume fraction was noted. The tensile yield strength for Al/C laminates also increases with an increasing carbon/epoxy composites volume fraction.

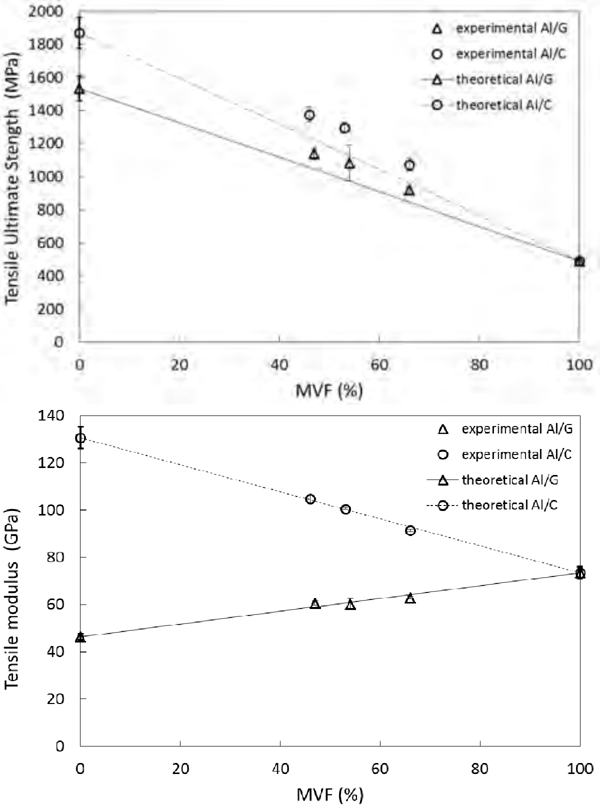

Fig. 2. Tensile properties versus Metal Volume Fraction approach - fibers direction (0)

Rys. 2. Wytrzymałość na rozciąganie oraz sztywność w odniesieniu do objętościowej zawartości metalu - kierunek włókien w warstwie kompozytowej (0)

Figure 2 shows the tensile strength of the laminates with the metal volume fraction. A linear relationship was observed.

The experimental results were compared with the metal volume fraction approach based on a rule of mixtures used to predict the properties of traditional composites. The MVF approach for prediction of the mechanical properties of fiber metal laminates reinforced with glass fibers is presented in [5, 10]. In carrying out the analysis, individual identities of the fibre and matrix were ignored. Each individual layer of laminate (aluminium alloy or composite layer) is treated as a homogeneous, orthotropic sheet and the laminated hybrid material was analyzed using the classic theory of laminated plates [8].

Thus, the ultimate tensile strength and tensile modulus may be predicted as follows:

$$\sigma_{ult}^{Lam} = \mathrm{MVF}\sigma_{ult}^{\mathrm{Al}} + (1 - \mathrm{MVF})\sigma_{ult}^{\mathrm{C}} \quad (1)$$

and

$$E^{Lam} = \mathrm{MVF}\, E^{\mathrm{Al}} + (1 - \mathrm{MVF})E^{\mathrm{C}} \quad (2)$$

where is the laminate ultimate strength, MVF is the metal volume fraction, is the aluminium alloy ultimate strength, is the fibre-reinforced composite ultimate strength, is the Young's modulus of the laminate, is the Young's modulus of the aluminium alloy and is the Young's modulus of the composite.

The predictions offered by Equation (1), included in Figure 2, and the experimental values show quite good correlation. However, the maximum deviation was calculated using the rule of mixtures and it was about 8÷10%.

A comparison between the experimental and theoretical prediction (Eq. (2)) results for the tensile modulus of Al/G and also Al/C laminates shows good agreement, within 2.5% and 1.7% accuracy, respectively.

Figure 3 shows a series of typical morphologies of failure modes observed in the laminates after the mechanical tests.

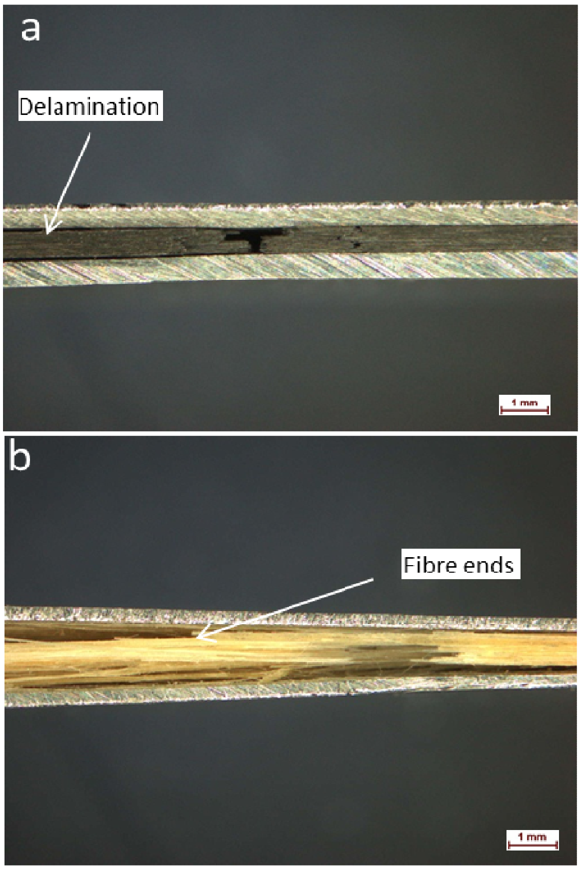

Fig. 3. Lateral surface of (a) Al/C and (b) Al/G specimens reinforced in (0) direction after tensile test

Rys. 3. Boczna powierzchnia próbki (a) Al/C i (b) Al/G (włókna w kierunku 0) po próbie wytrzymałości na rozciąganie

In the FMLs based on composites with (0) fibers orientation (Fig. 3), the micrographs revealed that the damage occurred in the laminates is related to complete failure of the composite layers and on the interface between the metal and fiber reinforced polymer composite. Evaluation of the character of damage indicates the presence of extensive debonding leading to broom-like failure morphology for the Al/G laminate. This is caused by poor interface strength between the glass fibers and epoxy matrix and is described in [11]. The Al/C laminate exhibits brittle failure with one major area of fibers separation. Delamination between the composite and metal layers occurring in both cases are the result of shear stresses in the plane of the interface, and the energy dissipated at the moment of failure.

Figure 4 represents a typical cross-section in the Al/C (±45) and Al/G (±45) laminates.

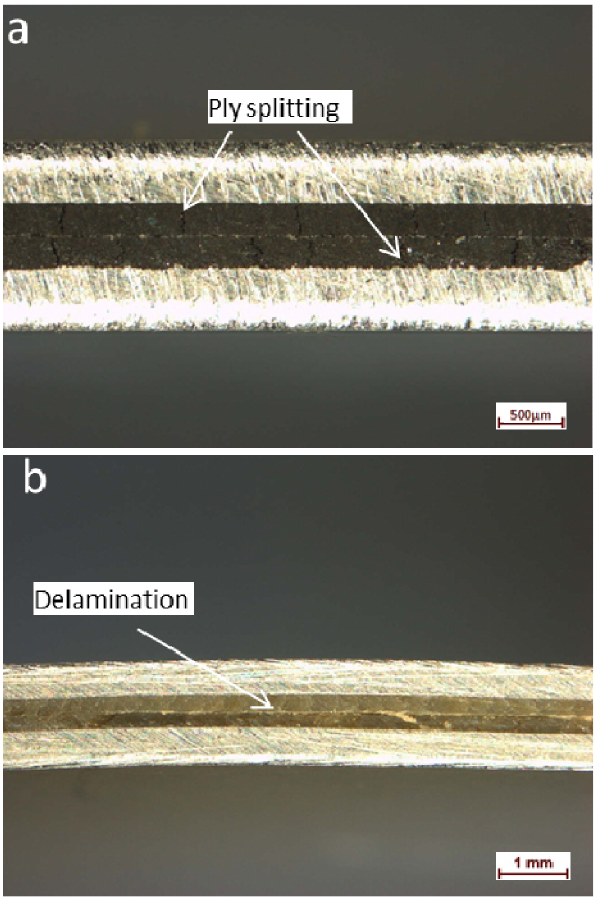

Fig. 4. Lateral surface of (a) Al/C and (b) Al/G specimens reinforced in (±45) direction after tensile test

Rys. 4. Boczna powierzchnia próbki (a) Al/C i (b) Al/G (włókna w kierunku ±45) po próbie wytrzymałości na rozciąganie

From Figure 4, it is evident that the laminates with fibers orientation angles of (±45) exhibited a mixture of shear failure and transverse fracture. Delaminations between the composite plies and transverse cracks were observed. For both the tested laminates, similar failure modes were observed.

The failure modes of the Al/C and Al/G laminates with a (0/90) stacking sequence of composite layers are shown in Figure 5. Examination of the micrograph revealed the presence of a number of cracks in the composite layers, delaminations and deformations of the outer side of the aluminium layers after unloading. Fracture in the (90) composite plies occurred in a brittle manner and transverse cracks oriented perpendicular to the direction of the applied load were observed.

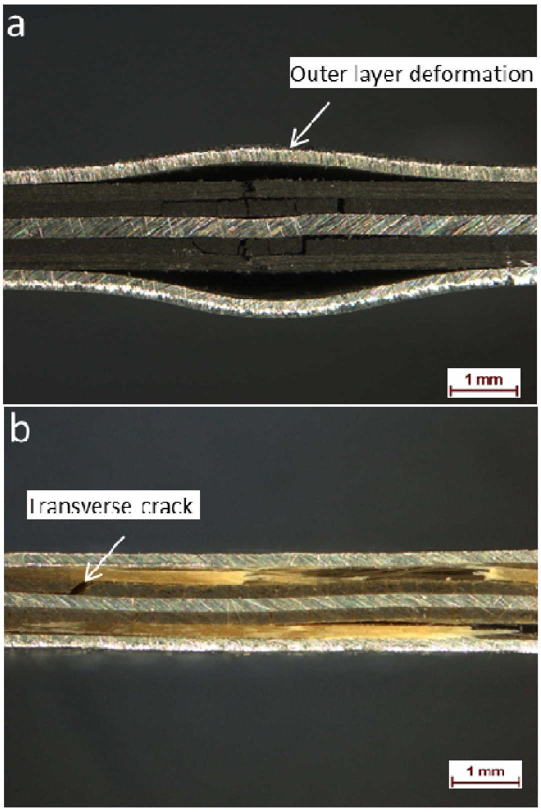

Fig. 5. Lateral surface of (a) Al/C and (b) Al/G specimens reinforced in (0/90) direction after tensile test

Rys. 5. Boczna powierzchnia próbki (a) Al/C i (b) Al/G (włókna w kierunku 0/90) po teście wytrzymałości na rozciąganie

CONCLUSIONS

In this paper fiber metal laminates based on glass and carbon fibers reinforcement polymers were introduced and the tensile properties of the laminates in different stacking sequences were analyzed. The tensile tests revealed that laminates with unidirectional fibers strongly exhibit directional properties. The fibers contribute to the strength and modulus in the direction along which they are aligned, while the metal layers control the laminate tensile properties in the transverse direction. Selected design properties of FMLs reinforced with glass and carbon fibers can be predicted as a function of their metal volume fraction, and this approach requires only a minimum testing effort on a few laminate configurations. Characteristic failure modes for laminates with different fibers orientation in composite plies were also found. Despite the different nature of failure observed in the meso-scale for individual FMLs, the Metal Volume Fraction approach is an important tool for the design of composite structures.

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