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FIBRE METAL LAMINATES - SOME ASPECTS OF MANUFACTURING PROCESS, STRUCTURE AND SELECTED PROPERTIES

Fibre Metal Laminates (FML) are hybrid materials, consisting of alternating layers of thin metal sheets and composite layers. FML possess superior properties of both metals and fibrous composite materials. Fibre Metal Laminates are characterized by excellent damage tolerance: fatigue and impact and characteristics, low density, corrosion and fire resistance. Glare as a type of FML are composites consisting of thin aluminium layers and glass fiber reinforced epoxy composites. The most common method used to produce FML including Glare is autoclave processing (under relatively high pressure, vacuum, elevated temperature). The first large scale application of Glare laminates is the fuselage and leading edges of the vertical and horizontal tail planes of the Airbus A-380 aircraft. Current and future research on FML is focused on generating new laminates, for example based on the combination of titanium and magnesium and carbon or glass polymer composites.

In this paper, the preliminary studies concerning the manufacturing method and the properties of new generation hybrid composite materials - titanium/glass fibre reinforced laminates (Ti-G) are described. The titanium/glass composites were characterized from the standpoint of their quality (ultrasonic technique- phased array C-scan method), microstructure and selected mechanical properties (tensile strength). The hybrid Ti-G laminates were prepared by stacking alternating layers of commercially pure titanium (grade 2) and R-glass fiber/epoxy prepregs. The lay-up scheme of the Ti-G composites were 2/1 (two layers of titanium sheet and one layer of glass/epoxy prepreg as a [0,90] sequence) and 3/2.

It was found that (1) manufacturing Fibre Metal Laminates including Ti-G composites using the autoclave technique is advantageous for the reason of obtaining higher quality and repeatability of the composite structures, (2) the titanium/glass fiber reinforced laminates demonstrated good bonding between the metal and composite layers and homogeneous structure without discontinuities, (3) manufactured Ti-G composites are characterized by high mechanical properties - tensile strength due to the excellent properties of both components, titanium and glass-fibre composite materials, (4) titanium/glass fiber reinforced laminates are new generation hybrid materials, which can be potentially used for composite structures in aerospace.

Keywords: **Fibre Metal Laminates, hybrid titanium composite, glass fibres, microstructure, mechanical properties**

LAMINATY METALOWO-WŁÓKNISTE - WYBRANE ASPEKTY PROCESU WYTWARZANIA, STRUKTURY I WŁAŚCIWOŚCI

Laminaty metalowo-włókniste *(Fiber Metal Laminates*) są materiałami hybrydowymi, składającymi się z kolejno ułożonych (na przemian) warstw metalu i kompozytu polimerowego. Laminaty FML łączą w sobie właściwości zarówno metalu, jak i materiału kompozytowego wzmacnianego włóknami. FML charakteryzują się wysoką tolerancją uszkodzeń, wysoką wytrzymałością zmęczeniową, odpornością na uderzenia, niską gęstością, odpornością na korozję oraz ognioodpornością. Laminaty Glare jako jeden z rodzajów FML stanowią kompozyty składające się z cienkich warstw aluminium oraz kompozytu polimerowego wzmacnianego włókami szklanymi. Najbardziej powszechną metodą wytwarzania laminatów FML, w tym Glare, jest technika autoklawowa (wysokie ciśnienie, podciśnienie, podwyższona temperatura). Pierwsze komercyjne zastosowanie laminatów typu Glare stanowią panele kadłuba oraz krawędzie natarcia pionowego i poziomego usterzenia ogonowego w samolocie Airbus A380. Zarówno aktualne, jak i przyszłe prace naukowo-badawcze w zakresie kompozytów FML ukierunkowane są na wytwarzanie nowej generacji laminatów zawierających tytan lub magnez, z kompozytami polimerowymi wzmacnianymi włóknami węglowymi oraz szklanymi.

W pracy przedstawiono wstępne badania dotyczące metody wytwarzania oraz właściwości nowej generacji hybrydowych materiałów kompozytowych typu: tytan/kompozyt polimerowy wzmacniany włóknami szklanymi (Ti-G). Kompozyty tytan/włókna szklane charakteryzowano pod kątem jakości (badania nieniszczące ultradźwiękowe - metoda phased array C-scan), mikrostruktury oraz wybranych właściwości mechanicznych (wytrzymałość na rozciąganie). Hybrydowe laminaty Ti-G stanowiły warstwy czystego technicznie tytanu (garde 2) oraz kompozytu polimerowego wzmacnianego włóknami szklanymi typu R, w układzie 2/1 (dwie warstwy tytanu oraz jedna warstwa kompozytu o ułożeniu warstw [0/90]) oraz w układzie 3/2. Wykazano, że: (1) wytwarzanie kompozytów metalowo-włóknistych (FML) metodą autoklawową jest korzystne ze względu na wysoką jakość i powtarzalność struktur kompozytowych, (2) laminaty tytan/włókna szklane charakteryzują się dobrą przyczepnością metal-kompozyt oraz jednorodną strukturą bez widocznych nieciągłości, (3) wytworzone kompozyty Ti-G odznaczają się wysokimi właściwościami mechanicznymi - wytrzymałością na rozciąganie dzięki wysokim właściwościom poszczególnych komponentów: tytanu i kompozytu polimerowego wzmacnianego włóknami szklanymi, (4) kompozyty tytan/włókna szklane stanowią nową generację materiałów hybrydowych, które mogą znaleźć potencjalne zastosowanie w przemyśle lotniczym.

Słowa kluczowe: **laminaty metalowo-włókniste, tytanowy kompozyt hybrydowy, włókna szklane, mikrostruktura, właściwości mechaniczne**

INTRODUCTION

Fibre Metal Laminates (FML) are hybrid materials consisting of alternating layers of thin metal sheets and composite layers [1, 2] (Fig. 1). These layers are bonded together with the matrix material of the composite layer. FML possess superior properties of both metals and fibrous composite materials. Fibre Metal Laminates are characterized by excellent damage tolerance: fatigue and impact characteristics, low density, corrosion and fire resistance [1-6]. Specific Fibre Metal Laminates are determined by the type of metal alloy and composite, layer thickness, number of layers in the laminate, and the fibre orientations [1, 7].

FML composites were developed at the Delft University of Technology at the beginning of the 1980's [2, 8] primarily under the trade name ARALL (Aramid Reinforced Aluminium Laminates) and then GLARE (GLAss REinforced aluminium).

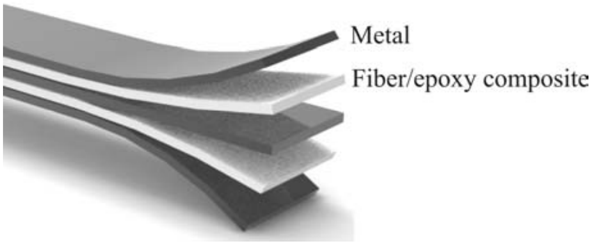

Fig. 1. Configuration of Fibre Metal Laminate (3/2 lay up)

Rys. 1. Schemat budowy (konfiguracji) kompozytu FML (układ 3/2)

Glare as a type of FML laminates are composites consisting of thin aluminium layers (0.2 to 0.5 mm) and glass fiber reinforced epoxy composites (layers in the range 0.25÷0.5 mm). The fibre orientations can occur in different directions [2, 4, 7]. The typical grades and configurations of Glare laminates are shown in Table 1.

TABLE 1. **Typical grades of Glare laminates [3, 5, 9]**
TABELA 1. **Typowe rodzaje laminatów typu Glare [3, 5, 9]**

Material grade	Sub	Alloy type and thickness	Fibre layers (orientation)	Main beneficial characteristics
Glare 1	-	7475-T76 (0.3-0.4)	Unidirectional	Fatigue, strength, yield stress
Glare 2	Glare 2A	2024-T3 (0.2-0.5)	Unidirectional	Fatigue, strength
	Glare 2B	2024-T3 (0.2-0.5)	90/90	Fatigue, strength
Glare 3	-	2024-T3 (0.2-0.5)	0/90	Fatigue, impact
Glare 4	Glare 4A	2024-T3 (0.2-0.5)	0/90/0	Fatigue, strength in 0° direction
	Glare 4B	2024-T3 (0.2-0.5)	90/0/90	Fatigue, strength in 90° direction
Glare 5	-	2024-T3 (0.2-0.5)	0/90/0/90	Impact
Glare 6	Glare 6A	2024-T3 (0.2-0.5)	+45/−45	Shear, off-axis properties
	Glare 6B	2024-T3 (0.2-0.5)	−45/+45	Shear, off-axis properties

The most common method used to produce FML laminates including Glare is autoclave processing (under relatively high pressure, vacuum, elevated temperature) [2, 3, 5].

Generally, the manufacturing process of FML composites is as follows [3, 5]: (1) preparation of tools and materials: pre-treatment of metal layers - anodizing and application of adhesive system - primer with corrosion-inhibiting properties; (2) forming of elements: including cutting, lay-up, vacuum bag preparation; (3) cure in the autoclave: consolidation process; (4) inspection: non-destructive and mechanical tests.

The first large scale application of Glare laminates is the fuselage of the Airbus A-380 aircraft (Fig. 2) and also applied in the leading edges of the vertical and horizontal tail planes of the A380 [1,10].

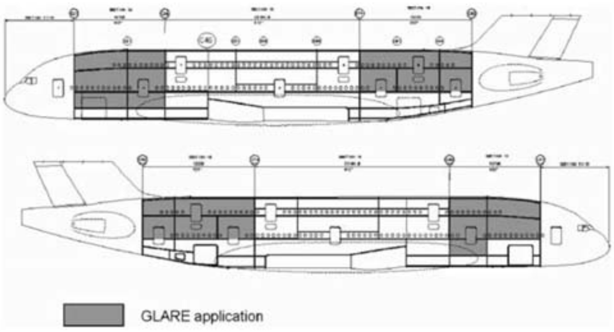

Fig. 2. Application of Glare in the upper fuselage panel for A380 [3,10]

Rys. 2. Zastosowanie Glare w górnych panelach kadłuba samolotu A380 [3,10]

Current and future research on FML is focused on generating new laminates [1, 2], for example based on the combination of titanium and magnesium and carbon or glass polymer composites [2, 3, 8, 11].

In this paper, the preliminary studies concerning the manufacturing methods and properties of new generation hybrid composite materials - titanium/glass fibre reinforced laminates are described. The titanium/glass composites were characterised from the standpoint of their quality, microstructure and selected mechanical properties.

MATERIALS AND METHODS

The subject of examination were titanium/glass fiber reinforced laminates (Ti-G). The Ti-G composites were manufactured at the Department of Material Engineering (Lublin University of Technology).

The hybrid Ti-G laminates were prepared by stacking alternating layers of commercially pure titanium (grade 2) and R-glass fiber/epoxy prepregs (Hexcel Co., USA). The lay-up scheme of the Ti-G composites were 2/1 (two layers of titanium sheet-0.5 mm per sheet and one layer of glass/epoxy prepreg-0.5mm as a [0,90] sequence) and 3/2. In this study, all titanium sheets used in the production of Ti-G laminates were only ultrasonically cleaned and degreased.

After the lay-up process (in a clean room), a vacuum bag was prepared and the laminates were placed in the autoclave system (Scholz Maschinenbau, Germany). The curing cycle was done at a heating rate from 2°C/min up to 135°C and held at this temperature for 2 hours (cooling rate: 2°C/min). The pressure and vacuum of 450 kPa and 80 kPa, respectively, were applied. Figure 3 shows a diagram of the autoclave cure cycle for titanium/glass-epoxy laminates.

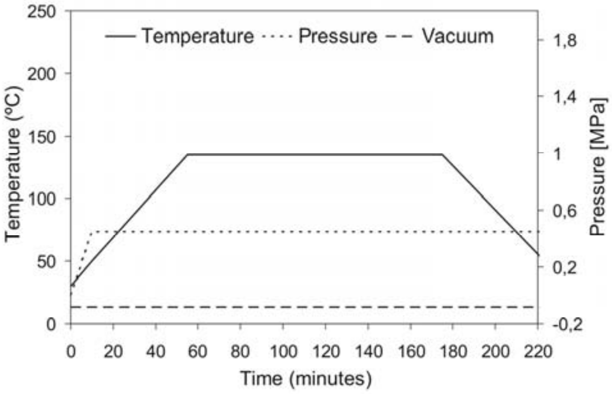

Fig. 3. Diagram of autoclave cure cycle for titanium/glass-epoxy laminates

Rys. 3. Schemat cyklu utwardzania w autoklawie lamiantów: tytan/włókna szklane-żywica epoksydowa

The structural quality inspection of Ti-G laminates was carried out through non-destructive testing using the ultrasonic technique (phased array method, C-scan).

The mechanical properties (tensile strength) were performed with the use of a universal testing machine (Z100, Zwick, Germany) according to PN-EN 10002-1+AC1 standard.

The microstructure analysis of titanium/glass fiber reinforced epoxy laminates were studied using optical and stereoscopic microscopes (Nikon MA200 and SMZ 1500, Japan).

RESULTS AND DISCUSSION

Figure 4 shows the titanium/glass fibre laminates after the curing cycle in the autoclave. The macroscopic observations and analysis of the curing parameters confirmed that the manufacturing process was performed properly.

The microstructures (cross-section) of titanium/glass fibre laminates are presented in Figure 5. From this figure the homogeneous structure of Ti-G laminates and quite uniform distribution of glass fibres may be observed. Microscopic observations of the interface, which directly influence the quality of bonding, indicate that in both cases quite good bonding between the polymer composite and the titanium sheet was obtained. No visible structural discontinuity such as, porosity, microcracks or delaminations in the microstructure were found.

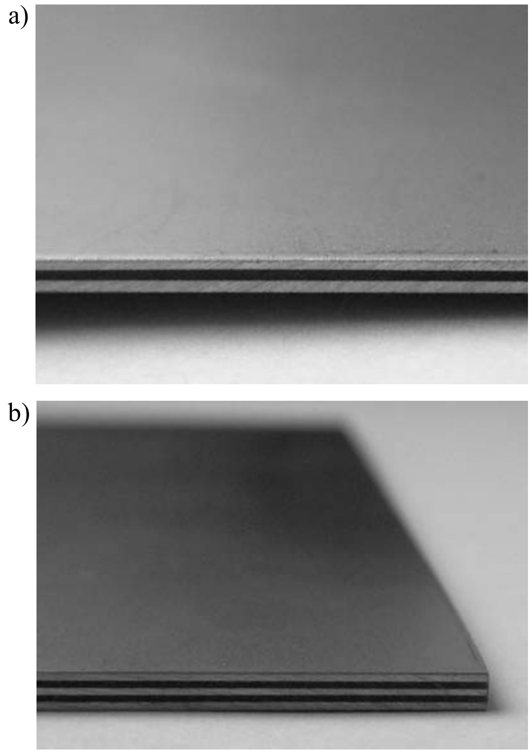

Fig. 4. Titanium/glass-epoxy laminates: a) Ti-G 2/1, b) Ti-G 3/2

Rys. 4. Laminaty: tytan/włókna szklane-żywica epoksydowa: a) Ti-G 2/1, b) Ti-G 3/2

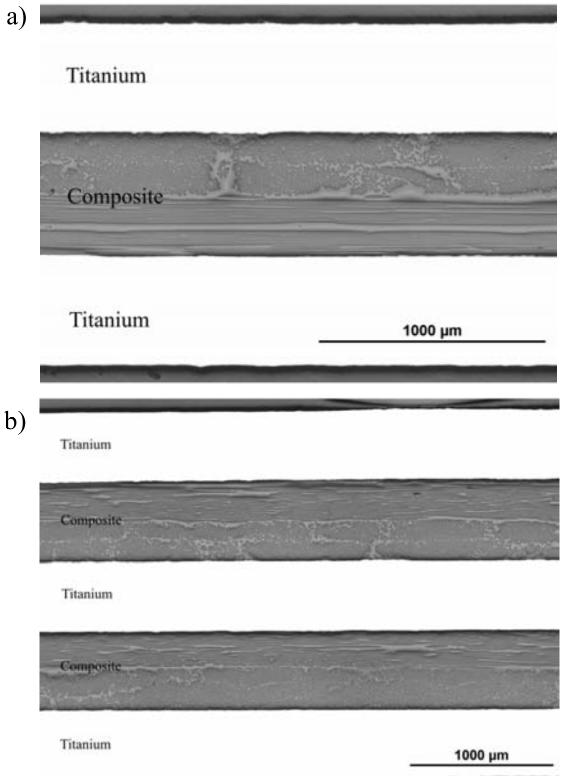

Fig. 5. Microstructure of titanium/glass-epoxy laminates; (a) Ti-G 2/1 and (b) Ti-G 3/2

Rys. 5. Mikrostruktura laminatów: tytan/włókna szklane-żywica epoksydowa; (a) Ti-G 2/1, (b) Ti-G 3/2

The results of the ultrasonic phased array C-scan of the studied Ti-G composite plates are shown in Figure 6. The C-scan images confirmed good quality of the created Ti-G laminates. Internal defects such as delaminations and interlaminar cracks as well as debonding areas in the laminates were not observed.

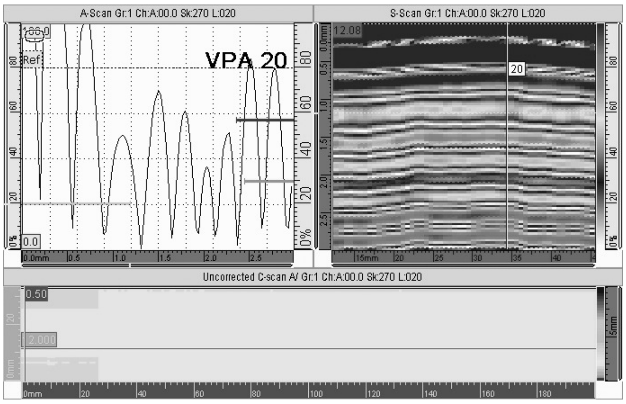

Fig. 6. Ultrasonic images: A-Scan (left), B-Scan (right) and C-scan (bottom) of Ti-G composite plates

Rys. 6. Obrazowanie A-Scan (lewa), B-Scan (prawa) i C-scan (dół) kompozytów Ti-G

The results of the tensile strength of the selected materials: Ti-G laminates, titanium and conventional glass fiber reinforced polymers are listed in Table 2. The mean values of the tensile strength ranged from 608 MPa (Ti-G 2/1) to 660 MPa (Ti-G 3/2). The tensile strength increased by 50% in comparison to the other materials, for example commercially pure titanium and composites with a quasi-isotropic sequence. There is a combination of high stiffness and strength from the composite layer and good mechanical, high resistance to elevated temperatures and corrosion properties from titanium.

TABLE 2. **Tensile properties of selected materials**

TABELA 2. **Wytrzymałość na rozciąganie wybranych materiałów**

Commercially pure titanium	Glass/epoxy composite [0/±45/90]s	Glass/epoxy composite [0]	Ti-G 2/1 [0/90]	Ti-G 3/2 [0/90]
450 MPa	378 MPa	1534 MPa	608 MPa	660 MPa

Figure 7 shows the typical morphologies of the failure modes observed in Ti-G laminates after the mechanical tests. The micrographs revealed that the damage in Ti-G laminates occurred at the interface between the metal sheet-titanium and glass fiber reinforced polymer (see Fig. 7). However, failure was also located inside the composite laminate particularly in the 90° layers. It indicates mixed adhesive and cohesive failure.

FML are new composite materials for advanced aerospace structural applications [2, 3]. FML offer a unique combination of properties and easy manufacture and repair. Manufacturing FML using the autoclave technique is advantageous for the reason of obtaining higher structural homogeneity and excellent quality of the composites, minimum void content (<1%), full control of the elements and process during curing and high strength properties of the composites [2, 3, 12]. In the present study, good quality of FML produced using the autoclave method is also confirmed.

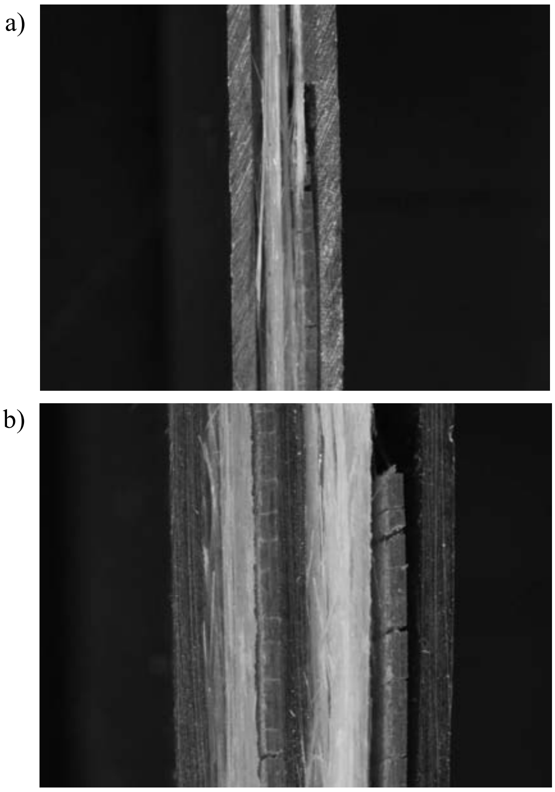

Fig. 7. Typical failure modes of titanium/glass-reinforced composites: a) TiG 2/1, b) Ti-G 3/2

Rys. 7. Typowy rodzaj zniszczenia kompozytów: tytan/włókna szklane-żywica epoksydowa: a) TiG 2/1, b) Ti-G 3/2

The mechanical behaviour of the laminates is influenced by a wide range of different parameters directly related to the properties of the metal and composites used in FML. The fibres have a significant impact on the stiffness and strength properties of the laminates. The high strength of the laminates, in fibre direction, depends mainly on the strength of the fibres. In the transverse direction however, the metal constituent dominates the strength of the laminate [1, 5]. In FML composites, the interface bond between the fiber/epoxy laminate and the metal plays an important role in the transfer of stresses in the composite, regarding the fiber/matrix interface [5]. Degradation of these components can therefore lead to a decrease in mechanical properties [13-15].

The failure process of FML is quite complicated and there are multi-fracture modes involved the failure in FML composites, such as matrix cracks, fiber-matrix debonding, fiber fracture, metal/composite failure, and interdelamination of the laminates [3]. For longitudinal tensile loading, fibre pull-out and an interface-matrix shear mode are commonly observed in the fiber-epoxy layer of FML. The metal layer prevents multiple overall longitudinal splits. Under transverse tensile loading, matrix failure and matrix-fiber interface debonding are the main fracture modes in the fiber-epoxy layer of FML [3, 5].

To sum up, it can be concluded that more investigations are needed to obtain a better understanding of the structure and properties of fibre metal laminates.

CONCLUSIONS

The following conclusions can be drawn from this study:

1) Manufacturing Fibre Metal Laminates including Ti-G composites using the autoclave technique is advantageous for the reason of obtaining higher quality and repeatability of the composite structures.
2) The titanium/glass fiber reinforced laminates demonstrated good boding between the metal and composite layers and homogeneous structure without discontinuities.
3) The manufactured Ti-G composites are characterized by high mechanical properties - tensile strength due to the excellent properties of both components, titanium and glass fibre composite materials.
4) Titanium/glass fiber reinforced laminates are new generation hybrid materials, which can be potentially used for composite structures in aerospace.

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