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COMPOSITES THEORY AND PRACTICE

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STRUCTURE CHARACTERISTICS IN GLASS/ALUMINUM HYBRID LAMINATES AFTER BENDING STRENGTH TEST

During the last few years, many scientists and industries have become interested in developing new materials which would maintain good mechanical properties and low density comparable with aluminum alloys. This can be observed predominantly in the aircraft or aerospace industry. Fiber metal laminates (FML) are a new kind of composite, particularly the Glare® type laminate, which consists of aluminum and a glass/epoxy composite. FML combine both the good characteristics of metal such as ductility and durability with the benefits of fiber composite materials such as high specific strength, high specific stiffness, good corrosion resistance and fatigue resistance.

In this paper, an FML consisting of aluminum and glass fiber/epoxy layers has been introduced. The FML were produced by the autoclave technique. The aluminum sheets were special prepared with chromic acid and sulphuric acid aluminum anodizing. Two combinations of fiber configuration were selected: Al/[0]/Al and Al[0/90]/Al. The structure characterization after bending tests is shown and discussed. Microstructural analysis has been carried out using an optical microscope. The three point-bending tests were conducted according to standard specifications. Preliminary studies have shown that the metal layers in the laminates and the composite polymer layer, particularly in the bend area in the laminate, have a significant impact on the nature of the damage. Laminate destruction indicates the complexity of the degradation process of these materials. The orientation of the reinforcing fibers has an influence on the degree of destruction of the laminate structure which may have a decisive effect on the ability of forming laminates. An important factor influencing the properties of the laminate as a whole is to provide high adhesive properties of the composite-metal connections.

Keywords: **fiber metal laminates, bending test, microstructure**

CHARAKTERYSTYKA STRUKTURY LAMINATÓW HYBRYDOWYCH SZKŁO/ALUMINIUM PO BADANIACH WYTRZYMAŁOŚCI NA ZGINANIE

W ciągu ostatnich kilkunastu lat zarówno wielu naukowców, jak i branże przemysłu zainteresowały się opracowaniem nowych materiałów, które posiadałyby dobre właściwości mechaniczne i małą gęstość, porównywalne ze stopami aluminium. W szczególności można zaobserwować to w przemyśle lotniczym i kosmicznym. Laminaty metalowo-włókniste ze względu na swoje wysokie właściwości mechaniczne znalazły zastosowanie właśnie w przemyśle lotniczym; dotyczy to zwłaszcza laminatów typu Glare®. Posiadają one, tak jak metale, zespół dobrych charakterystyk, takich jak plastyczność i trwałość. Korzyści płynące z włókien kompozytowych to między innymi wysoka wytrzymałość, wysoka sztywność, odporność na korozję i odporność na zmęczenie mechaniczne.

W artykule przedstawiona została charakterystyka laminatów metalowo-włóknistych na bazie aluminium i włókien szklanych po badaniach wytrzymałości na zginanie. Laminaty zostały wytworzone metodą autoklawową. Zastosowano dwa typy anodowania aluminium w kwasie chromowym i w kwasie siarkowym. Wybrano dwie kombinacje ułożenia włókien: Al/[0]/Al i Al[0/90]/Al. Przedstawiono charakterystykę struktury po badaniach wytrzymałości na zginanie za pomocą mikroskopii optycznej. Testy wytrzymałości na zginanie przeprowadzono zgodnie z normą.

Wstępne próby wykazały, że istotny wpływ na charakter zniszczenia mają warstwy metalowe w laminatach i warstwy kompozytu polimerowego zwłaszcza w miejscu zgięcia laminatu. Zniszczenie laminatów wskazuje na złożoność procesu degradacji tych materiałów. Orientacja włókien wzmacniających ma wpływ na wielkość zniszczenia struktury laminatu, które może mieć decydujący wpływ na zdolność do formowania laminatów. Ważnym czynnikiem wpływającym na właściwości laminatów jako całości jest zapewnienie wysokiej wytrzymałości adhezyjnych połączeń metalowo-kompozytowych.

Słowa kluczowe: **laminaty metalowo-włókniste, zginanie, mikrostruktura**

INTRODUCTION

During the last few years, many scientists and industries have been involved in developing new materials which would maintain good mechanical properties and low density comparable with aluminum alloys. This can be observed predominantly in the aircraft or aerospace industry.

A new type of laminated composites are Fiber Metal Laminates. Thin metal layers of aluminum and glass fiber epoxy resin pre-pregs are called Glare®. They combine both the advantageous characteristics of metal such as ductility and durability with the benefits of fiber composite materials such as high specific strength, high specific stiffness, good corrosion resistance and fatigue resistance [1]. Glare® was optimized for aircraft fuselage skins when the first member of the FML family (Arall) was not to be able to meet all the expectations of engineers [2]. The main advantage of hybrid laminates, which is a positive balance of mechanical properties, is achieved through a sandwich laminate structure. A construction of this type may in principle be susceptible to delamination, which substantially improves the validity of the adhesive connection between the layers of the laminate. There is a variety of tests for measuring strength and adhesion that rely on relatively simple mechanics. For complete information about the properties of composite materials, failure observations are performed, more numerous than that required for metal products. Basic measurements like tensile, compressive, flexural strength and interlaminar shear strength are conducted on samples [3]. Lawcock et al. [4, 5] concentrated on failure characteristics such as crack growth behavior in the aluminum and composite layers and delamination between layers. During bending in a particular state of stress, depending on the state of the material and the bending conditions, it is desirable to obtain complex loading conditions, thereby producing a mixed nature of damage. From the bend tests, more information about the failure behavior of composites under conditions of actual use is received [6]. Surface preparation can play an important role in determining the adhesive bond strength between the polymer composite and metal in laminates and it is governed by the adhesion. There are a few methods for surface preparation for example mechanical, electrochemical and chemical treatment. Beside this, the same properties of FMLs are governed by the interface bond between the composite ply and metal ply [7]. In the literature, various test methods like interfacial fracture or interlaminar shear have been proposed to evaluate the adhesive connection in composite laminates. It depends on the application and destination like aerospace or motorization [3-5].

In this paper, an FML laminate consisting of aluminum and glass fiber/epoxy layers has been introduced. The structure characterization after bending tests is shown and discussed.

MATERIALS AND METHODS

The laminates chosen for this study were FMLs composed of 2024 T3 aluminum alloy sheets with a glass fibre reinforced polymer (Al/GFRP). The sheet gauge was 0.5 mm. The composite layers consist of unidirectional prepregs (Hexcel, USA) based on R-type high-strength glass fibres with an epoxy resin matrix (thickness of 0.255 mm). The nominal fibre content was about 60 vol.%. Two types of metal sheet surface preparation were used: chromic acid anodizing (CAA) and sulphuric acid anodizing (SAA) with a primer (corrosion inhibitor). The FMLs were produced at the Department of Materials Engineering - Lublin University of Technology by the autoclave technique (ScholzMaschinenbau, Germany): curing temperature 135°C, pressure 450 kPa, vacuum - 80 kPa, heating and cooling rate of 2 K/min. Two FMLs with different fiber configuration combinations were produced:

- Al/[0]/Al
- Al[0/90]/Al

Microstructural analysis was carried out using an optical microscope (Nikon MA200, Japan). Three-point bending tests using the specifications of CRAG 3-point were carried out on an MTS Insight. These tests were undertaken at a crosshead displacement of 5 mm/min and were stopped when the sample reached - 25 mm deflection. The sample load increases slowly, uniformly to the destruction of the sample or to determine the conventional deflection.

RESULTS AND DISCUSSION

In Figure 1, the macroscopic image of fiber metal laminates after bending strength tests is shown. In this research clear disbonding and delamination in metal-polymer were not observed, whilst an angle of flexure in the center of the samples was noticed. For both (CAA) and (SAA) samples, the same scheme of macroscopic flexure was seen.

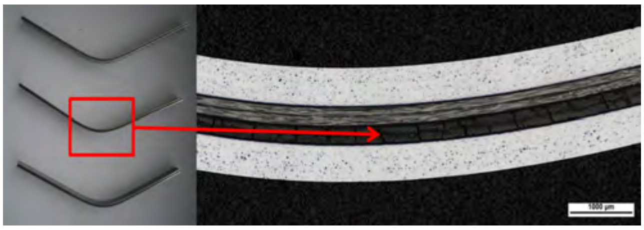

Fig. 1. Macroscopic image of aluminum- epoxy/glass laminate after bending test

Rys. 1. Makroskopowy obraz laminatu aluminium-kompozyt epoksydowo/szklany po teście zginania

Table 1 shows the main strength parameters after the bending test. In this case, there was nointerlaminar shear because there was a bigger distance between the supports in the bending test. In thesestudies similar values were obtained. σ_{max} was slightly higher for the aluminium epoxy/ glass anodized in SAA. With regard to the observations of the bending stress and how to destroy an FML, the thickness of the composite laminate and aluminum sheets plays an important role. First of all, a more important role was played by the metal properties than the same configuration of fibers.

TABLE 1. **Strength parameters after bending test of laminates**
TABELA 1. **Parametry wytrzymałościowe po teście zginania laminatów**

Configuration of fibers	Anodizing	F_{max} [N]	σ_{max} [MPa]
AlG [0]	CAA	109.19	564.63
AlG [0]	SAA	113.99	576.20
AlG [0/90]	CAA	109.30	558.20
AlG [90/0]	CAA	109.50	556.73

F_{max} - maximum force of load, σ_{max} - maximum nominal stress of carry bending.

Fig. 2. Panoramic microstructure of aluminum (CAA)-epoxy/glass laminate in [0] configuration after bending test

Rys. 2. Panorama mikrostruktury laminatu aluminium (anodowanie w kwasie chromowym) - kompozyt epoksydowo/szklany w układzie [0] po teście zginania

Figures 2, 3a and 3b illustrate the typical microstructures of the 0˚ direction laminates after the bending test. In both microstructures (3a and 3b), fiber cracks in the tension zone were observed. On reaching the assumed deflection, the fibers exceed the failure strain.

a)

b)

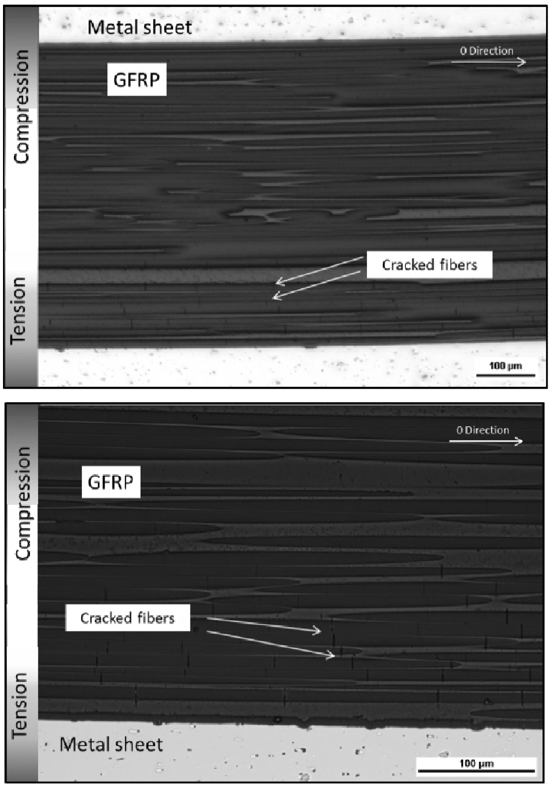

Fig. 3. Microstructure of aluminum: a) CAA, b) SAA-epoxy/glass laminate in [0] configuration after bending test

Rys. 3. Mikrostruktura laminatu aluminium: a) anodowanie w kwasie chromowym, b) anodowanie w kwasie siarkowym - kompozyt epoksydowo/szklany w układzie [0] po teście zginania

The observations showed no cracks in the matrix. Vlot et al. [2] observed two general types of failure after bending tests. One is interlaminar shear failure and the second is constituents failure. The relationship between the failure mode and the loading for Glare is mainly based on the distance between the supports in relation to the thickness of the laminate, nor are there traces of damage in compression zone. Greenhalgh et al. [8] found that the scale of destruction of composite laminates in the compression zone is larger in the case of specific flexural loadings such as buckling.

Figure 4a shows the microstructures of multidirectional laminates [0,90] after bending tests. Transverse cracks observed in the 90º plies are a consequence of stress concentrations induced by the embedded fibers and small failure strain in the perpendicular direction. Vlot et al. [2] observed transverse cracks only for laminates with at least 5 layers.

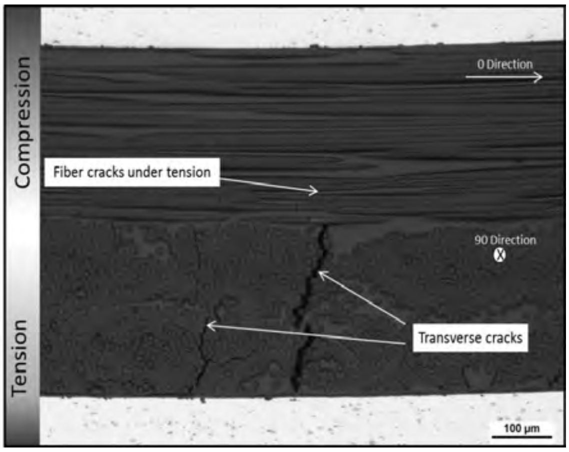

Fig. 4. Microstructure of aluminum (CAA) epoxy/glass laminate in [0,90] configuration after bending test

Rys. 4. Mikrostruktura laminatu aluminium (anodowanie w kwasie chromowym) - kompozyt epoksydowo/szklany w układzie [0,90] po teście zginania

McDevitt and Braun [9] carried out one of the earliest studies on metal-to-metal adhesive joints. These investigators found the curious result that apparently the three-point bend test was more sensitive to interfacial weaknesses than other tests they performed such as the T-peel, wedge, and lap shear test [1]. It is clearly shown in the literature [9-11] that this technique can be a powerful tool for investigating the effect of different surface preparation procedures and adhesive formulations on the adherent/substrate adhesion strength. In the previous Figures, there was good adhesion in both anodizing for CAA and SAA.

Figure 5 shows the microstructure of [0,90] laminates after bending tests in different stacking sequences. The 90° direction layer is in contrast to the previous microstructure in the compression zone. It was noted that the degree of failure is much smaller respectively for this orientation.

The fiber orientation within the layers of the composite has an impact on the nature of the destruction of the laminate during bending. The possibility of obtaining small damage at a given deflection is affordable due to the possibility of forming laminates [2].

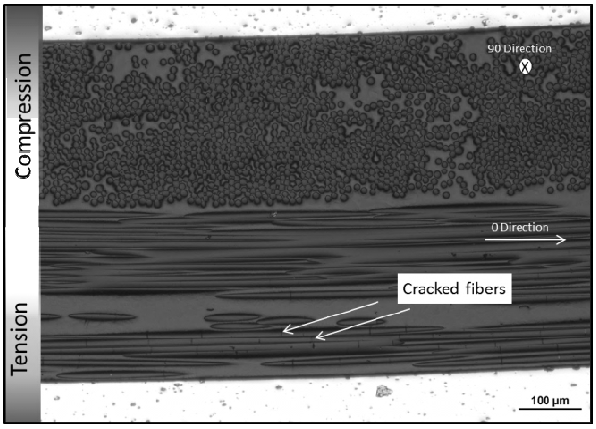

Fig. 5. Microstructure of aluminum with cracked fibers in 0° direction (CAA) in [0,90] configuration after bending strength test

Rys. 5. Mikrostruktura laminatu aluminium z widocznymi włóknami w kierunku 0°, anodowanie w kwasie chromowym - kompozyt epoksydowo/szklany w układzie [0,90] po teście zginania

Khalili et al. [1] concluded that FML samples show more flexible behavior than composite structures. They compared a glass fiber epoxy resin composite and an FML on the base of aluminum and steel with a glass composite manufactured by the hand lay-up method. Pijanowski et al. [12] assessed the bending strength. They observed in woven fabric reinforcement composites that the number of layers in the laminate affects the strength, while Klasztorny et al. [13] observed compatibility with the expected theoretical model, that in the bending test, subsequent layers crack starting from the bottom layer.

CONCLUSIONS

By comparing the results obtained in evaluating the structure characterization in the Figures, the following conclusions can be drawn:

- A higher adhesion of the metal to the polymer composite causes damage in the laminate during the bending process without the observation of delamination (destruction in the epoxy/glass composite). It is probably due to the influence of the thickness of the metal and the polymer composite to the whole laminate.
- The bending stresses were higher in the laminates, which is observed in different fiber configurations.
- The scheme of cracking is similar to the polymer composite.
- The stress concentration has a detrimental effect on the destruction in the polymer layers.
- In the 0° fiber configuration failure of the fibres was observed.
- The kind of fiber cracking depends on the stress direction: for compression, there were few cracks in the 0° layer and for tension there were cracks in the matrix of the 0° and 90° layers.

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