Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

Kompozyty 11: 2 (2011) 130-135

KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 11.02.2011

INSPECTION METHODS FOR QUALITY CONTROL OF FIBRE METAL LAMINATES IN AEROSPACE COMPONENTS

Composite materials have been applied in aerospace structures in recent years. Presently, the new generation of structural composite materials for advanced aircraft are Fibre Metal Laminates (FML). They are hybrid composites consisting of alternating thin layers of metal sheets and fiber-reinforced composite material. FMLs have both low density and good mechanical properties (high damage tolerance: fatigue and impact characteristics, corrosion and fire resistance). The quality control of the materials and structures in aircraft is an important issue, also for FMLs. For FML parts, a 100% non-destructive inspection for the internal quality during the manufacturing process is required. In the case of FML composites, the most relevant defects that should be detected by non-destructive testing are porosity and delaminations. In this paper, the use of non-destructive different methods for the inspection of Fibre Metal Laminates were studied. The possibility of quality control of manufactured FML by means of defect detection procedures and processes are presented and discussed.

Keywords: **Fiber Metal Laminates, Non Destructive Testing, failure modes in composites**

PROBLEMATYKA BADANIA KOMPOZYTÓW TYPU FML W KONSTRUKCJACH LOTNICZYCH

Materiały kompozytowe, w szczególności w konstrukcjach lotniczych, odgrywają coraz większą rolę z uwagi na większe wartości wytrzymałości właściwej niż stopy aluminium, możliwość formowania dowolnych kształtów oraz odporność na przepalenia i korozję. Szczególnym typem konstrukcji kompozytowej o charakterze hybrydowym są tzw. włókniste laminaty metalowe (ang. Fibre Metal Laminates - FML). Wykonuje się je na bazie włókien szklanych, aramidowych z warstwami wytworzonymi z aluminium (np. GLARE - Glass ALuminum REinforced) lub tytanu. Laminaty FML są już stosowane m.in. w konstrukcji płatowca samolotu Airbus A-380. Pomimo szeregu zalet takich materiałów w trakcie wytwarzania lub eksploatacji mogą powstać wady produkcyjne lub uszkodzenia eksploatacyjne wpływające na trwałość konstrukcji, w której zostaną zastosowane. W artykule przedstawiono podejście do badań takich materiałów wykonanych z FML z wykorzystaniem badań nieniszczących metodami: ultradźwiękową i prądów wirowych. Ponadto pokazano wyniki badań z omówieniem konieczności wykonywania badań i zaletami/wadami poszczególnych metod.

Słowa kluczowe: **laminaty FML, badania nieniszczące, uszkodzenia w kompozytach**

INTRODUCTION

Composite materials have been applied in aerospace structures in recent years. Presently, the new generation of structural composite materials for advanced aircraft are Fibre Metal Laminates (FML). They are hybrid composites consisting of alternating thin layers of metal sheets and fiber-reinforced composite material. FMLs have both low density and good mechanical properties (high damage tolerance: fatigue and impact characteristics, corrosion and fire resistance) [1, 2].

The quality control of materials and structures in aircraft is an important issue, also for FMLs. For FML parts, a 100% non-destructive inspection for the internal quality during the manufacturing process is required. In the case of FML composites, the most relevant defects that should be detected by non-destructive testing are porosity and delaminations [3-5].

In general, ultrasonic inspection is the most appropriate. **N**on **D**estructive **T**esting (NDT) methods are applicable for the inspection of FML parts for in-production and in-service tasks. Eddy current testing and thermography have also been used in the inspection of FMLs in specific situations [3, 4].

However, due to the complex laminate nature, its inhomogeneous structure of alternating metal and fiber-reinforced epoxy composite layers, the application of non-destructive inspection methods during the manufacturing process, and for in-service maintenance tasks is a great challenge [3, 4].

Therefore, non-destructive inspection of these complex composed materials makes high demands on inspection equipment and techniques.

In this paper, the use of different non-destructive methods for the inspection of Fibre Metal Laminates were studied. The possibility of quality control of manufactured FML by means of defect detection, procedures and processes are presented and discussed.

EXPERIMENTAL PROCEDURE

FML composites were prepared with different inserts to simulate foreign object inclusion - delamination in the control plate. The hybrid laminates were manufactured by stacking alternating layers of 1.4301 stainless steel (0.5 mm per sheet) and R-glass fiber/epoxy prepregs (0.25 mm thickness; Hexcel Co., USA). The defects (simulated delaminations) were made with polytetrafluoroethylene film with a 125 μm thickness. The lay-up scheme, dimensions and specifications of the investigated plate are shown in Figure 1.

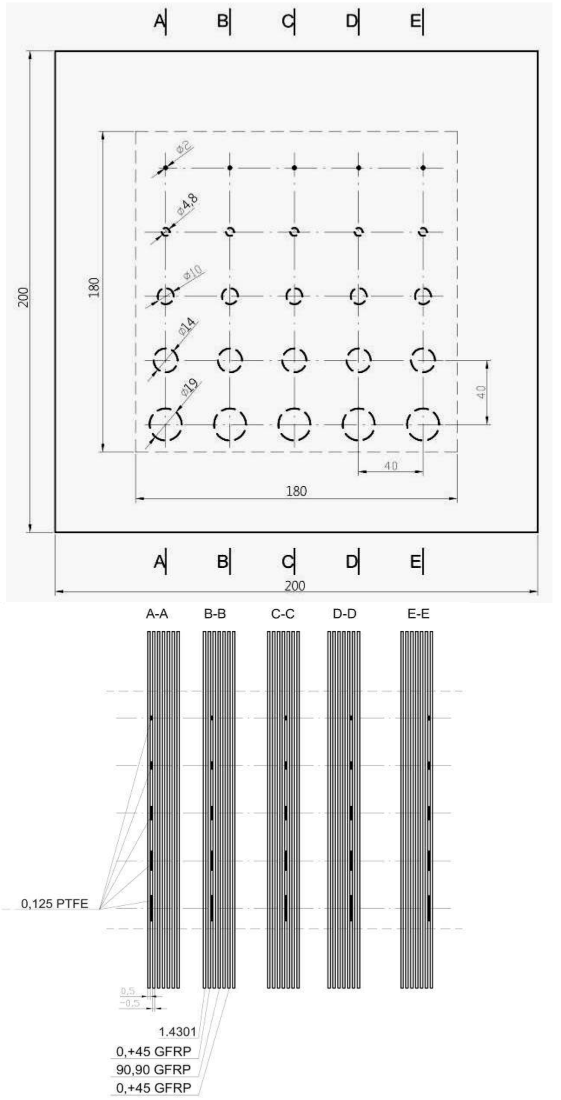


Fig. 1. Scheme of investigated FML laminate with simulated defects

Rys. 1. Schemat rozmieszczenia symulowanych wad w laminacie FML

The FML composites were produced at the Department of Materials Engineering - Lublin University of Technology by the autoclave technique (*Scholz Maschinenbau, Germany*) with the following parameters: heating and cooling of 2°C/min, curing time 135°C, pressure of 450 kPa and vacuum of 80 kPa.

For the purpose of monitoring the structure integrity of the failure modes which may occur in the FML panels, the above described NDT methods may be used [6, 7]. However, depending on the material (e.g. GLARE, ARALL) as well as material thickness and inspected geometry, the selection of an appropriate NDT technique must be made [8], which is an important issue for the possibility of damage detection. For the purpose of FML inspection, the following techniques can be applied [7, 9-11]:

- Visual (especially for inspection of fasteners and curved panels e.g. C & D checks of aircraft).
- Eddy current (application of paramagnetic materials such as aluminum alloy enable use of this technique as best for crack detection).
- Ultrasonic (most accurate inspection which enables flaw sizing and flaw depth estimation as well as thickness of the material. Failure modes possible to detect are the following: disbonds, delaminations and foreign object inclusion). Moreover depending on layers of thickness, use of dynamic B-scans or the multiple A-scans enable layer characterization [10].
- Bond Testing (use of low frequency methods based on acoustic wave generation such as: resonance, **MIA** - **M**echanical **I**mpedance **A**nalysis, Pitch - Catch which are used for disbond monitoring).
- Others such as: thermography, shearography which are under investigation at ITWL.

RESULTS AND DISCUSSION

Figure 2 shows the FML after the curing cycle in an autoclave. The macroscopic observations and analysis of the curing parameters confirmed that the manufacturing process was performed properly.

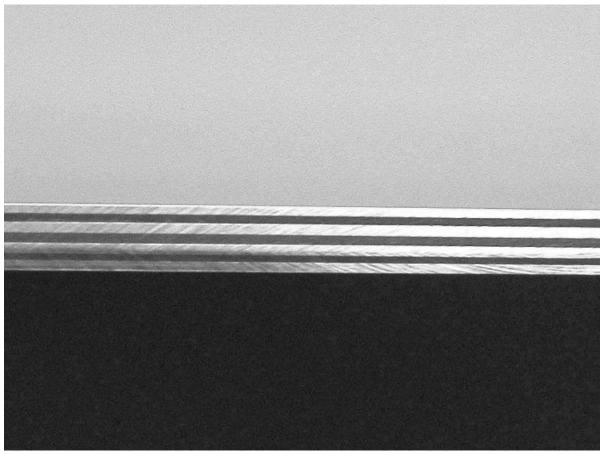


Fig. 2. Fibre Metal Laminates reference standard

Rys. 2. Próbka odniesienia wykonana z laminatu FML

The use of Non Destructive Testing for laminate manufacturing quality as well as for maintenance purposes enables damage detection and characterization in laminates [6]. The main reason for NDT is the detection of the presence of damage in such structures as well as damage growth monitoring. The main problems to achieve the structural integrity of FML composites are the possible presence of the following damages [9, 10]:

- Delaminations and foreign object inclusions (FOD)
- Cracks in aluminium layer
- Impact Damages (Barely Visible Impact Damages)

For the purpose of the sensitivity description assessment of Non Destructive methods and the possibility of damage detection evaluation, the use of so called *reference standards* or *calibration specimens* are required. An example of a reference standard with simulated damage is presented in Figure 1.

The main purpose of damage simulation is to create so called *artificial flaws* which may occur mainly in the manufacturing stage but may arise as well during the service life of the aircraft. The reasons for such behavior of FML composites during the service life of the aircraft are among others the following: manufacturing faults, impact damages, fatigue cycles and the aging process of the composite.

The flaw distribution in the specimen presented in Figure 1 enables sensitivity evaluation of the employed NDT methods and assessment of the:

1. flaw size detection possibility (i.e. the smallest detectable size)
2. detectability of damage depending on depth of damage location
3. material parameters affecting detectability (ply response, attenuation, etc.)

In the article, the approach for specimen inspection with the use of ultrasonic longitudinal (compressional) waves and eddy current techniques are presented. Moreover the ultrasonic phased array was used to provide a more detailed inspection assessment possibility.

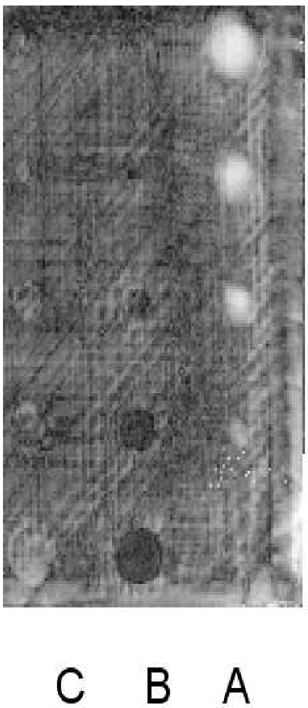
For the purpose of the damage size determination for the ultrasonic inspection, the following formula has been used:

$$SNR\,[dB] = 10\,log_{10}\frac{f(x,y)\_S}{f(x,y)\_B} \qquad (1)$$

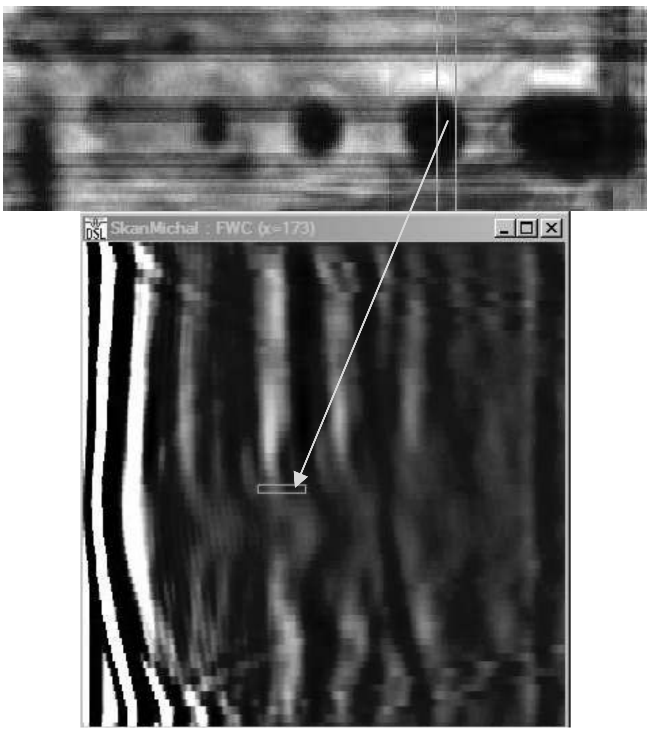
where: *f(x,y)_S* - average value of signal amplitude in damage area, *f(x,y)_B* - average value of signal around damage area (noise value).

Inspection of the multilayer structures of the FML with the use of the ultrasonic is one of the most effective techniques. The reason for that is not only the damage size description but also the depth of the damage location which is very important from the point of view of FOD and delamination detection.

Figure 3 presents the ultrasonic inspection results with the use of an automated system and single sensor as well as the Phased Array technique. The use of a single sensor did not succeed in characterizing all the damages. The use of a single sensor enabled A – B – C cross-section characterization only (Fig. 1).



I - C-scan of single sensor



II - C-scan (top) and B-scan (bottom) of Phased Array system (arrow indicates bottom flaw location)

Fig. 3. Ultrasonic results of Fibre Metal Laminate inspection

Rys. 3. Wyniki badań ultradźwiękowych laminatu FML

The reason for that was the wide band response of the single layer which makes flaw characterization difficult, especially in the bottom layers (small SNR). The use of Phased Arrays and the possibility of dynamic sound path focusing as well as data post processing permitted characterization [12, 13]. Moreover the use of the Phased Array facilitated Dynamic B-skan visualization (as presented in the Fig. 3). That data presentation technique provided a cross-section view and more detailed data analysis (for real time view inspection) than the single sensor approach. On the right side of Figure 3 only one row of the deepest located flaws is presented (E-E crossection - Fig.1). Use of the so called active gate does not make it possible to detect the presence of all damages in one image. Dynamic gate range selection and work on the collected results provide the means for the visualization of all partial damage. The important information obtained during inspection of the specimen is the following:

- Use of 0.5 mm metal sheets gives wideband reflection impulses from single layers which makes flaw characterization difficult. Especially the deepest located flaws with use of single sensor inspection are hard to characterize.
- Use of single sensor is also sensitive to flaw size determination (use of appropriate transducer diameter selection is required or transducer type) frequency generation and Pulse Repetition Frequency are other issues which have to be taken in consideration (avoidance of resonance phenomena, appropriate time resolution, non linear effects exclusion, diffraction phenomena decrease) use of Phased Array and Data Compounding (dynamic post processing) enable all depth flaw characterization - but they require a skillful data processing operator and specialized processing unit.
- Damage size estimation relative error is less than 1% (higher for deeper located flaws and smaller flaws).

The above described damages were detected with the use of the so called longitudinal (**compressional**) ultrasonic wave technique called Pulse – Echo. The main disadvantage of ultrasonic inspection is the difficulty in locating in-plane damage which is not perpendicular to the sound path (such as cracks in the metal layer). The detection of such damages may be possible with the use of so called **shear** waves. The concept of longitudinal (compressional waves) and shear waves may be explained with the use of the following wave equation formula [14]:

$$(\lambda + \mu)u_{j,ji} + \mu u_{j,jj} + \rho f_i = \rho \ddot{u} \qquad (2)$$

where λ and μ are the Lame constant, ρ is the medium density, u is the displacement.

If we use the Hemholtz decomposition theory, equation (2) may be presented as follow:

$$\mathbf{u} = \nabla\Phi + \nabla \times \mathbf{H} \qquad \nabla \cdot \mathbf{H} = 0 \qquad (3)$$

where: Φ - scalar potential, **H** - vector potential.

$$\text{I} \quad \nabla^2\Phi = \frac{1}{c_l^2}\ddot{\Phi}, \quad c_l = \left(\frac{\lambda + 2\mu}{\rho}\right)^{\frac{1}{2}}$$

$$\text{II} \quad \nabla^2\overline{H} = \frac{1}{c_s^2}\ddot{\overline{H}}, \quad c_s = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}} \qquad (4)$$

The final obtained solution may be divided into two equations: I - for compressional waves and II for shear waves. As we can see from equation (4), the acoustic wave velocities in solid media are different (c_l - velocity of the compressional wave, c_s - velocity of shear wave). Solution II for non solid media does not exist. The correct values of the velocity depends on the material properties (Lame constants λ and μ) and for depth damage description, there is a requirement to determine the correct value of the wave velocity.

For equation (4) it is possible to obtain a solution for different directions (e.g. metal structure - due to the isotropy of the medium). For composites, that problem is more difficult because such media has acoustic anisotropy due to the fiber directions. Moreover in such thin structures under shear wave excitation, the dispersion phenomena occurs. The response of the structure to such excitation is very complex and also because of the multiple layers, reflection of the signal from a crack may be hard to collect.

For that reason, to detect cracks in an FML structure, the use of eddy currents is the solution which enables in-plane damage characterization. In Figure 4a, the scheme of a GLARE structure obtained from a 0.5 mm 2024 aluminum alternating layer with GFRP layers is presented.

a)

b)

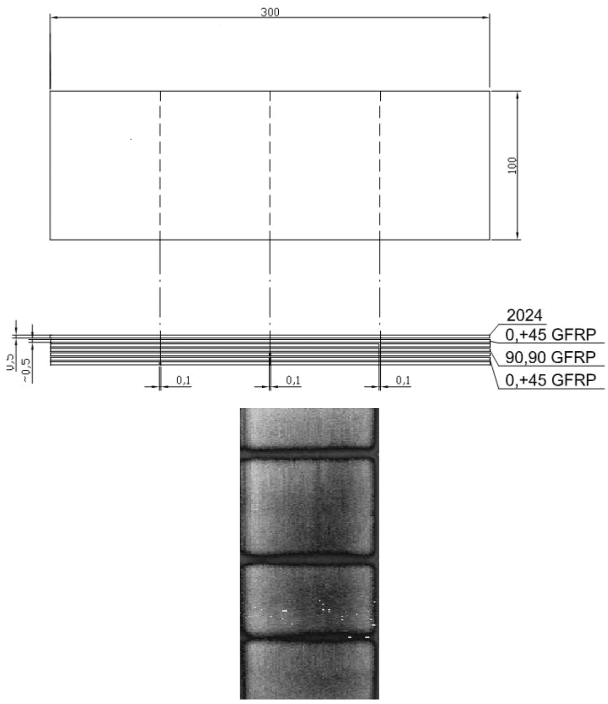


Fig. 4. GLARE crack inspection results with use of eddy currents (Im display) and specimen scheme

Rys. 4. Wyniki badań prądowirowych laminatu GLARE (zobrazowanie Im) z pęknięciami i schemat próbki

Figure 4b presents the eddy current results based on surface probe inspection with the use of a 1 kHz frequency. In the specimen, three EDM notches were made to simulate crack propagation in the metal layer of the FML. The depth of the location of the notches was different. The eddy current signal may be presented as a real (**Re**) and imaginary (**Im**) component. The visualization may be presented on the so called Impedance Plane (as the so called - flying dot display) or as an image (presented in the article). The real part of the signal characterizes the damage size (signal amplitude) the imaginary part of the signal characterizes the depth of the flaw location. In Figure 4, the results of the **Im** part of the signal are presented. The noticeable intensity gradients in the damage area refer to the damage location (on the bottom, the deepest located flaw) - the more intensive signal, the closer the damage is located to the surface.

For the eddy currents, the frequency of signal generation is the key issue for successful damage characterization. Generally, based on the frequency, the depth of the penetration of the eddy currents may be determined. The formula which covers the standard depth of penetration Dp [mm] can be expressed as follows:

$$Dp = \frac{661}{\sqrt{f \cdot \delta \cdot \mu}} \tag{5}$$

where: δ - electrical conductivity, % IACS, μ - magnetic permeability, f - inspection frequency, kHz.

The accuracy of the inspection results is based on appropriate frequency selection as well as the probe size. The limitation of the technique is connected to the material thickness and also material treatment (e.g. anodizing) which may affect the signal. Moreover an important issue is the drop in sensitivity with a decrease in frequency. That phenomena is described as the eddy current density parameter. Current density J_x decreases with an increasing depth of penetration (frequency decrease). The formula which expresses that phenomena can be written as follows:

$$J_x = J_o e^{-\frac{x}{d}} \tag{6}$$

where: J_0 - current density on surface, A/m^2, x - distance from surface, d - standard depth of penetration.

Such phenomena should be considered as the inspection searches for deeper crack locations. In practice, it means that the sensitivity of the currents is reduced for a greater depth of penetration. This leads to the conclusion that small flaws located deep in the structure may be missed during inspection. For that reason, tests on the specimen as well as determination of the smallest flaw size for the selected technique is the key issue.

SUMMARY

The article highlights only the approach for the diagnostics of FML structures. Those structures are the most commonly used in aerospace components. The advantages of such structures are moving toward durability improvement, however, different failure modes in the structure of FML may occur. The failure modes which may occur in such structures are similar to those in epoxy composites but some of them are associated with fracture mechanics similar to e.g. aluminum alloys.

The use of NDT will bring information about the structure integrity of such elements. In the article only the approach to ultrasonic inspection and eddy current inspection was presented. There is a high readiness level of NDT technique capabilities for flaw detection in FMLs, however, there are still some concerns which have to be resolved. The examples of such concerns for the NDT techniques presented in the article are as follows:

1. Inspection parameters optimization for eddy currents and ultrasonic (frequency, probe/transducer size, signal to noise ratio).
2. Signal processing may be an issue especially for ultrasonic (complicated shape, wideband response of signal, structure attenuation), use of Phased Array greatly improves flaw detection. Use of full raw data collection and diversity of signal compounding/ steering functions may enhance sensitivity of the technique. That may enable use of highly qualified staff and elaboration of signal processing algorithms.

In the article, the approach to impact damage was not presented. Failure mode complications and the existence of multiple flaws are not possible for a short description of that phenomena in this article. At present, further work of the ITWL and the Lublin Technical University on BVID detection and crack growth monitoring are in progress.

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