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COMPOSITES THEORY AND PRACTICE

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THE ISSUES OF MANUFACTURING GEOMETRICALLY COMPLICATED ELEMENTS USING FML LAMINATES

The present study is an attempt to evaluate the developed exclusive technology for the production of high quality thin-walled Z profiles from Fibre Metal Laminates on the basis of an aluminium and epoxy-glass pre-impregnate using the autoclave process. The research examined Fibre Metal Laminates (Al/GFRP) based on metal sheets made of aluminium alloy and pre-impregnated tape made of glass fibres in an epoxy resin matrix. FML were produced in a 3/2 lay-up (three aluminium layers and two composite layers in 0/90 configuration). The following conclusions have been drawn on the basis of our exclusive technology for the production of thin-walled profiles made of FML laminates: (1) the hardening technology for preformed components in the autoclave process ensures the achievement of excellent dimensional tolerance of thin-walled profiles made of FML; (2) no delaminations, cracks, gas blisters etc. were detected by means of structural tests; (3) the process of forming Fibre Metal Laminates by means of component pre-forming does not significantly limit the values of selected profile angles. In the case of proper precision of component pre-formingand maintained regime in the case of the FML laminating process, the risk of structural defects, including profile corner zones, is significantly limited.

Keywords: FML, autoclave, NDT, microstructure

PROBLEMATYKA WYTWARZANIA ZŁOŻONYCH GEOMETRYCZNIE ELEMENTÓW Z LAMINATÓW FML

W pracy podjęto próbę oceny opracowanej autorskiej technologii wytwarzania wysokojakościowych, cienkościennych profili typu Z z laminatów metalowo-włóknistych na bazie aluminium i preimpregnatu epoksydowo-szklanego z wykorzystaniem technologii autoklawowej. Przedmiotem badań był laminat metalowo-włóknisty (Al/GFRP) na bazie arkuszy blach metalowych stopu aluminium i preimpregnowanej taśmy z włókien szklanych w osnowie żywicy epoksydowej. Laminaty FML wytworzono w układzie 3/2 (trzy warstwy aluminium i dwie warstwy kompozytu w konfiguracji 0/90). Na podstawie przeprowadzonej analizy opracowanej technologii wytwarzania cienkościennych profili z laminatów FML sformułowano następujące wnioski: (1) technologia utwardzania wstępnie ukształtowanych komponentów z wykorzystaniem techniki autoklawowej zapewnia otrzymanie wysokiej stabilności i tolerancji wymiarowej cienkościennych profili z laminatów FML; (2) badania strukturalne nie wykazały rozwarstwień, pęknięć, pęcherzy gazów itp. w strukturze laminatu; (3) kształtowanie profili z laminatów metalowo-włóknistych przez wstępne formowanie komponentów nie ogranicza istotnie wartości dobieranych kątów kształtowników. Przy zachowaniu odpowiedniej precyzji wstępnego formowania komponentów oraz przy przestrzeganiu technologii laminowania kompozytów FML ryzyko defektów w strukturze, w tym w strefach naroży profili, jest znacznie ograniczone.

Słowa kluczowe: FML, autoklaw, badania nieniszczące, mikrostruktura

INTRODUCTION

Fibre Metal Laminates (FML) are the modern hybrid materials consisting of light metal alloys e.g. aluminium and a polymer-fibre composite. Owing to their high strength and fatigue properties as well as high impact resistance, these materials are widely used e.g. in the construction of airships, mainly for fragments of their skins [1-3]. As the authors of studies [2, 3] emphasized, the skin elements of airships consist of flat areas and of integrated reinforcements, beams and other structure stiffening profiles [1, 4]. The scope of basic shapes applied in aircraft structures most frequently encompasses curved panels, thin-walled tubes, closed profiles, Z and C-shaped profiles etc. In the first place, these profiles are characterized by high rigidity, while preserving low mass and high ultimate strength [5, 6]. In the opinion of the authors of [7], thin-walled load-carrying structures are characterized by high rigidity and strength-to-weight ratio. Owing to these properties, thin-walled elements are applied in light weight constructions, such as aircraft structures, which must meet rigorous requirements with regard to operating under complex loads. The thin-walled profiles used in the aircraft industry can be successfully made of composite materials. Many studies have been published in this field describing the benefits but also the problems resulting from the application of this type of materials for thin-walled profiles [7-10]. Among others, Kubiak et al. [11] as well as Paszkiewicz et al. [12] described the topics associated with the compression and bending as well as load-bearing capacity of thin-walled profiles until their destruction and in a further loading phase, indicating that profiles with complex shapes maintain their capability to withstand loads in the post-buckling state.

Taking into account the recently discovered properties of composite materials, including FML (e.g. fatigue resistance, ultimate strength and rigidity, while preserving low density [13, 14]), it has been found that thin-walled profiles with complex shapes, ensuring additional favourable properties, among others as a result of increased rigidity and buckling resistance, can be produced from fibre metal laminates (FML) [1, 3, 15].

However, the production of thin-walled FML profiles with complex shapes which could be characterized by dimensional stability and repeatability of structure quality without any defects, would be associated with numerous problems, e.g. the occurrence of cracks in the profile bends [1, 3, 15]. The authors of studies [1, 3] determine plastic forming e.g. in the form of bending, wounding FML previously produced in the form of panels as one of the possible methods of FML forming. However, they indicate that this type of solution has significant limitations in the scope of the formability of these materials associated with the brittleness of the composite filling of the laminate. In the opinion of the author of [1], the applicable plastic strain is limited to the maximum failure strain of the fibre in the fibre direction. Since the deformation of fibres is elastic until failure, a laminate shows considerable springback after deformation in the fibre direction, springback that reduces the permanent strain in the fibre direction to a mere 2÷3% in the case of GLARE. The deformation perpendicular to the fibre direction, only relevant for unidirectional laminates, is limited by the failure strain of the resin or the metal alloy. An excessive deformation range may lead to local buckling, delaminations, polymer matrix cracks and even to fibre cracks in the structure [1].

In order to increase the possibility to build more complex shapes consisting of FML, it is desirable to develop the process of FML shaping before their final hardening. Another possible alternative method described by Edwardson et al. [15] consists in the use of the laser technique in FML shaping. However, this method can be used for selected types of FML, with filling based on a thermoplastic matrix with a limited number of layers. Unfortunately, this method can lead to delaminations on the metal-composite interface as a result of the occurrence of shear stresses. The potential applicability of this method is additionally limited because the deformability is lower than twenty degrees.

An alternative process of FML forming consists in independent preliminary component forming and in their connection thereafter. However, this process may lead to other structural defects e.g. mismatching corner radii and general variability of profile wall thicknesses [3].

The present study is an attempt to evaluate the developed exclusive technology for the production of high quality thin-walled Z profiles from Fibre Metal Laminates on the basis of aluminium and an epoxy-glass pre-impregnate using the autoclave process.

MATERIALS AND METHODS

The research examined Fibre Metal Laminates (Al/GFRP) based on metal sheets made of 0.3 mm thick 2024-T3 aluminium alloy and pre-impregnated tape made of R type glass fibres in an epoxy resin matrix (Hexcel, USA) with the thickness of a single layer after hardening of 0.25 mm. The autoclave method was selected as the manufacturing process in order to produce finished Z-shaped profiles in accordance with the assumptions (Fig. 1) in the same technological process. FML were produced in a 3/2 layup (three aluminium layers and two composite layers each in 0/90 configuration) (Fig. 1). The final thickness of the laminates was established at the level of 1.9 mm (theoretical thickness, design value) and profile length at 1000 mm.

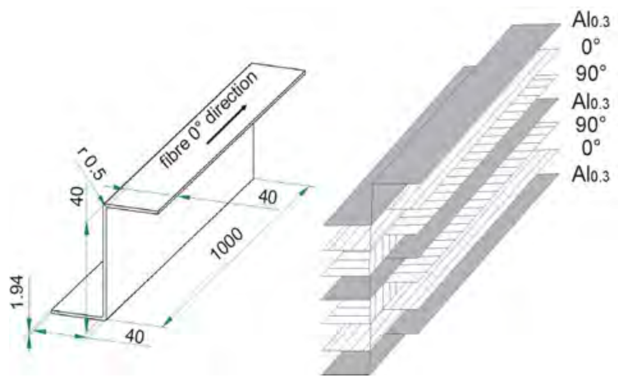

Fig. 1. Diagram of Al/GFRP 3/2 (0/90) laminate in shape of Z

Rys. 1. Schemat laminatu Al/GFRP 3/2 (0/90) w postaci profilu typu Z

The following steps were completed after the manufacturing process: (1) laminate hardening process parameters analysis, (2) dimensional tolerance was checked for the profile by means of multi-point thickness measurements, (3) non-destructive laminate testing was carried out by means of the ultrasonic phased array method (OmniScan MXI, Olympus, Japan) and (4) laminate structure quality microscopic analysis was performed in selected cross-sections (optical microscope Nikon MA200, Japan).

RESULTS AND DISCUSSION

Manufacturing

The manufacturing process of the Al/GFRP laminate in the form of Z-shaped profiles encompassed the operations of preliminary forming of metal sheets by means of a bending machine (Fig. 2a). After such preparation, the metal layers were subjected to a surface preparation process. This process consisted of the following phases: anodizing oxidation of the aluminium alloy surface in a chromium acid solution in water (CAA) and application of a primer based on synthetic polymer resins with a corrosion inhibitor (3M, USA).

The laminating process was carried out in a negative mould made of aluminium in the form of a cuboidal solid profile with dimensions corresponding to those of the profile to be produced. The laminating process (Fig. 2b) was carried out maintaining the order of metal and composite layers, applying the layers one by one in accordance with the scheme (Fig. 1). The laminating process was completed by vacuum bag preparation (Fig. 2c) using proper separating foils, de-aerating textiles, valves and sealing foil.

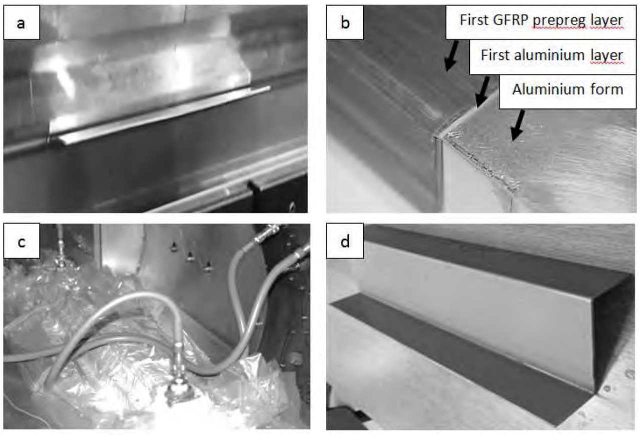

Fig. 2. Some stages of manufacturing FML profile: forming metal layers (a), lamination (b), vacuum bag preparation (c) and macroscopic inspection (d)

Rys. 2. Wybrane etapy wytwarzania profilu FML: gięcie warstw metalowych (a), laminowanie (b), przygotowywanie pakietu podciśnieniowego (c), ocena makroskopowa (d)

The hardening process for Z-shaped profiles made of Fibre Metal Laminates was carried out by means of an autoclave (Scholz Maschinenbau, Germany). The hardening process (Fig. 3) encompassed the following steps; temperature increase (1) in controlled pressure conditions, isothermal holding (2) during the period of time required for completion of the matrix polymerization process and cooling (3) thereafter. The hardening process was completed using the following parameters: pressure 0.4 MPa; vacuum 0.08 MPa; hardening temperature 135°C, hardening time: 120 minutes, heating / cooling gradient 2°C/min.

Based on our knowledge, we selected the hardening parameter values in a manner ensuring the highest possible quality of the produced composites. The issues associated with the impact of hardening parameters on the quality and properties of polymer composite materials were described in study [16]. Modelling the laminate hardening process parameters and full control of these parameters in real time enable the preliminary evaluation of FML structure quality after the manufacturing process. The comparison between the measured and theoretical parameters of the hardening process did not indicate any deviations. Therefore, it can be suggested that the probability of defects in the structure is minimal.

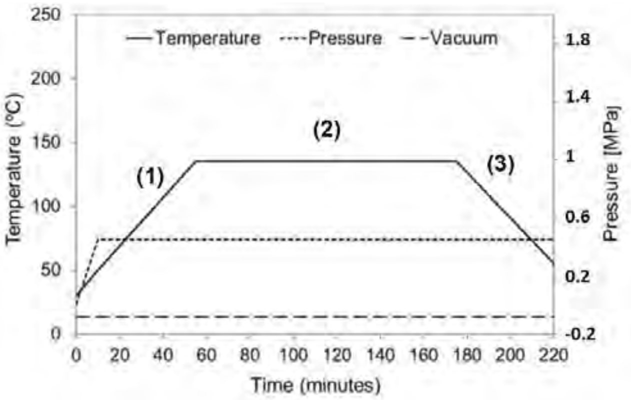

Fig. 3. Process parameters of Al/GFRP laminate curing

Rys. 3. Parametry procesu utwardzania laminatu Al/GFRP

DIMENSIONAL TOLERANCE

One of the primary issues associated with the forming of complex shapes from Fibre Metal Laminates is to maintain proper dimensional tolerance e.g. the thickness in the bends and linear parts of the profiles [17]. The dimensions for the wall thicknesses of the produced Z-shaped profile in specific measurement points are shown in Table 1.

TABLE 1. **Thickness and deviation of wall thickness of FML profile type Z.**

TABELA 1. **Grubość i odchylenie grubości ścianki profilu typu Z**

Wall thickness in measurements points [mm]							
Line A		Line B		Line C		Line D	
1	2.04	1	2.06	1	2.07	1	2.07
2	2.1	2	2.05	2	2.07	2	2.08
3	2.09	3	1.99	3	1.98	3	2
4	2.03	4	2.04	4	2.06	4	2.09
5	1.78	5	1.86	5	1.78	5	1.79
6	2.07	6	2.11	6	2.06	6	2.05
7	2.02	7	1.99	7	2.01	7	2
av.	2.02	av.	2.01	av.	2.00	av.	2.01
st.d.	0.10	st.d.	0.07	st.d.	0.10	st.d.	0.10
Average thickness				2.01 mm			
Av. standard deviation				0.09 mm			
Theoretical thickness				1.9 mm			

On the basis of the analysis of the results obtained from the wall thickness measurements, it has been found that the average laminate thickness is greater than the theoretical thickness resulting from the pre-impregnate thickness specified by the manufacturer. The difference is equal to about 0.1 mm and may be caused by the presence of a metal sheet as the external layer preventing effective removal of part of the excessive matrix from the pre-impregnate. The produced profile is characterized by a uniform thickness regardless of the distance from its edge, except the measurement points marked with number 5 in the individual measuring lines characterized by a significantly lower thickness (by about 0.2 mm) than in other laminate areas. Such a change has been observed along the whole length of the profile. An average reduction in wall thickness by 10% in one axis along the profile may lead to a reduction in its mechanical properties among others due to deviation from cross-section symmetry.

The Z-shaped FML profile according to the carried out dimension measurements fulfils the criteria of a thin-walled structure. The profile wall thickness to the lowest in-plane dimension ratio is 2.01/40 - so despite no strictly defined limits, it definitely meets the condition of a thin plate. Depending on the application and loading conditions, in many cases not strength and bearing capacity but rather buckling resistance is the deciding factor. The buckling load of thin-walled members is very sensitive to initial imperfection which seriously affects this load value. As a function of the imperfection magnitude, the buckling load decreases significantly. To predict this influence on the buckling load in nonlinear buckling analysis, one assumes the initial imperfection of an analysed plate or shell type thin-walled structure usually with reference to the first static buckling mode (the worst scenario). The magnitude of the introduced imperfection is in reference to the wall thickness. In literature this is within the range of 0.01÷0.5 wall thickness. Greater initial deformation reduces the quality of a manufactured structure as a load carrying member.

Another approach sometimes employed is connected with introducing a real imperfection shape into the nonlinear buckling analysis. In the case of the manufactured Z shape type FML profiles, they were cut into three experimental specimens for buckling tests. Preceding these tests, the shape of each singular specimen was estimated by applying coordinate measuring machines supported with PC DMIS CAD software. This is rather a metrological tool useful in industrial technology, however, of a high accuracy and inspection capacity. As an example, the results of such a metrological inspection of the Z shape type FML profile are presented. In Figure 4, the methodology of the measurement is depicted. The dimension data was collected in discrete points marked in the figure with coloured dots.

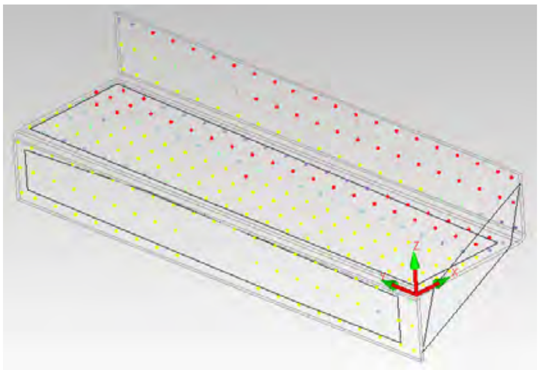

Fig. 4. Principle of FML Z type profile shape measurement

Rys. 4. Zasada pomiaru kształtu profilu FML typu Z

Analysis of the coordinate values allowed the authors to determine the manufacturing imperfection of each profile wall. The magnitude of these imperfections was different for a singular wall and the lowest for the web - less than 0.222 mm. For obvious reasons, the detected deformations were greater in the walls of both flanges. They were located close to the free edge (in the measurement row 5 mm above the flange edge) and within the band of 20÷30 mm from the cut edges. The greatest measured deflection of the flange was equal to 1.743 mm (for the point of coordinates y = 165, z = 35) where the lower one was equal to 0.495 mm (in the point y = 295, z = 5). The second flange was of a 'better' shape and its highest initial deflection was measured as 0.636 mm (in the point y = 270, z = –35).

The shape of the scanned Z type profile walls is presented in Figure 5.

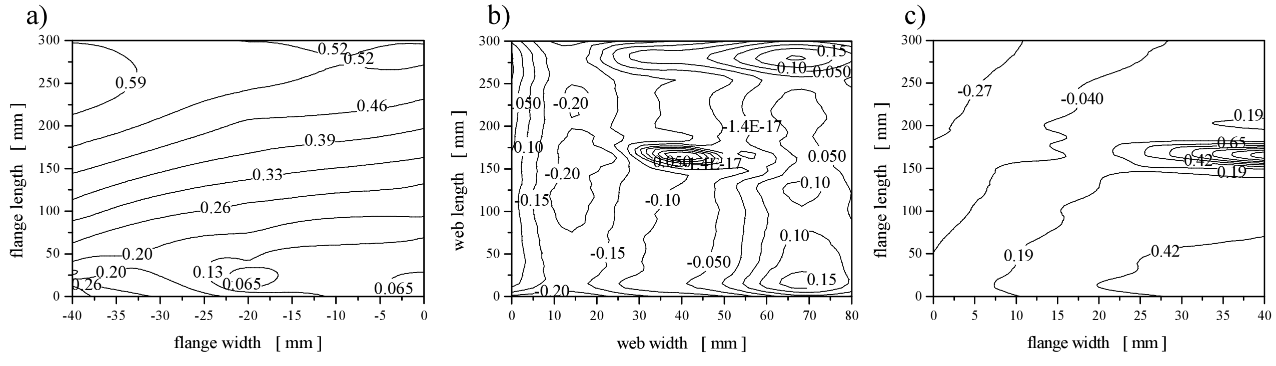

Fig. 5. Shape of initial imperfections measured on Z type profile walls: a) flange X = 0, c) flange X = 80 according to Fig. 4

Rys. 5. Kształt niedoskonałości wstępnych zmierzonych w ścianach profilu Z: a) półka X = 0, c) półka X = 80 wg rys. 4

It can be concluded that the imperfections of the web are in the expected range whereas those of the flanges are comparatively high. Those located close to the loaded edges of the Z type profile were compensated by the supporting test grips. The imperfections located in the middle of a flange wall would influence the buckling response of the investigated profile. The shape of these imperfections is in agreement with the static first buckling mode determined in the eigen-buckling analysis and was taken into account in nonlinear buckling analysis (FEM and ANM). In the manufacturing process cutting technology would be improved.

NON-DESTRUCTIVE TESTS

Figure 6 shows an example of an ultrasonic image of the inner structure quality for a flat shelf made of FML (for Z-shaped profile).

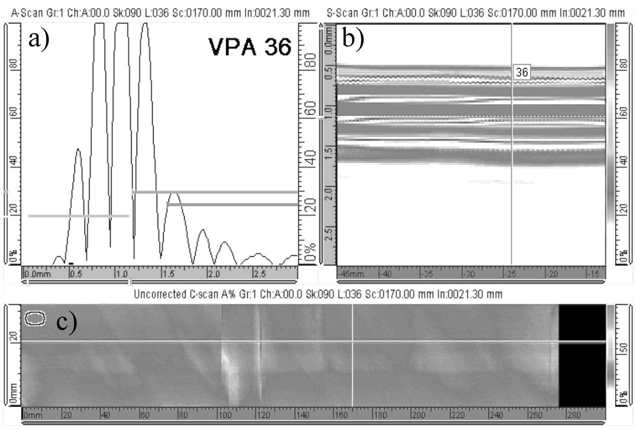

Fig. 6. A-scan (a), B-scan (b) and C-scan (c) imaging by using ultrasonic phased array method ofZ type profile wall

Rys. 6. Obrazowanie typu A-scan (a), B-scan (b) i C-scan (c) ultradźwiękową metodą wieloprzetwornikową ściany profilu FML typu Z

Due to the multi-layer nature of laminates and the presence of alternatively arranged layers of materials with different acoustic impedance (different wave resistance), the value of the selected wave propagation velocity in the material is equal to 4700 m/s. It is an average value between the composite and aluminium (composite 3100 m/s, aluminium 6300 m/s). The multilayer nature of composites consisting of various layers with different physical features leads to the occurrence of secondary reflections from individual layers (Fig. 6) in the ultrasonic image. Individual represented layers are visible on the display in the B-scan cross-section. The essence of the testing of such types of materials by means of this method is to capture the laminate reference area and to compare the shape of signals received from this area with the areas tested in other places in the sample. The comparative analysis is facilitated by C-scan imaging which indicates potential signal changes on a colour scale. The places with different colour were subjected to repeated signal analysis in the A and B-scan mode.

Profile ultrasonic testing after the manufacturing process did not indicate the presence of any areas with a potential occurrence of structural discontinuities in the laminate.

This observation has been confirmed by the the results of imaging in three modes with uniform signals along the whole length of the tested walls of the profiles. A-scan imaging did not indicate any detectable signal distortions. C-scan imaging is characterized by a uniform colour representing a reflected flexible wave. No delamination or air blister concentrations were detected, therefore a high structure quality is ensured in the autoclave process for profile production from FML.

Due to technical constraints, the corners measurement has not been checked by means of the ultrasonic method. In order to evaluate the Z-shaped profile corners quality, microstructural tests were carried out on cross-sections.

MICROSTRUCTURAL CHARACTERIZATION

Figure 7 shows selected images of the FML microstructure taken from the Z-shaped profile.

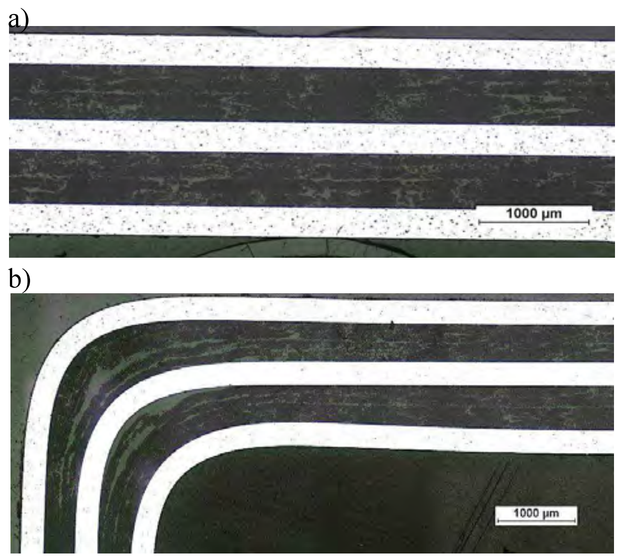

Fig. 7. Microstructure of some parts (a - flat area, b - corner) of FML profile type Z

Rys. 7. Mikrostruktura wybranych obszarów (a - część płaska, b - narożnik) profilu FML typu Z

Our microscopic observations indicate that the FML microstructure is correct. No structural discontinuities have been found in the form of delaminations, particularly on the metal/composite interface. The structure of the connection between the individual components i.e. the individual composite layers, metal layers and composite layers as well as the fibre-matrix interface is correct. The distribution of the reinforcing fibres in the composite structures is uniform.

Insignificant mismatching of individual metal layers (increase or reduction of Total thickness of profile wall) (Fig. 7b) has been observed for the analysed zones of the FML profile corners. These zones are characterized by the presence of areas where the prepreg layers do not closely adhere to the metal layers. However, these places are perfectly filled with the matrix material-epoxy resin in the hardening process which contributes to the assurance of a correct metal layer/composite layer connection in this area. Most likely, this effect is caused by mismatching in the metal profile preparation process in the course of plastic forming-bending of individual profiles, while preserving proper radii and considering the entry of the composite material between the metal layers. This effect can also be also associated with the impact of high pressure in the course of the autoclave process and specific form and geometry of the profiles. Nonetheless, the high quality of the produced FML profiles and correct structure of the composite profiles are not positively affected by the issues referred to above.

The corner zones detected on the cross-sections are characterized by high quality. De Jong et al. [17] presented the forming effects after the laminate hardening process in their study and presented a corner zone characterized by the presence of matrix cracks and delaminations on the metal composite interface. The authors of [17] justified that the fracture of a prepreg layer is one of the most common failures in Glare. In the fibre direction, the deformation is limited by the small failure strain of the fibres. The same effect is perpendicular to the fibres because of the low failure strain value of the epoxy resin. Furthermore, they concluded that delaminations are caused by the occurrence of shear stresses on the metal composite interface in the course of the forming process.

These problems do not occur in the case of the technology proposed in the present study. Therefore it is possible to improve the quality of FML produced in the form of profiles.

CONCLUSIONS

The following conclusions have been drawn, on the basis of our exclusive technology for the production of thin-walled profiles made of FML:

- The hardening technology for pre-formed components in the autoclave process ensures the achievement of excellent dimensional tolerance of thin-walled profiles made of FML.
- Manufacturing Fibre Metal Laminates using the autoclave technique is advantageous for the reason of obtaining a higher quality and repeatability of the composite structures which has been confirmed by non-destructive testing and microstructural analyses of produced the FML. No delaminations, cracks, gas blisters etc. were detected by means of structural tests.
- The process of forming Fibre Metal Laminates by means of component pre-forming does not significantly limit the values of selected profile angles. In the case of proper precision of component pre-forming (accuracy of corner matching) and maintained regime in the case of the FML laminating process (vaccumbag, cleanroom), the risk of structural defects, including profile corner zones, is significantly limited.

Acknowledgments

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REFERENCES

[1] Sinke J., Manufacturing of GLARE parts and structures, Applied Composite Materials 2003, 10, 293-305.

[2] Alderliesten R.C., Benedictus R., Fiber/Metal composite technology for future primary aircraft structures, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23-26 April 2007, Honolulu, Hawaii.

[3] Vlot A., Gunnik J.W., Fibre Metal Laminates an Introduction, Kluwer Academic Publishers, 2001.

[4] Sinke J., Jalving S., Curved Panels [in:] A. Vlot, J.W. Gunnik, Fibre Metal Laminates an Introduction, Kluwer Academic Publishers, 2001, 355-368.

[5] Magnucka-Blandzi E, Magnucki K., Buckling, and optimal design of cold-formed thin-walled beams: review of selected problems, Thin-Walled Struct. 2011, 49, 554-61.

[6] Turvey G.J., Zhang Y., A computational and experimental analysis of the buckling, postbuckling and initial failure of pultruded GRP columns. Comput. Struct. 2006, 84, 1527--1537.

[7] Debski H., Teter A., Kubiak T., Numerical and experimental studies of compressed composite columns with complex open cross-sections, Composite Structures 2014, 118, 28-36.

[8] Taheri F., Nagaraj M., Khosravi P., Buckling response of glue-laminated columns reinforced with fiber-reinforced plastic sheets, Compos. Struct. 2009, 88, 481-90.

[9] Debski H., Kubiak T., Teter A., Experimental investigation of channel-section composite profiles behavior with various sequences of plies subjected to static compression, Thinn-Walled Struct. 2013, 71, 147-54.

[10] Teter A., Kolakowski Z., Buckling of thin-walled composite structures with intermediate stiffeners, Compos. Struct. 2005, 69(4), 421-8.

[11] Kubiak T., Kaczmarek L., Estimation of load-carrying capacity for thin-walled composite beams, Composite Structures 2015, 119, 749-756.

[12] Paszkiewicz M., Kubiak T., Selected problems concerning determination of the buckling load of channel section beams and columns, Thin-Walled Structures 2015, 93, 112-121.

[13] Wu G., Yang J.-M., The mechanical behavior of GLARE laminates for aircraft structures, JOM 2005, 57, 1, 72-79.

[14] Botelhoa E.C., Silva R.A., Pardinia L.C., Rezendea M.C., A review on the development and properties of continuous fiber/epoxy/aluminum Hybrid composites for aircraft structures, Materials Research 2006., 9, 3, 247-256.

[15] Edwardson S.P., French P., Dearden G., Watkins K.G., Cantwell W.J., laser forming of fibre metal laminates, Lasers in Eng. 2005, 15, 233-255.

[16] Bienias J., Gliszczynski A., Jakubczak P., Kubiak T., Majerski K., Influence of autoclaving process parameters on the buckling and postbuckling behavior of thin-walled channel section beams, Thin-Walled Structures 2014, 85, 262-270.

[17] de Jong TW., Kroon E., Sinke J., Formability [in:] A. Vlot, J.W. Gunnik, Fibre Metal Laminates an Introduction, Kluwer Academic Publishers, 2001, 337-353.

