EFFECT OF TEMPERATURE ON THE SHEAR STRENGTH OF GFRP-ALUMINIUM ALLOY 2024-T3 SINGLE LAP JOINT

Wpływ temperatury na wytrzymałość na ścinanie połączenia adhezyjnego pomiędzy kompozytem GFRP a blachą ze stopu aluminium 2024-T3

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Abstract: The paper presents the results of experimental studies determining the effect of temperature on the shear strength of the adhesive joint between the layers of the fiber metal laminate (FML). The tests were carried out for composites being a combination of 2024-T3 aluminum alloy sheet and Glass Fiber-Reinforced Polymer (GFRP) made in the autoclave process. The key factor determining the quality of layered composites is the high strength adhesive joint between the layers. Due to the possibility of extreme temperature conditions during utilization of the composite structure, tests were carried out at reduced temperatures, i.e. -60°C, as well as elevated temperatures, i.e. 80°C. The obtained results were related to the results obtained at a room temperature (RT). The study showed that at the elevated temperature the shear strength increased by approx. 10% compared to the result obtained at room temperature. There is also a significant reduction in the stiffness of the joint as the temperature increases. In turn, a slight increase in joint stiffness was demonstrated for the reduced temperature.

Keywords: FML composites, adhesive joints, shear strength, 2024-T3 aluminium alloy, GFRP composites

Streszczenie: W pracy przedstawiono wyniki badań eksperymentalnych określających wpływ temperatury na wytrzymałość na ścinanie połączenia adhezyjnego pomiędzy warstwami składowymi hybrydowego kompozytu metalowo-włóknistego (FML). Próby przeprowadzono dla kompozytów będących połączeniem blachy ze stopu aluminium 2024-T3 oraz kompozytu szklanego polimerowo-włóknistego (ang. Glass Fiber-Reinforced Polymer - GFRP) wykonanych w procesie autoklawowym. Kluczowym czynnikiem determinującym jakość kompozytów warstwowych jest wysokiej wytrzymałości połączenie adhezyjne pomiędzy warstwami. Ze względu na możliwość występowania różnych warunków temperaturowych w procesie eksploatacyjnym struktury kompozytowej, zrealizowano badania w temperaturach obniżonej tj. -60°C, a także podwyższonej tj. 80°C. Uzyskane rezultaty odniesiono do wyników uzyskanych w temperaturze pokojowej. W pracy wykazano, że w podwyższonej temperaturze dochodzi do wzrostu wytrzymałości na ścinanie o ok. 10% w stosunku do rezultatu uzyskanego w temperaturze pokojowej. Dochodzi tu także do znacznego obniżenia sztywności połączenia wraz ze wzrostem temperatury. Dla obniżonej temperatury wykazano z kolei nieznaczny wzrost sztywności połączenia.

Słowa kluczowe: kompozyty warstwowe FML, połączenia adhezyjne, wytrzymałość na ścinanie, stop aluminium 2024-T3, kompozyty GFRP

Introduction

Composite materials, which are more and more widely used, especially in aviation constructions, despite many obvious advantages, have some limitations that make them impossible to appear in the whole aircraft structure. This limitation applies especially to the places in the structure where the temperature is high. Therefore, there is a frequent need to combine polymer-fiber composites with other materials, mainly metals such as aluminum alloys or titanium [27]. Adhesive joints have the advantage over the riveting technique, popular in aircraft construction, that they do not require holes, which are often the cause of stress concentrators, and do not affect the weight of the structure as much as rivets [27], hence the adhesive joints are widely used in the aviation industry.

Due to the growing interest in FML composites, recently there has been an intensive increase in the number of publications in the field of strength analysis of adhesive joints between fiber composites and light metals. For analysis of cracking the connection between the layers of FML composites, samples in the form of a double cantilever beam are most often used. The purpose of such research is to determine the behavior of crack propagation and obtain energy data for numerical analysis of the fracture mechanism [10, 14]. In turn, for determining the shear strength of the considered joints, usually one or two-fold metal-composite joints

Table 1. Chemical composition (wt. %) of 2024-T3 aluminum alloy

Alloy	Cu	Mg	Fe	Si	Mn	Zn	Ti	Cr	Other
2024-T3	4.35	1.50	0.50	0.50	0.30	0.25	0.15	0.10	0.20

Table 2. The basic mechanical parameters of 2024-T3 aluminium alloy sheet

Thickness t, mm	Young's modulus E, GPa	Poisson's ratio	Yield stress $R_{p0,2}$, MPa	Ultimate tensile stress R_m, MPa
0.4	72,874	0.33	302	449

are tested [7, 12, 17, 22]. Many authors also address the issue of analytical and numerical analysis related to the shear strength of glued joints of various materials [2, 9,16]. Fatigue strength of adhesive joints is also a very important issue.

The interlaminar shear strength (ILSS) is mainly used for the assessment of bond strength between fibres and the matrix resin in FML. ILSS may be determined in many shear tests [18, 21], including the short-beam shear test which is the simplest and most feasible [8, 19]. Naik et al. [5] observed that the interlaminar shear strength increases with increasing shear strain rate. The differences in the thermal expansion coefficients of the matrix and fibre and cure shrinkage in thermosetting matrices result in the development of residual stresses at the fibre/matrix interface [13]. The aircraft structure is subjected to multiple rapid changes in temperature. So, it is important to assess the degradative effect of thermal fatigue on conditioning times during exposure to above-zero and sub-zero temperatures [20].

When considering the issue of adhesive bonding of materials with significantly different coefficients of thermal expansion, one should take into account the stresses in the plane of connection of these materials that are the cause of the variable operating temperature, which may contribute to reducing the strength of the connection. Hence, many studies focus on the possibility of minimizing the negative effects resulting from different properties of materials joined by proper selection of the bonding layer [23, 24].

It can be stated that a properly made adhesive connection in the composite manufacturing process determines the later operational quality of the layered composite structure. FML composites based on prepregs based on epoxy resins are produced in such a way that the adhesive connection between the layers is formed by an epoxy resin which is the resin of the prepreg [25].

It is very important to know the strength of the adhesive joint between the layers of the FML composite depending on the temperature conditions. The issue of adhesive joints based on epoxy resins has been described in the work [3]. The authors presented the effect of temperature on both strength and stiffness of the joint.

This paper presents the effect of temperature on the shear strength of the GFRP-Aluminum alloy adhesive joint made according to the technology of producing FML composites in an autoclave process.

Materials and methods

A 2024-T3 aluminum alloy sheet with a thickness of 2 mm was used in this study for the fabrication of layered specimens. This aluminum was selected because it is widely used to manufacture adhesively bonded aircraft structures due to its excellent specific strength and fatigue performance, good conformability and surface finishing capabilities [5, 13]. 2024-T3 aluminum alloy is commonly used to manufacturing FML composites [14]. The chemical composition is listed in Table 1, and the mechanical properties determined in the uniaxial tensile test according to ISO 6892-1 standard [11] is listed in Table 2.

The preparation of the surface of the sheets before adhesive bonding with the fibre layers was carried out according to the technology used in the aviation industry [28]. First, the sheets were anodized.

The oxide coatings were produced onto the alclad substrate in the anodizing process. The specimens were abraded with sand paper of grade 320, rinsed with water and degreased in the NaOH aqueous solution (100 $g \cdot dm^{-3}$) for 1 minute at 25°C, rinsed with deionised water, pickled in the 400 $g \cdot dm^{-3}$ for 1 minute at 25°C$g \cdot dm^{-3}$) at 15°C. The constant current density equal to 1 $A \cdot dm^{-2}$ was applied. When the anodizing process was completed, the

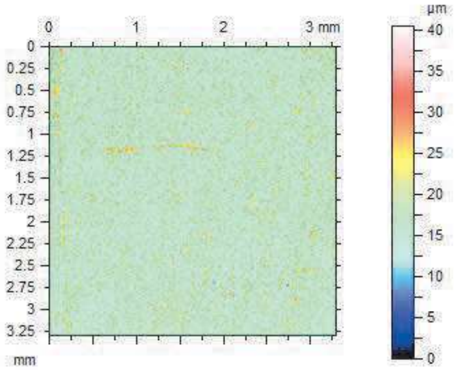

Fig. 1. Three-dimensional structure of the sheet surface

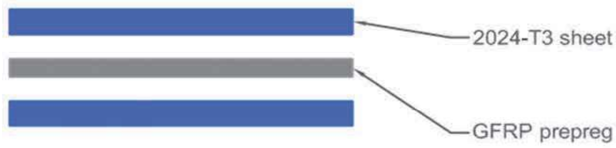

Fig. 2. Configurations of FML composite (2/1 lay-up) considered

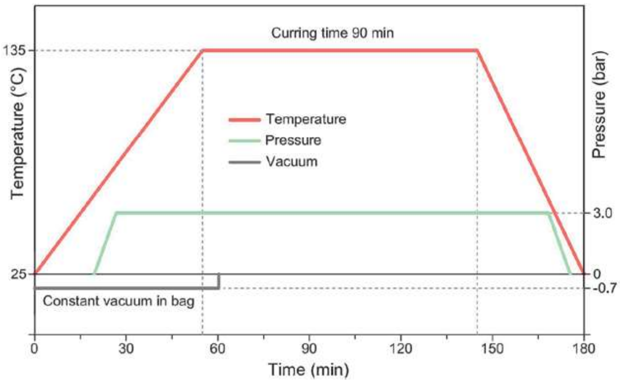

Fig. 3. The autoclave cure cycle

Table 3. Sheet surface roughness parameters for three-dimensional analysis

Roughness parameter	Value for the sheet used
S_q [µm]	4.32
S_{sk} [µm]	1.39
S_{ku} [µm]	3.75
S_p [µm]	22.9
S_v [µm]	17.6
S_z [µm]	40.5
S_a [µm]	3.36
S_{al} [µm]	0.00726
S_{tr} [µm]	0.756
S_{td} [µm]	84.5

coatings obtained were rinsed with deionised water and dried in air. Their thickness was determined by using the eddy-current method (Dualscope FMP100, Fischer). For substrate thickness equal to 2 mm the thickness of the coating was 10 ± 1 *µm*.

After anodizing, the surfaces of the sheets were measured by white light interferometer Talysurf CCI Lite using objective 5x. Parameters of surface textures were calculated using TalyMap software. The measured areas of 3.3 mm x 3.3 mm contained 1024 x 1024 points. Textures of surfaces were only levelled, digital filtration was not used.

Fig. 1 shows the three-dimensional structure of a fragment of the surface of sheets joined with a GFRP layer. Table 3 summarizes the sheet surface roughness parameters for three-dimensional analysis.

Immediately after anodizing the surfaces were primed with EC3924B (3MTM, Maplewood, Minnesota, USA) primer. As a polymer-fibrous layer, a prepreg based on glass fibres with a thermosetting epoxy matrix was used. The prepreg was supplied from HEXCEL, its trade symbol is HexPly 916G-1581-53.5%.

The composites were prepared in a 'clean room' by placing complex layers (Fig. 2) in a vacuum bag, and then cured in an autoclave according to the parameters shown in Fig. 3.

The composite was made in the form of a panel with the dimensions of 360×200 mm (Fig. 4a).

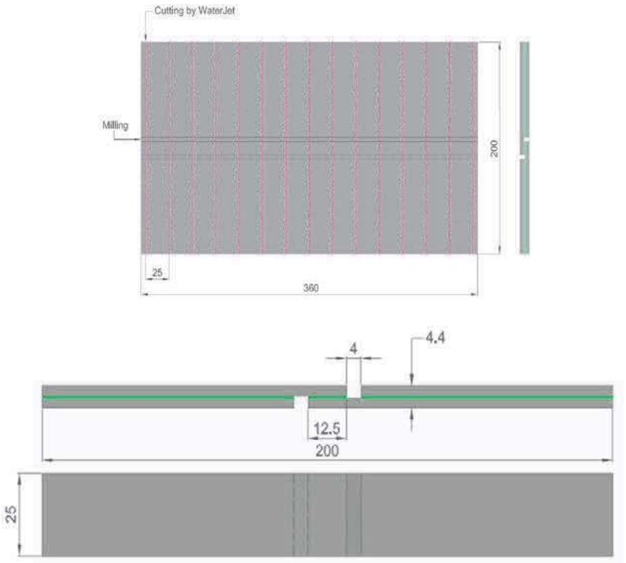

Fig. 4. Dimensions of sample sheets with the cutting path for the shear test (a); geometry and dimensions of specimens for shear strength test (b)

Fig. 5. Specimen view in a temperature chamber at -60°C

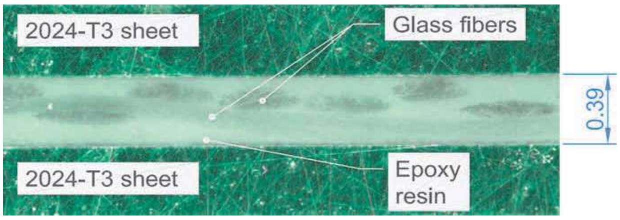

Fig. 6. Structure of the composites studied showing the direction of the fibers and the thickness of the GFRP

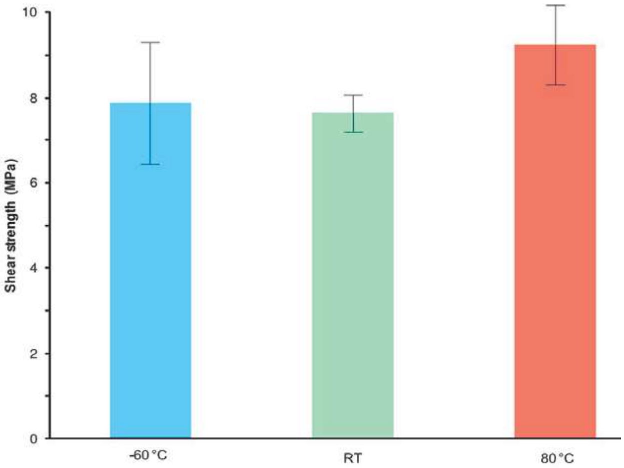

Fig. 7. Average values of shear strength for the samples tested at considered temperatures

Samples for individual strength tests were cut from these sheets (Fig. 4b). Before cutting the sheet, it was milled along its entire length on both sides to obtain an overlap (Fig. 4a).

The samples were cut using a high-pressure water jet technique. The treatment was carried out at a water pressure of p = 350 MPa, an abrasive mass flow rate of ma = 300 g min^{-1} and a speed of cutting head v_f = 250 mm min^{-1}.

The endurance test was carried out on a Zwick/Roell Z030 testing machine with a temperature chamber, a jaw feed speed of 2 mm/min was used. Extensometers were used to measure sample deformation during the test.

In order to obtain a reduced test temperature of -60°C, the temperature chamber was cooled with liquid nitrogen; the view of the chamber during tests at this temperature is shown in Fig. 5.

Results and discussion

After curing the samples in the autoclave process, the thickness of the GFRP layer was measured and the fiber direction was determined. Fig. 6 shows a view of the microsection the structure of the resulting composite as a combination of three layers. The thickness of the GFRP has been shown to be 0.39 mm. The fibers were obtained evenly parallel and perpendicular to the direction of load of the sample.

Fig. 7 shows the average values of shear strength together with the standard deviation for individual temperature levels at which the tests were carried out.

The study showed that at elevated temperature, i.e. 80°C, there was a significant increase in strength. The average value in this case was 9.24 MPa, which is almost by 11% higher compared to the average value of the strength obtained at a room temperature, which was 7.65 MPa. At the reduced temperature, i.e. -60°C, the average shear strength increased slightly, i.e. by less than 2%, to the value of 7.96 MPa.

It should be noted that in the case of tests at the reduced temperature, the largest spread of results occurred. The most reproducible test results were obtained for the samples tested at a room temperature.

Fig. 8 presents stress-displacement curves for the samples tested. Based on the nature of the course of individual curves, significant differences can be observed in the way the samples are destroyed at the considered temperature levels. In the case of samples at a room temperature and reduced temperature, i.e. -60°C, the course of stretching curves is generally similar in nature, with a clear increase in stiffness of samples tested

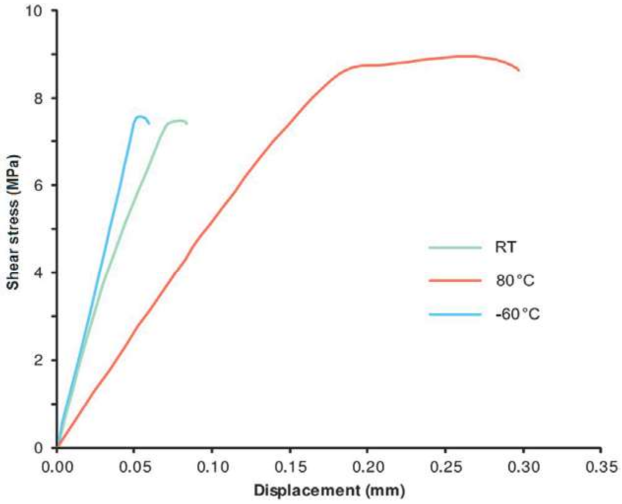

Fig. 8. Typical tensile/shear test curves of the FML composites studied.

at reduced temperature. The increase in the rigidity of adhesive joints based primarily on epoxy resins at reduced temperatures is also confirmed by the authors of the papers [1, 4, 6, 12, 26].

Turning to the test variant at an elevated temperature of 80°C, the distinct nature of the stretching curve is clearly seen here. First of all, there is a significant decrease in stiffness, which coincides with the results of the research presented by the authors of work [3]. In the same work, the authors noticed, that at elevated temperature, the strength of the adhesive connection made on the basis of epoxy resin increases to the glass transition temperature Tg of the adhesive, while after exceeding this temperature it decreases markedly. This tendency was confirmed by showing an increase in shear strength of the joint at 80°C, thus below the glass transition temperature of the epoxy resin used, which is about 150°C [29].

Conclusions

The purpose of the work was to determine, by the experimental method, the properties of the adhesive joint between GFRP and metal layers in the FML composite. The research showed that the extreme temperature conditions that may occur in the operation process do not lead to a reduction in the shear strength of the joint between the layers of the composite. At the elevated temperature, i.e. 80°C, an increase in shear strength of almost 11% was observed compared to the result obtained at room temperature. Importantly and in line with the observations of the authors of other papers [3], it has been shown that there is a close relationship between the stiffness of the connection and the temperature. As the temperature increases, the stiffness of the connection decreases, while at -60°C, the stiffness is higher than that recorded at room temperature.

Attention should also be paid to the distribution of strength results at individual test temperature values. At negative temperature the largest spread of results was recorded, while at a room temperature the highest repeatability was obtained.

To ensure the required properties of FML composites, it is necessary to obtain a high-strength joint between layers, the properties of which do not change significantly in the expected operating conditions. The study confirms that in the presented temperature range, layered composites can be safely exploited, as no significant decrease in the strength of the connection has been demonstrated.

The presented test results propose a methodology for testing the strength of the interlayer joint in FML composites.

The research results presented in the work are part of a series of the tests conducted by the authors in the field of the influence of temperatures on the properties of FML composites. The work [15] presents the influence of temperature gradient thermal shock cycles on the interlaminar shear strength of FML composite determined by the short beam test.

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