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THE INFLUENCE OF FEATURES OF ALUMINIUM ALLOYS 2024, 6061 AND 7075 ON THE PROPERTIES OF GLARE-TYPE COMPOSITES

WPŁYW WŁAŚCIWOŚCI STOPÓW ALUMINIUM 2024, 6061, 7075 NA CECHY KOMPOZYTU TYPU GLARE

The above paper presents the assumptions and results of the research whose aim was to determine the influence of 2024, 6061 and 7075 aluminum alloys on the final properties of GLARE-type composites. GLARE 3 2/1 type composites, made of two layers of the epoxy prepreg, reinforced with unidirectional glass fibers, arranged in the direction of 0°/90°, and two sheets of aluminum with a thickness of 0.4 mm, were investigated. Composites of various stacking configurations of alloy layers, made of one type of aluminum alloy (so-called 'homogeneous composites'), and two different alloys (mixed composites), were analyzed. The properties of the composites were evaluated with the use of the mixing rule and compared with the test results.

The influence of the used aluminum alloys on mechanical properties of GLARE-type composites has been determined. GLARE-type composite made of 7075 alloy sheets had the most favorable mechanical properties in comparison to properties of composites with 2024 and 6061 sheets. It has been shown how the properties of GLARE-type composites depend on the type of the aluminum alloy. It has been also proved that the properties of GLARE-type composites can be evaluated with the use of the mixing rule.

Keywords: GLARE composites, aluminum alloys, mixing rule

W pracy przedstawiono założenia i wyniki badań, których celem było określenie wpływu właściwości zastosowanych stopów aluminium 2024, 6061 i 7075 na własności finalne kompozytów typu GLARE. Analizie poddano kompozyty typu GLARE 3 2/1 wykonane z dwóch warstw prepregu epoksydowego, zbrojonego włóknem szklanym, ułożonego w kierunku 0°/90°, oraz z dwóch arkuszy stopu aluminium o grubości 0,4 mm. Przeanalizowano kompozyty o różnych konfiguracjach ułożenia warstw stopów, składające się z jednego gatunku stopu aluminium (tzw. kompozyty jednorodne), oraz z dwóch różnych stopów (kompozyty mieszane). Własności kompozytów oszacowano na podstawie reguły mieszania i porównano je z wynikami badań.

Określono wpływ zastosowanego stopu aluminium na własności wytrzymałościowe kompozytów typu GLARE. Najkorzystniejsze własności wytrzymałościowe wykazał kompozyt z udziałem arkuszy stopu 7075 w stosunku do właściwości kompozytów z udziałem arkuszy blach stopów 2024 oraz 6061. Określono jak właściwości kompozytu typu GLARE zależą od rodzaju zastosowanego stopu aluminium. Wykazano również, że cechy kompozytów typu GLARE można oszacować na podstawie reguły mieszania.

1. Introduction

Commercial applications of advanced materials characterized by high quality, strength and low density for construction of aircraft structures has become a topic of major interest in the aerospace sector. The search for new materials has led to significant development and implementation of modern aluminum and titanium alloys, shape memory alloys and composite materials. Hybrid materials are particularly noteworthy, including layered composites, combining different characteristics of the component materials, the geometry of the reinforcement and the alignment sequence of layers.

Since the late 1980s, intensive research on composites consisting of metal layers and fiber-reinforced polymers has been conducted. These materials, called Fiber Metal Laminates (FML), can be made of different alloy layers, e.g. Aluminum, Titanium and polymer composites (thermoplastics or thermosetting), reinforced with different types of fibers (glass, aramid or carbon fibers) [1-8]. The basic FML concept comprises metallic layers with unidirectional fiber reinforced polymer layers [3].

In 1982, the ALCOA Company introduced the first commercial layered composite ARALL (Aramid Reinforced Aluminum Laminates), made of aluminum sheets and prepreg layers with aramid fiber reinforcement. It was used to build

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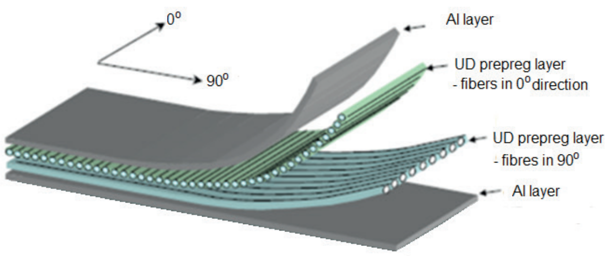
a cargo door on the plane C17 [2]. Kevlar was replaced by fiberglass (cheaper material, but possessing similar performance characteristics). This material was patented by AKZO under the name of GLARE (GLAss REinforced). Further research led to a composite made of titanium alloy layers (TiGr), and a composite CARALL (CArbon Reinforced Aluminum Laminates) (Tab. 1).

TABLE 1

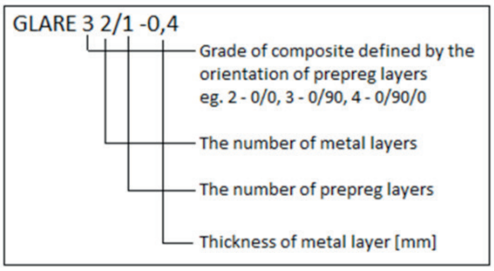
FML type composites [3]

FML Type	Metal Constituents	Fiber Constituents
ARALL	Aluminum 7075-T6	Aramid
GLARE	Aluminum 7475-T761 Aluminum 2024-T3	Glass (S2)
CARALL	Aluminum 2024-T3	Carbon
TiGr	Titanium Ti-15-3	Carbon

As a result of the combination of thin aluminum metal layers with unidirectional (UD) fiber-reinforced polymer layers (Fig. 1a), GLARE composites are characterized by excellent fatigue strength, impact strength with good corrosion resistance, and resistance to electrical discharge.



a)



b)

Fig. 1. a) Scheme of the layer arrangement in the GLARE 3 composite (b) the method of marking GLARE composites [11]

A kilogram of GLARE composite is approx. 5 to 10 times more expensive in comparison to the aluminum alloy, conventionally used in aircraft. However, the application of glass fiber reinforced polymer layers, having a density of 1,96 g/cm3 (density of aluminum is 2,77 g/cm^3), it provides at least 20% lighter construction. The use of 27 composite panels made of GLARE in A380 resulted in a reduction of aircraft weight by approx. 25% [3].

Six major variants of GLARE composites are known. They differ in the type of the used aluminum alloy, stacking sequence of layers, and the orientation of the fibers in the prepreg (Tab.2) [1].

In order to obtain a desired property, unidirectional prepreg layers are oriented in different directions, according to the sequence characteristic of different types of GLARE. For example GLARE 1 and GLARE 2 have fibers only in one direction, and they have excellent fatigue properties and high strength. GLARE 3 has 50% of the fibers in one direction and 50% in the transverse direction [11]. These composites are used for primary structures (structures subjected to heavy loads), as elements of the aircraft skin. They are also applied in the less demanding aircraft components, as elements of the floor in the cargo hold, engine covers and containers. These applications result from material properties (a combination of durability, damage and fatigue tolerance, along with resistance to corrosion, and resistance to fire) [2].

The properties of GLARE composites depend mainly on the properties and the type of individual metal and polymer layers (prepregs). Depending on the type and quantity of applied materials and the method of layer arrangement (fiber orientation), composites exhibit different properties (fatigue resistance, stiffness, strength, resistance to shear).

The final properties of GLARE composites are affected, among other things, by the following factors:

- Type and volume fraction of the metallic phase and the thickness of the individual layers of metal,
- Type, the volume and the orientation of the fibers in the prepreg,
- Type of resin in the prepreg,
- Sequence alignment and the total number of metal and prepreg layers in the composite.

For an initial assessment of the properties of a composite

TABLE 2

Types of GLARE composites [3]

GLARE grade	Sub grade	Metal type and metal thickness [mm]	Prepreg orientation in each fiber layer
GLARE 1	-	0,3-0,4 (7475-T761)	0/0
GLARE 2	GLARE 2A GLARE 2B	0,2-0,5 (2024-T3)	0/0 90/90
GLARE 3	-	0,2-0,5 (2024-T3)	0/90
GLARE 4	GLARE 4A GLARE 4B	0,2-0,5 (2024-T3)	0/90/0 90/0/90
GLARE 5	-	0,2-0,5 (2024-T3)	0/90/90/0
GLARE 6	GLARE 6A GLARE 6B	0,2-0,5 (2024-T3)	+45/-45 -45/+45

a theory of laminating and the mixing rule is applied, taking into account the share and the properties of individual components in the composite.

In FML composites, it is necessary to know the characteristics and parameters of the metal layers and the layers of prepreg to evaluate the properties of the composite.

For GLARE composites Metal Volume Fraction (MVF) approach is applied (equation no. 1), specifying the number and the thickness of metal sheet, which is the content of the metallic phase in the composite (Fig. 2) [5].

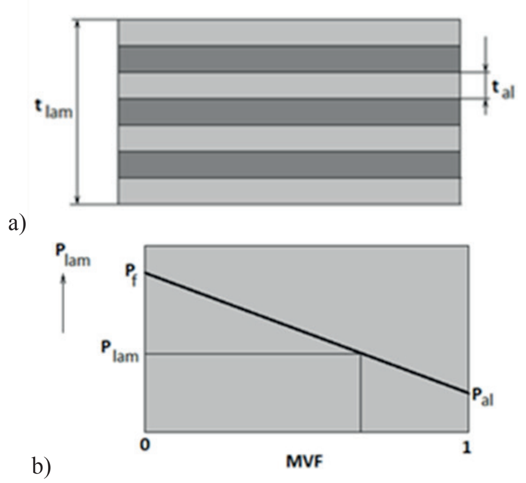


Fig. 2. Definition of MFV Approach: a) scheme of laminate layers ; b) properties of laminate [5]

$$MVF = \frac{\sum_1^p t_{al}}{t_{lam}} \quad (1)$$

where: MVF - Metal Volume Fraction, t_{al} - thickness of aluminum layer, t_{lam} - thickness of laminate, p - number of aluminum layers

Research has shown that the metallic phase determines the composite properties such as impact resistance [10-12]. It has been shown that the properties of GLARE type composites and the ability to plastic forming, are affected by the properties and thickness of aluminum sheets and the number of metal layers [13].

The properties of a fiber-reinforced polymer composite are affected by the orientation of the fibers. A composite (prepreg) reinforced with a unidirectional glass fiber (UD) shows anisotropic properties. Young's modulus and strength are a function of the fiber volume fraction and the matrix. These parameters are much higher in the direction of the fibers than in the perpendicular direction.

In the case of a composite loaded in parallel to the axis of the fiber Young's modulus of the composite is calculated with the use of equation no. 2. And for the composite loaded perpendicular to the axis of the fiber, Young's modulus is calculated according to equation no. 3 [18].

$$E_c = (1 - V_f)E_m + V_f E_f \quad (2)$$

Where: E_c – Young's modulus of the composite, E_m - Young's modulus of the matrix (epoxy resin), E_f - Young's modulus of the fibre, V_f - a volume fraction of the fibers, V_m - a volume fraction of the matrix

$$E_c = \frac{E_m E_f}{(1-V_f)E_f + V_f E_m} \quad (3)$$

In the composite GLARE 3 2/1, two unidirectional prepreg layers are arranged perpendicular to each other (orientation 0/90).

To achieve the effect of strengthening, the volume fraction of the fibers in the composite must exceed the critical volume. In the polymer composites with glass fiber, the optimal fiber proportion ranges from 50% to 60%. Above this volume, the strength of the composite decreases.

Based on the rule of mixing and MVF properties of the composite can be specified:

$$P_{lam} = MVF * P_{al} + (1 - MVF) * P_p \quad (4)$$

where: P_{lam} - properties of the GLARE composite (laminate), P_{al} - the properties of the metal layer, P_p - the properties of the prepreg, (1-MVF) - the relative share of prepreg in laminate.

When designing new composite materials, particularly for the applications in the aerospace industry, it is necessary to analyze the properties of the material designed for specific applications. The search for new compositions of composite materials consisting of different types of materials, the geometry and the number of layers is aimed to design and develop a new composite material with specific parameters resulting from future exploitation conditions. Proper selection of materials for specific elements of aircraft structures is important to guarantee the required fatigue strength at the lowest weight possible and the definition of corrosion and fire resistance [15-16]. The properties of aviation structures made of FMLs are closely related to the strength of the metallic phase and the fibers. The reduction of strength parameters of aircraft structures is also affected by the presence of stress concentrators, such as holes for rivets, or the presence of notches. These elements can result in damage or could lead to destruction of the structure during exploitation conditions [9].

The aim of this work is to analyze the characteristics of the newly developed composite materials with respect to future applications for components of aircraft structures by analyzing the effect of the different layers of metal and studying the possibility of estimating properties of designed composite materials based on the mixing rule.

The research presents an analysis of the strength properties of developed GLARE-type composites, made of different aluminum alloys: 2024, 7075 and 6061, at constant thickness of aluminum sheets and the number of metal layers. The first two types of alloys are materials commonly used in the aerospace industry. Aluminum alloy 2024 is the most popular alloy due to its strength, density and resistance to corrosion. Aluminum alloy 6061 has lower strength properties as well as lower density. The choice of the aluminum alloys for the construction of GLARE composite aims to provide a composite material for the use in aviation, having the required properties.

The purpose of this research was to analyze GLARE-type composites which contained two layers of unidirectional prepreg and a transverse orientation of the fibers (0/90). The composite continuous fibers were loaded in parallel to the fiber axis of the composite and Young's modulus (prepreg) was a weighted average of the fiber and the matrix modules.

By the application of the mixing rule (MVF approach), the properties of new materials were determined and then compared with the data achieved in the tests depending on the type of the aluminum alloy being used. The parameter evaluation of the composites was determined based on the tensile tests of samples with and without notches and on the basis of the flammability test. Tensile tests were performed to compare the properties of composites made up of different aluminum alloys. An analysis of the influence of the presence of notches of different geometry on the strength parameters of the developed composites was also conducted.

2. The experimental procedure

In the tests GLARE 3 2/1 -0,4 type composite was used – material made of two aluminum sheets and two prepreg layers. The aluminum layers were 0,4mm thick sheets of 2024, 6061 and 7075 alloys. Unidirectional, 0,25 mm thick prepreg layer consisted of epoxy resin and long R type glass fibers (fiber diameter 10μm). The fiber content in the prepreg was approx. 60%. The thickness of two prepreg layers (0/90) in the composite was 0,5mm and the total thickness of GLARE 3 2/1 type composites was 1,3 mm.

In order to evaluate the effect of the type of aluminum alloys on the final properties of GLARE type composites, several types of composites were developed. The materials include those made of one type of aluminum alloy (e.g. 2024/prepreg/prepreg/2024) and so called mixed composites (e.g. 2024/prepreg/prepreg/7075). The sequence of arrangement of the individual layers of aluminum alloy sheet is shown in Figure 3.

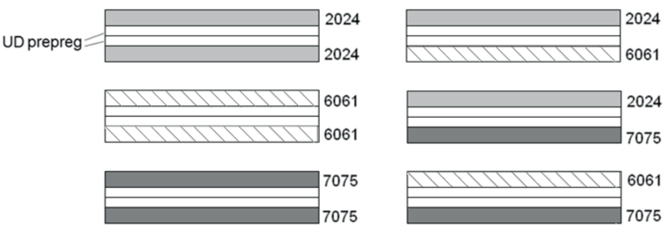


Fig. 3. Composition of the layers of aluminum alloys in the developed GLARE composites

Table 3 shows the composition of 2024, 6061 and 7075 aluminum alloys. The properties of constituent materials of the composite are given in Table 4.

TABLE 3

The chemical composition of the aluminum alloys

Aluminum alloy	2024 T3		6061 T6		7075 T6	
Composition	Cu	4.6	Mg	1.03	Zn	5.1-6.1
	Mg	1.4	Si	0.69	Mg	2.1-2.9
	Mn	0.54	Fe	0.41	Cu	1.2-2.0
	Fe	0.18	Cu	0.27	Fe	0.5
	Zn	0.1	Cr	0.17	Si	0.4
	Si	0.09	Mn	0.15	Mn	0.3
	Ti	0.02	Ti	0.05	Cr	0.18-0.28
	Cr	0.01	Zn	0.04	Ti	0.2
	rest	0.05	rest	0.02		

TABLE 4

The mechanical properties of materials for a GLARE-type composite

Material type	Properties		
	Density [g/cm^3]	E [GPa]	R_m [MPa]
7075	2,81	71	517
2024	2,79	73	458
6061	2,70	69	336
Epoxy resin	1,13	5	70
R glass fiber	2,50	84	4400

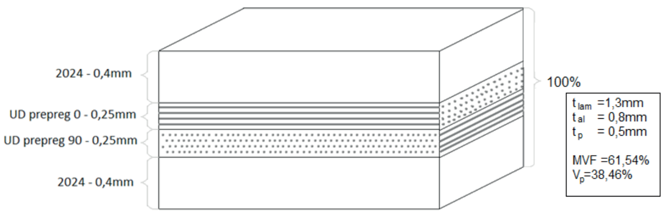


Fig. 4. The scheme of GLARE 3 2/1-0,4 composite with two 2024 alloy layers and two prepreg layers with 60% of glass fiber content

Based on the mixing rule, the properties of composites made up of different aluminum alloys at constant volume fraction and the thickness of the layers of the composite were estimated. The estimated properties of the GLARE 3 2/1 -0,4 type composites were calculated using the mixing rule and they are shown in Table 5.

Composites were made by curing in an autoclave. The arranged, plane, anodized aluminum sheets and prepreg layers have been subjected to appropriate temperature and pressure

TABLE 5

The mechanical properties of GLARE-type composites calculated in accordance with MVF

GLARE 3 2/1 -0,4	Estimated Properties		
	Density [g/cm^3]	E [GPa]	R_m [MPa]
7075/prepreg/prepreg/7075	2,48	63,8	1345
2024/prepreg/prepreg/2024	2,47	65,1	1309
6061/prepreg/prepreg/6061	2,41	62,6	1234
7075/prepreg/prepreg/2024	2,45	64,5	1327
2024/prepreg/prepreg/6061	2,42	63,8	1271
7075/prepreg/prepreg/6061	2,42	63,2	1290

ranges in the autoclave. Figure 5 shows the ranges of required temperature and pressure applied during curing and the time of each stage of the process [14].

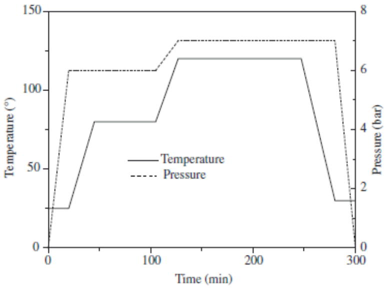


Fig. 5. Parameters of autoclave process [14]

The test procedure consisted of the following tests:

- Static Tensile Test samples without notch,
- Static Tensile Test V-notched samples,
- Static Tensile Test U-notched samples,
- Flammability Test.

Tensile Testing of composite samples relied on the static test of flat samples (Fig. 6a), made of a composite of different aluminum alloys. "Homogeneous" samples consisted of one type of aluminum alloy. A study was also conducted for materials consisting of two different types of aluminum alloys e.g. 2024 sheet/prepreg/prepreg/7075 sheet (so-called "mixed" composites).

In order to compare the properties of the composite material with the properties of the single sheet, the static tensile test was conducted for samples of aluminum alloy 2024, having a thickness of 1,0; 1,6 and 2,4mm. Additionally, tests were conducted for analogue samples of polymer composite reinforced with glass fabric having a thickness of 1,0mm.

The aim of experimental work was to determine the effect of the notch presence and its geometry, on the strength of the composite. Static tensile test was performed for homogeneous samples (2024/prepreg/prepreg/2024, 6061/prepreg/prepreg/6061, 7075/prepreg/prepreg/7075) with the notch in the shape "V", and for analogical materials with "U" shaped notch.

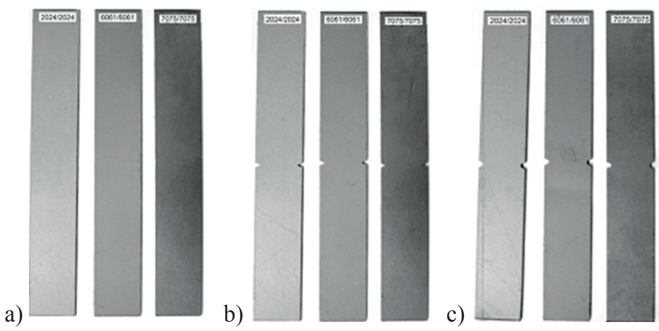


Fig. 6. Samples of the composites made of GLARE alloys 2024, 6061 and 7075: a) un-notched sample, b) V notched sample, c) U notched sample

Experimental work was carried out according to the standard, on a programmable, hydraulic uniaxial testing machine (Zwick Z100), test instrumentation (EN 10002-1 + AC1, 2004) at room temperature (21±0,5°C).

In order to assess the degree of flammability of GLARE composite made of 2024, 6061, 7075 aluminum alloy, vertical burning test was performed according to the method of UL-94 (IEC 60695-11-10: 2002, BS EN 60695/A1 "2005-11-10: 2005). The diagram of the method is shown in Fig. 7. Samples of dimensions defined in the standard were weighed before and after the flammability test, thus the amount of burned material was determined.

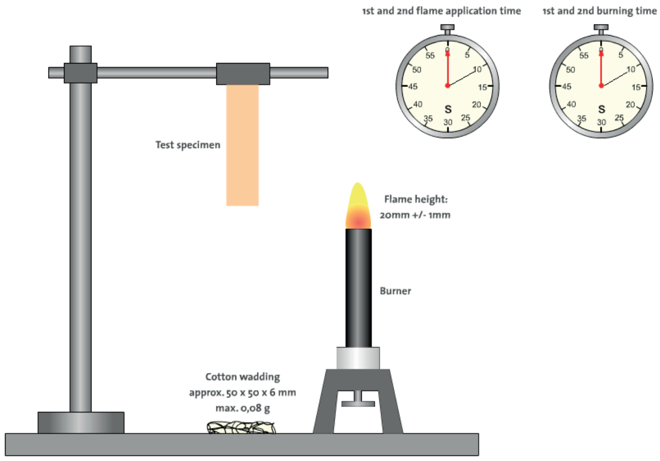


Fig. 7. Scheme of vertical burning test for class flammability UL-94

3. Results and discussion

3.1. Static Tensile Tests

The tensile test was carried out until the destruction of the composite samples (Fig. 8). During the tests, step changes in the value of the forces were found (Figure 9). They result from work of the individual layers of the composite. The aluminum alloy deforms plastically, while the layer of brittle epoxy resin and glass fibers are materials with a high stiffness. After the disruption of continuity of the aluminum layer, all the work was taken over by strong fibers.

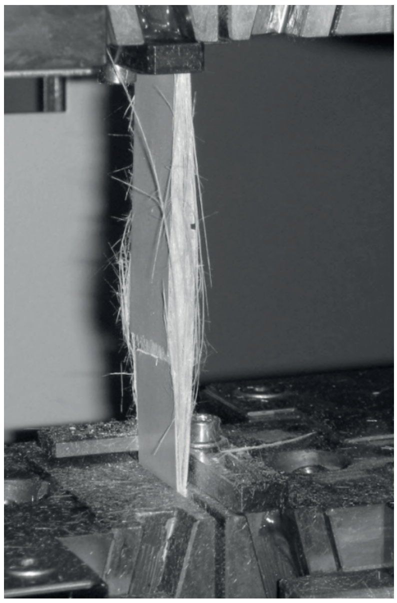


Fig. 8. Photo of the composite samples after fracture

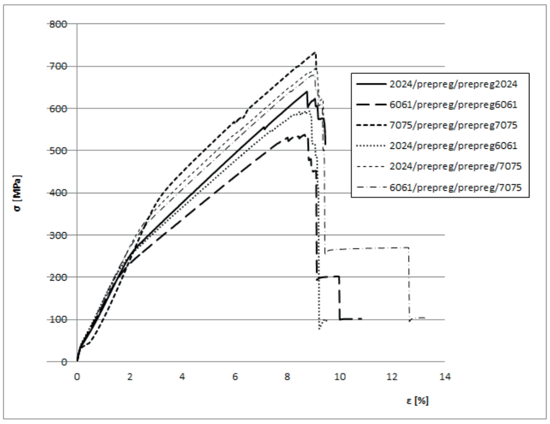


Fig. 9. σ- ε charts for homogenous samples and samples with various aluminum alloy

Based on the results, a significant effect of the aluminum alloy in the structure of the composite layer on the composite strength parameters was observed. As expected, based on the values derived on the basis of the mixing rule (MVF approach), the highest strength values were achieved by the composite made of 7075 alloy.

For composite materials made of different aluminum alloys (so-called 'Mixed composites'), the properties of the final composite are roughly averaged values on the basis of the properties of its constituent materials.

The results of the tensile test of composite samples made of a 2024 alloy, sheet having a thickness of 0.4 mm (the total thickness of the composite - 1,3 mm), were compared and analyzed with the results for 2024 alloy samples having different thicknesses (respectively 1,0; 1,6 and 2,4 mm). Additionally, the composite has incorporated the results reinforced with glass fiber fabric having a thickness of 1 mm.(Fig.10). There are noticeable differences in the properties of the various materials. The composite having a thickness of 1,3 mm and estimated (MVF) density of 2,36 g/cm^3, has a strength comparable to a solid sheet of aluminum of similar thickness. Most stiff material is aluminum with a thickness of 2,4 mm.

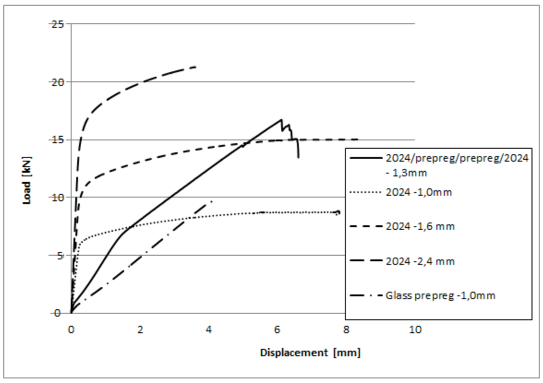


Fig. 10. A comparison of characteristics (load-displacement) of the 2024 alloy samples of different thickness with a GLARE composite sample having a thickness of 1.3 mm and prepreg sample, reinforced by glass mat

The photos of composite samples at break notched specimens, the "V" and notched "U" are shown in Fig. 11 and 12. There are visible differences in the process of breaking the samples, depending on the type of aluminum alloy and depending on the geometry of the notch.

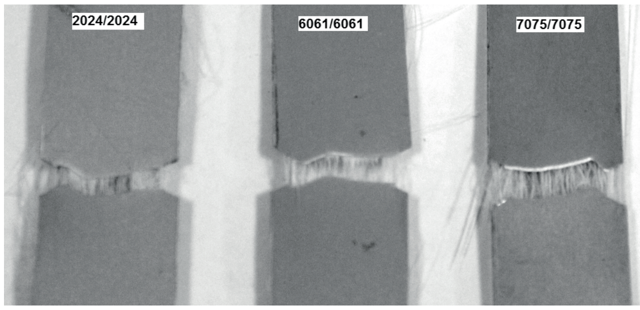


Fig. 11. V notched composite samples after tensile test

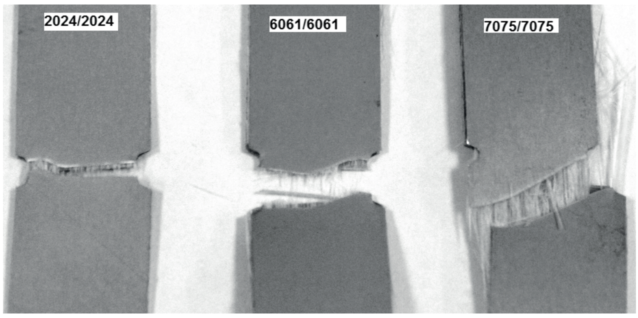
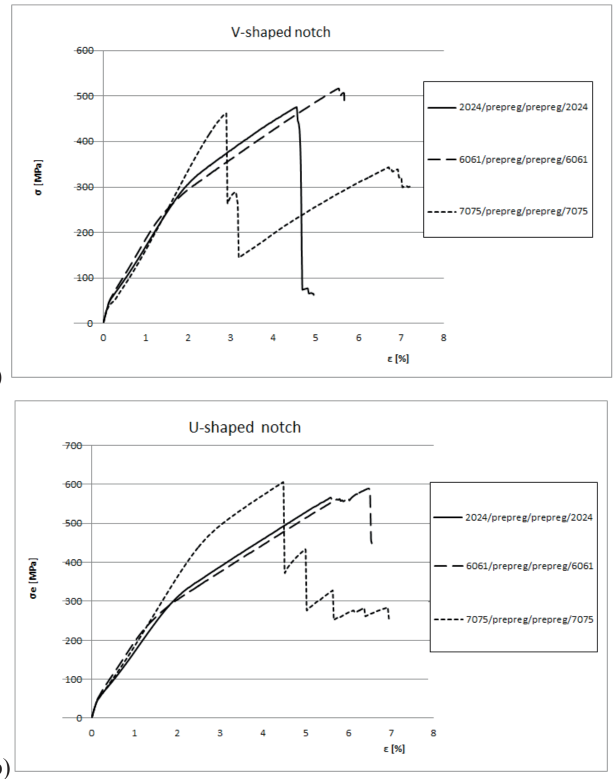


Fig. 12. U notched samples after tensile test

There are significant differences in the behavior of composite samples with "V" notch (Fig.13a) and for samples with "U" notch (Fig. 13b), depending on the type of the used aluminum alloy.



a)

b)

Fig. 13. A plot of the σ –ε of the samples: a) with the "V" notch, b) with "U" notch

The geometry of a notch has a significant impact on the strength characteristic of the composite material. Samples with notches have much lower strength parameters compared to those without notches. The least tough are “V” notched samples (Fig.14).

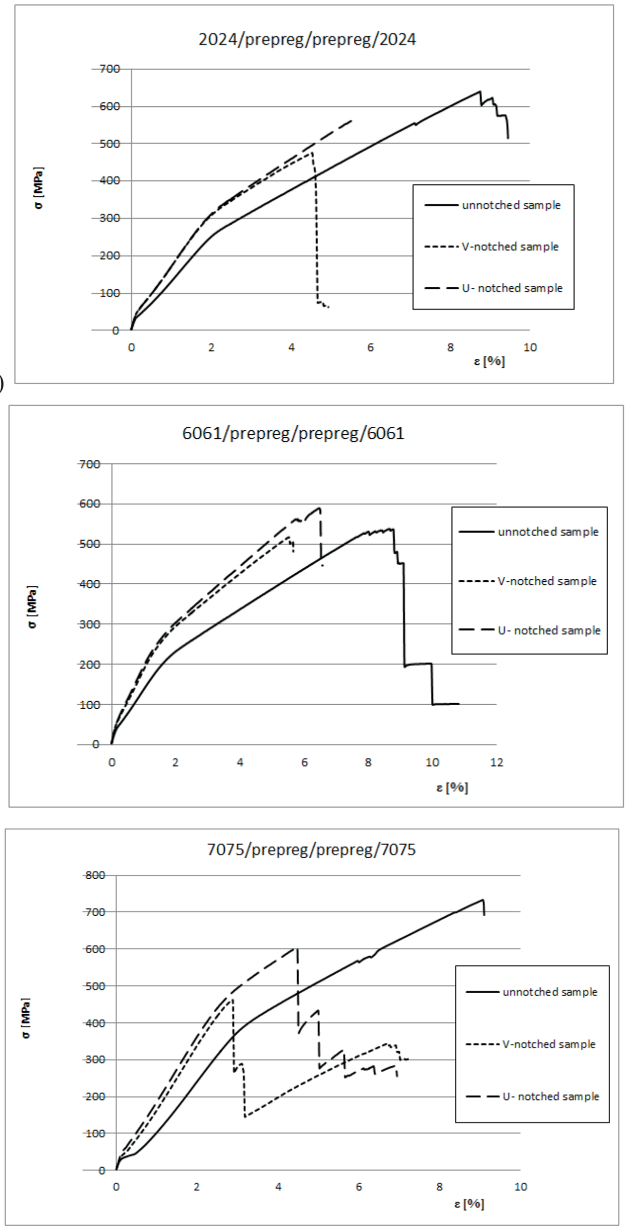


Fig. 14. Graphs illustrate the dependence of the σ - ε of composite samples without the notch, with the notch “V” and the U notch made of: a) 2024 alloy, b) 6061 alloy, c) 7075 alloy

3.2. Flammability test

Composite samples with the dimensions of 127 mm long, 13 mm width, 1.32 mm thick were pre-weighed. Samples were set in a vertical position in a holder, and were exposed to the flame for 10 seconds. After removal from the flame, the samples were burned for another 10 seconds. Having removed the flame, the sample burning time was measured. After the test, samples were weighed, the results are shown in Table 6. During the test, resin layers started to burn and melt. Further destruction of the material was blocked by the metal layer. According to the guidelines stated in the standard and based on test results, GLARE composites received V0 flammability class, which means that they are considered to be non-combustible.

TABLE 6

Results of GLARE burning test

GLARE 3 2/1	Time of burning [s]			weight loss [%]
	I	II	III	
2024/prepreg/2024	0	0	9	0.6
6061/prepreg/6061	0	0	0	0,3
7075/prepreg/7075	0	0	0	0,4

4. Conclusions

The experimental work carried out within this study found the following:

- the type of the aluminum alloy has big influence on the final mechanical properties of GLARE type composites ,
- it has been demonstrated that the properties of the layer composite can be estimated with the use of the mixing rule,
- values estimated with the use of the mixing rule are comparable to those obtained on the basis of the tests carried out,
- GLARE type composite made of 7075 alloy has the highest mechanical properties,
- This types of GLARE composites demonstrate V0 flammability class, they are nearly non-combustible.

The experimental work presented in the paper is the base for the evaluation of the properties and suitability of new type of GLARE composites. The analysis of results will allow for the determination of the safety level of composite aircraft structures.

Acknowledgements

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