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Original Research

Analysis of the Thermal Expansion Coefficient of Glass- and Carbon-Fibre-Reinforced Composites

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Abstract

With the development of manufacturing processes, an increase in the importance of metal-fibre composites in mechanical engineering is observed. These are materials consisting of appropriately arranged layers of metal and various types of fibres. The very wide use of composite materials in the construction of machine and equipment components means they are often exposed to work in variable temperature conditions. The aim of this article was analysis of the thermal expansion of typical composites: carbon fibre-reinforced polymer, glass fibre-reinforced polymer, glass-reinforced aluminium laminate and carbon-fibre reinforced aluminium laminate. EN AW-6060 aluminium alloy was used as the reference material. The aim of the dilatometric tests was to determine the coefficient of thermal expansion and the dimensional stability of composite materials at elevated temperatures up to 100 °C. The EN AW-6060 aluminium alloy was characterized by the highest linear expansion coefficient (20.27×10^{-6} 1/K). Composites containing glass fibres were characterized by the lowest positive linear thermal expansion coefficient. Among the composite materials tested, CARALLs exhibit the lowest thermal expansion coefficient.

Keywords: coefficient of thermal expansion, composites, dilatometric analysis, temperature, thermal expansion

1. Introduction

Composite materials play an increasingly important role in many fields of engineering. A composite is a hybrid material consisting of at least two materials with different properties (Ashrith et al., 2023). Such a material combination makes it possible to obtain elements that cannot be produced using conventional methods (Wang et al., 2007). Composites play a significant role in many areas of the aerospace (Bielawski et al., 2015), space (Samuel et al., 2021), shipbuilding (Barsotti et al., 2020), defence (Siengchin, 2023), sports and recreation (Ribeiro et al., 2019) and automotive (Garofano et al., 2023) industries. Carbon fibres used in carbon-fibre-reinforced polymers (CFRPs) allow for a significant reduction in vehicle weight while increasing safety (Ahmad et al., 2020). The unique properties of fibre metal laminates (FMLs) (Jakubczak et al., 2016) and composites with anti-wear properties (Walczak et al., 2017) means they are increasingly used in the automotive industry.

Each material has different physical, chemical and mechanical properties and not all materials can work together. This is due, among other things, to different electrical potentials or different values of the thermal expansion coefficients. If the potential difference between the components of the composite is large, a galvanic cell phenomenon occurs and corrosion may occur inside the composite (Hamill et al., 2017; Song et al., 2021). In the case of different thermal expansion, delamination may occur. In particular, this concerns FMLs consisting of alternating layers of metal and a polymer matrix laminate reinforced with continuous fibres (Costa et al., 2023). In composite materials subjected to long-term thermomechanical loads, there is a phenomenon of gradual changes in mechanical properties as a result of the gradual development of microcracks. Fibre breakage is a characteristic feature in carbon- and glass-fibre-reinforced polymers. In this context, the directionality of the reinforcing phase compared to the loading direction of the composite is important. In flat composite elements compressed in the plane, the primary damage is delamination (Trębacki & Królicka, 2017).

The basic goal of thermomechanical research is to understand how specific materials behave under particular temperature conditions. Based on the results of thermal and thermomechanical tests, it is possible to obtain characteristic properties such as the melting point, phase transformations and thermal expansion (James, 2017). When the thermal expansion of the matrix material and the reinforcing particle differ significantly, there is a risk of delamination at the interface and dimensional instability of the products (Fu et al., 2019; Ray, 2005). Knowledge of the relationship between rheological behaviour of materials and their behaviour under load is particularly important in the case of non-uniform members such as stepped, tapered columns (De Macêdo Wahrhaftig et al., 2023). There are many ways for measuring the mechanical characteristics of the macroscale samples, i.e. indentation tests, tensile and compression tests, three-point bending tests etc. (Al-Abboodi et al., 2023). However, methods for determining thermal properties of materials are limited. Due to the research method, thermomechanical analysis (TMA) (Saba & Jawaid, 2018), dynamic-load TMA (DLTMA) (Shaikh et al., 2023), and dilatometry (DIL) (Dergal et al., 2022) can be distinguished. The DLTMA method is based on periodic monitoring of a sample subjected to force. The tested element can be cyclically bent, stretched, compressed or sheared. The result of such a study is the measurement of the change in the sample's Young's modulus depending on temperature. In TMA analysis, the pressure exerted on the sample does not change over time. As a result of the applied force, the element changes its dimensions. In this method, pressure is applied through variously shaped measuring probes, which may be flat or semicircular. Dilatometric tests enable the registration of changes in the length of a sample of the tested material caused by temperature changes. Due to the measurement method, the following thermal expansion coefficients are distinguished: linear, surface and volume.

The study of thermomechanical properties has been the subject of many works over recent years. Łągiewka et al. (2009) investigated the thermal expansion of metal composites based on the AlMg9 alloy reinforced with chopped carbon fibres and composites containing graphite particles. It was found that the coefficient of thermal expansion in the tested composites is higher than for the matrix alloy. This may indicate the lack of adhesive connections at the phase interface. Dilatometric tests of composites based on the AK9 alloy with various ceramic fibre contents (10, 15, 20 vol.%) show the dependence of the thermal expansion coefficients on the fibre content in the composite. The mismatch in the coefficient of thermal expansion between fibre-reinforced polymers (FRPs) and metal is the main cause of residual stresses in FRP/metal composites (Tinkloh et al., 2020), which can lead to delamination in the absence of any external loads (Prussak et al., 2018). Large thermal residual stresses induce low static strength and low fatigue strengths of carbon-fibre-reinforced aluminium laminates (CARALLs) (Hu et al., 2022). Xue et al. (2011) used thermal expansion of the clamp during the curing process to apply tensile stress to CFRP layers. Dul (2013) presented an overview of the possibilities of thermal expansion analysis for composites with high thermal conductivity. Based on the literature analysis, it can be concluded that most authors focused on examining limited number of materials or they investigated thermal expansion of group of similar materials, which makes it difficult to compare the results. Moreover, research on the thermal expansion of hybrid materials is quite limited. Inspired by the results of other researchers, the authors of this work decided to test and compare the behaviour of various construction materials with different structures, including fibre-metal laminates.

This article compares the thermal expansion coefficients of five materials: EN AW-6060 aluminium alloy, CFRP, GFRP and two aluminium-based laminates. In the experimental studies, dilatometric analysis was used.

2. Material and methods

2.1. Materials

An aluminium alloy EN AW-6060 (EN 573-3+A1, 2022), GFRP, CFRP, Glass-Reinforced Aluminium Laminate (GLARE) and Carbon-Reinforced Aluminium Laminate (CARALL) in the form of rods with a diameter of $8_{-0.1}$ mm were used as the test materials (Fig. 1). The length of all samples for dilatometric tests was 30±0.1 mm. Selected physical and mechanical properties of EN AW-6060 aluminium alloy are listed in Table 1. Carbon fabric weighing 160 g/m^2, with a thickness of 0.25 mm and twill weave, and glass fabric weighing 80 g/m^2, a thickness of 0.4 mm, and twill weave were used as reinforcement.

Using the lamination operation, samples of a circular cross-section with a diameter of 8 mm were made with a core of aluminium alloy EN AW-6060. Aluminium alloy rods with a diameter of 6 mm were used as a semi-finished product to produce the GLARE and CARALL.

Schematic diagram of the dilatometric test is presented in Fig. 2. To laminate two different materials with different characteristics, special brass sleeves were prepared as shown in Fig. 3.

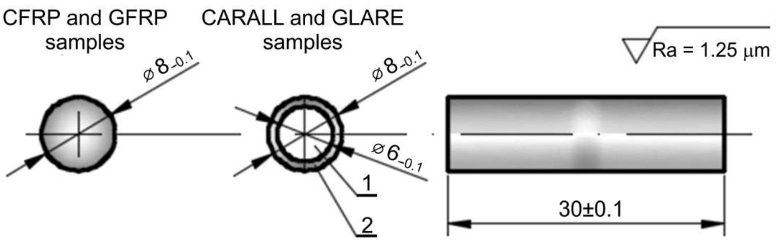

Fig. 1. Dimensions of the samples for dilatometric (dimensions in mm): 1 – metal core, 2 – continuous fibre-reinforced laminate.

Table 1. Physical properties of the EN AW-6060 aluminium alloy, prepared on the basis of (PA38, 2023).

Parameter	Value
Flow temperature	655 °C
Freezing point	610 °C
Thermal conductivity	209 W/mK
Electric conductivity	54 %
Specific heat	898 J/kgK
Rigidity modules (G)	26 100 MPa
Young's modulus (E)	69 000 MPa
Poisson's ratio	0.33
Density	2.7 g/cm^3
Thermal expansion coefficient	23.4×10^{-6} 1/K

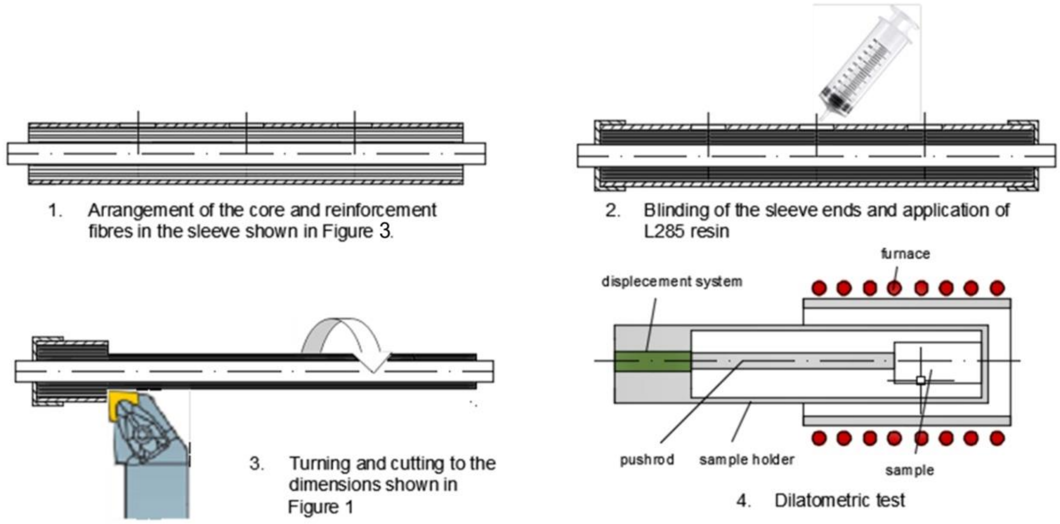

Fig. 2. Schematic diagram of dilatometric test.

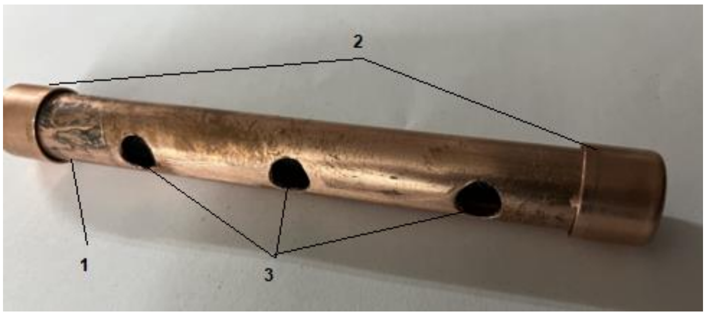

Fig. 3. Brass sleeve: 1 – sleeve, 2 – blinds, 3 – holes for resin application.

The purpose of using the sleeves was to fix the bonded elements in an appropriately symmetrical, stationary position. Holes with a diameter of 8 mm were drilled in three symmetrically placed points, through which a binder (liquid epoxy resin L285) was applied. Strips about 20 mm wide, cut from carbon or glass fibre fabric, were wound onto the rod. The prepared samples were subjected to the lamination process.

2.2. Experimental procedure

Dilatometric tests were carried out using the DIL 402 PC (Erich NETZSCH GmbH & Co. Holding KG, Selb, Germany) dilatometer, which is shown in Fig. 4. The DIL 402 PC dilatometer combines easy operation and high adaptability to various applications. The optimized design of the measurement system with an inductive transducer ensures a high degree of reproducibility even without external cooling. The dilatometer was turned on two hours before the measurements began.

Fig. 4. DIL 402 PC dilatometer.

The samples were installed in a sample carrier. Using an adjustment screw, the sample was initially pressed to the measuring tip. The correct pressure is indicated by the diode on the base unit. After ensuring the thermocouple was close to the workpiece under test (without touching it), the furnace was closed. The ambient temperature and heating rate were T_0 = 31.3 °C and 5 °C/min, respectively. The increase in length during the test was measured using an inductive transducer, which monitors the pushrod displacement resulting from the expansion of the sample.

Measurements with a dilatometer involves observing the change in the length of the tested sample depending on the increase in temperature ΔT (Fig. 5). As a result, a dilatometric curve is obtained, which is helpful in determining one of the most important values characterizing the tested material – the coefficient of linear thermal expansion. In this method, no external force acts on the sample (Sierpiński, 2023). The value of the thermal expansion coefficient is determined based on the Eq. (1):

$$\alpha = \frac{\Delta L}{L(T_1) \times \Delta T} \tag{1}$$

where α is the coefficient of thermal expansion, ΔL is the increase in length, $L(T_1)$ is body length at the reference temperature (31.3 °C), ΔT is the temperature increase.

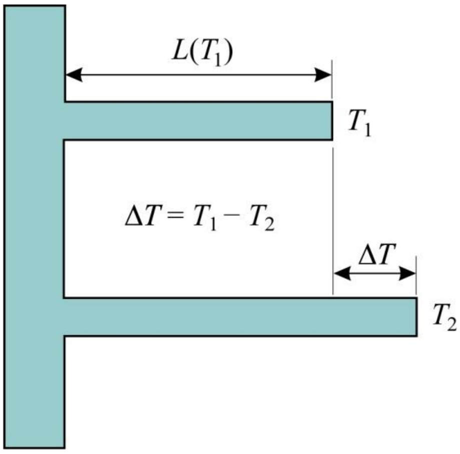

Fig. 5. The linear change in sample dimension due to temperature change.

3. Results and discussion

Based on the results obtained, the value of the linear expansion coefficient and the value of the stresses occurring in the individual samples were determined. According to Hooke's law (Eq. (2)), the dependence of the stresses σ on the thermal expansion coefficient α was derived (Eqs. (3)-(5)). The adopted values of Young's modulus E and the obtained results are presented in Table 2.

$$\sigma = E \cdot \varepsilon \tag{2}$$

$$\varepsilon = \frac{\Delta L}{L} \tag{3}$$

$$\alpha = \frac{\varepsilon}{\Delta T} \tag{4}$$

$$\sigma = \alpha \cdot E \cdot \Delta T \tag{5}$$

where σ is stress, E is the Young's modulus, ε is strain, ΔL is the increase in sample length, L is the initial length, ΔT is the temperature increase.

As a result of the measurements, diagrams of the changes in sample length and temperature during the tests were obtained (Figs. 6-10). The diagrams clearly show that the highest coefficient of linear expansion is characterized by the EN AW-6060 aluminium alloy (Fig. 6). The value of the thermal expansion coefficient of this alloy is $20.27 \cdot 10^{-6}$ 1/K (Table 2) and is close to the requirements of manufacturers of metallurgical materials (Aluminium 6060, 2023; EN AW-6060, 2023). The change in the dimensions of the tested sample is regular – as the temperature increases, the elongation value gradually increases and reaches an extreme when the temperature is above 100 °C (Fig. 6).

Table 2. Values of Young's modulus E, stresses σ and coefficient of thermal expansion α for specific materials.

Material	E, MPa	α, 1/K	σ, MPa
EN AW-6060	69 000	$20.27 \cdot 10^{-6}$	106.24
GLARE	49 000 (Bieniaś et al., 2020)	$5.73 \cdot 10^{-6}$	21.53
CARALL	100 000	$14.5 \cdot 10^{-6}$	111.21
GFRP	69 000	$4.74 \cdot 10^{-6}$	24.75
CFRP	160 000	$-24.17 \cdot 10^{-6}$	−292.75

A sample of the glass-reinforced aluminium laminate behaves similarly to an aluminium alloy sample at temperatures up to approximately 50 °C (Fig. 7). Both samples achieve an elongation value of 0.0004 mm. Then, the composite sample quickly obtains a negative increase in length, and in the final stage of the measurement it stabilizes. During the entire duration of the tests, the elongation value changes with a very large amplitude.

The carbon-fibre-reinforced aluminium laminate showed an equally large amplitude of changes in the elongation value (Fig. 8). When the temperature reaches 70 °C, a local extreme occurs and the material shows a high elongation value. In the next stage, the elongation begins to decrease rapidly, down to negative values (approximately $\Delta L/L_0 = -0.0004$). In the final part of the test, the sample reaches the minimum elongation value, approaching zero.

The glass-fibre-reinforced polymer has the lowest positive coefficient of thermal expansion (Fig. 9). This value is more than five times lower compared to the EN AW-6060 aluminium alloy. This confirms the commonly known feature of glass fibres, that is, it is a material that is insensitive to temperature changes. The GFRP composite sample achieved the greatest elongation at a temperature of approximately 100 °C, but the elongation curve is uneven. In the initial phase of the test, the material showed a negative growth value (Fig. 9).

The elongation curve of the carbon fibre-reinforced polymer sample has an unusual shape (Fig. 10). In the first phase, until the material reaches a temperature of approximately 60 °C, the material shows almost no reaction to the temperature change. However, at higher temperatures the results mean that the CFRP exhibits a negative thermal expansion coefficient. In terms of absolute value, the greatest value of length change is achieved at a maximum temperature of approximately 105 °C. Then, as the temperature slowly decreases, the elongation value remains almost unchanged (Fig. 10).

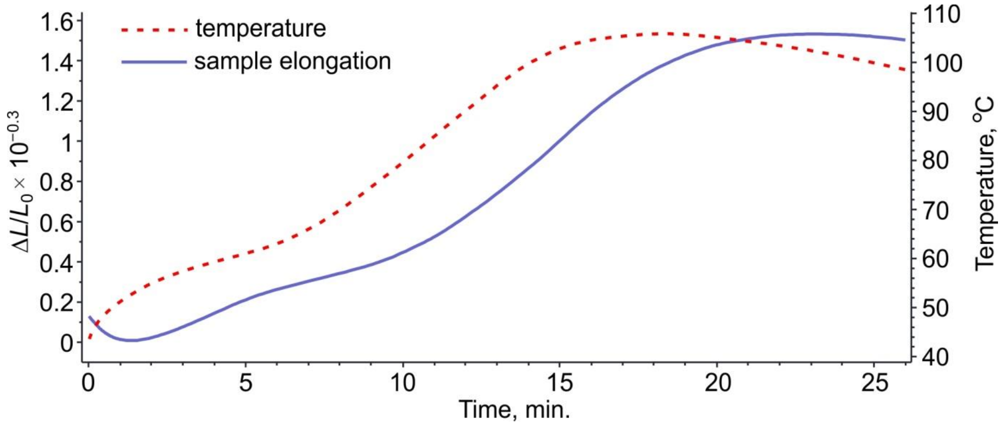

Fig. 6. Dilatometric analysis of the EN AW-6060 sample.

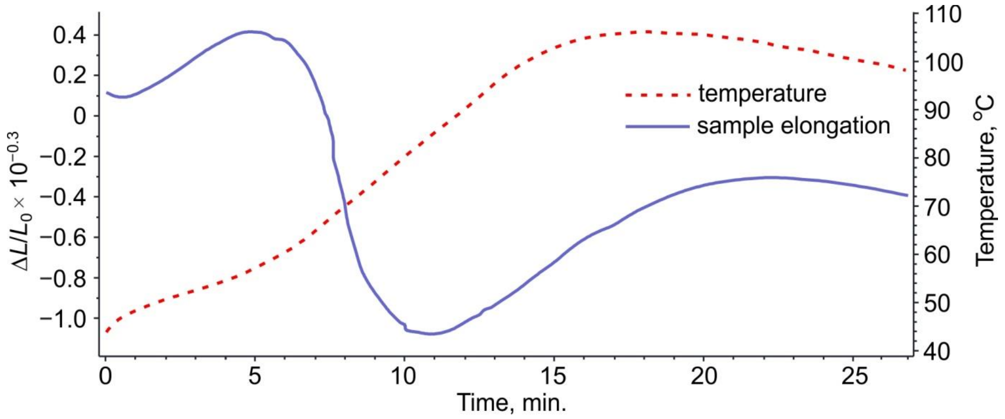

Fig. 7. Dilatometric analysis of the GLARE sample.

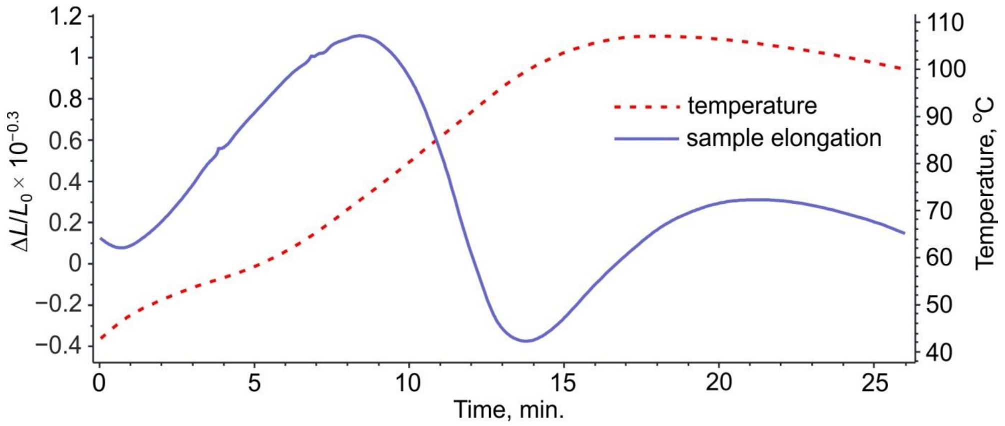

Fig. 8. Dilatometric analysis of the CARALL sample.

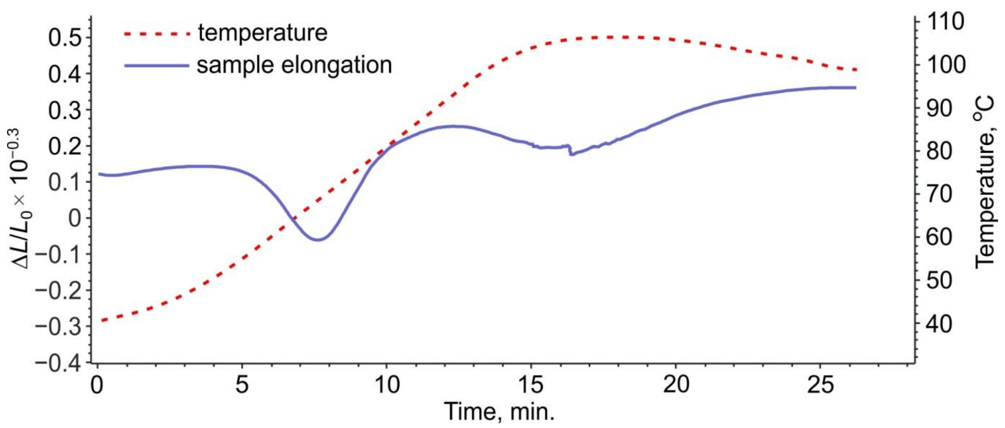

Fig. 9. Dilatometric analysis of the GFRP sample.

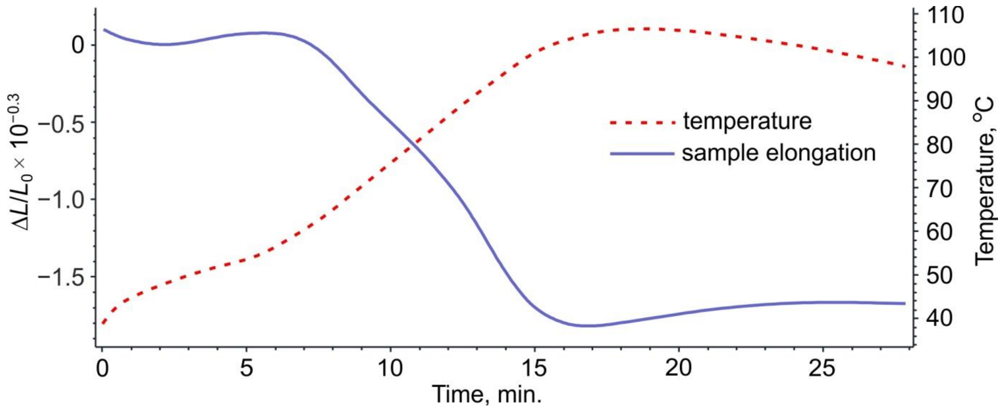

Fig. 10. Dilatometric analysis of the CFRP sample.

The values of the maximum elongations of the samples and the corresponding temperature increases are presented in Table 3. The value of relative elongation was automatically determined by the software, while the temperature increase was determined based on Eq. (6).

Table 3. Sample length and temperature increases.

Material	ΔL/L₀	ΔT, °C
EN AW-6060	0.0154	75.96
GLARE	0.00044	76.7
CARALL	0.00111	76.7
GFRP	0.000359	75.7
CFRP	−0.00183	75.7

$$\Delta T = T_k - T_0 \tag{6}$$

where ΔT is temperature increase, T_k is final temperature and T_0 is initial temperature.

Samples containing glass fibres have the lowest positive linear thermal expansion coefficient. Therefore, when testing these materials, the lowest stresses occurred, which are closely related to the value of the thermal expansion coefficient. In the case of the absolute value, the highest stress value occurred in the CFRP sample (Table 3). These are compressive stresses resulting from the negative coefficient of thermal expansion.

The difference in the internal structure of the fibres and the aluminium alloy causes an uneven increase in the length of the composite samples during heating. The aluminium alloy has a positive coefficient of thermal expansion, while the carbon fibre sample shows a negative coefficient of thermal expansion, similar to glass fibres over a certain temperature range. Carbon fibre fabric shrinks in size under the influence of increased temperature, in contrast to the aluminium alloy. Moreover, fibre-reinforced composites, as anisotropic materials, have different properties depending on the arrangement of the fibres. These are important factors in the production of hybrid composites. There is a risk of an inappropriate combination of materials, which will result in stresses causing cracks and delamination in the composite.

However, it should be assumed that fibre-reinforced composites are characterized by greater durability than popular metal-fibre composites. Therefore, the use of CARALL and GLARE composites at elevated temperatures cannot be completely disqualified. However, one must make sure that such materials will not be operated at too high temperatures.

4. Conclusions

Determining the value of the thermal expansion coefficient makes it possible to determine changes in body dimensions under the influence of increased or decreased temperature. This property is particularly important for materials operating in rapidly changing atmospheric conditions. Changing the dimensions of materials causes the occurrence of internal stresses of variable values, which intensifies material fatigue. Based on the research results contained in this article, the following conclusions can be drawn:

- During dilatometric tests, the elongation value of the GLARE composite changes with a very large amplitude. This is the result of a large difference in the thermo-mechanical properties of the component materials of this composite.
- The elongation value of the CARALL composite is subjected to strong changes from positive values in the temperature range of 45–90 °C to negative elongation values in the temperature range of 90–105 °C.
- The glass-fibre-reinforced composite exhibits the lowest positive coefficient of thermal expansion. This value is more than five times lower compared to the EN AW-6060 aluminium alloy.
- The composite reinforced with carbon fibres does not undergo significant deformation until the temperature reaches approximately 50 °C. However, at higher temperatures it turns out that the carbon-fibre-reinforced polymer exhibits a negative thermal expansion coefficient.

In future research, it would be desirable to perform thorough tests of these types of composites at reduced temperatures and under thermal shock conditions. It would also be advisable to carry out strength tests of materials at elevated and reduced temperatures.

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Analiza Współczynnika Rozszerzalności Cieplnej Kompozytów Wzmocnionych Włóknami Szklanymi i Węglowymi

Streszczenie

Wraz z rozwojem techniki, możemy zaobserwować wzrost znaczenia kompozytów metalowo-włóknistych w inżynierii mechanicznej. Są to materiały składające się z odpowiednio ułożonych warstw metalu oraz różnego rodzaju włókien. Bardzo szerokie zastosowanie materiałów kompozytowych w budowie elementów maszyn i urządzeń powoduje, że niejednokrotnie są one narażone na pracę w warunkach zmiennych temperatur. Celem tego artykułu była analiza rozszerzalności cieplnej typowych materiałów kompozytowych wzmocnionych włóknami węglowymi i szklanymi oraz laminatów typu GLARE i CARALL. Jako materiał referencyjny wykorzystano stop aluminium EN AW-6060. Celem badań dylatometrycznych było określenie rozszerzalności cieplnej i stabilności wymiarowej materiałów kompozytowych w podwyższonych temperaturach do 100°C z szybkością nagrzewania 5°C/min. Największym współczynnikiem rozszerzalności liniowej (20,27 $\times 10^{-6}$ 1/K) charakteryzował się stop aluminium EN AW-6060. Najmniejszym dodatnim liniowym współczynnikiem rozszerzalności cieplnej charakteryzowały się kompozyty zawierające włókna szklane. Spośród materiałów kompozytowych, najmniejszym współczynnikiem rozszerzalności cieplnej charakteryzował się kompozyt typu CARALL.

Słowa kluczowe: współczynnik rozszerzalności cieplnej, kompozyty, analiza dylatometryczna, temperatura, rozszerzalność cieplna