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THEORETICAL AND EXPERIMENTAL REVIEW OF APPLIED MECHANICAL TESTS FOR CARBON COMPOSITES WITH THERMOPLASTIC POLYMER MATRIX

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Abstract

This article has a theoretical and experimental character. It presents the characteristics of two main thermoplastics used in the aerospace industry – poly ether ether ketone (PEEK) and poly phenylene sulphide (PPS). The selected materials are compounds for the production of thermoplastic polymer matrix composites. The paper presents a literature review of the application of thermoplastic polymer matrix composite materials in aviation. Additionally, the paper focuses on the characteristics of carbon fibre-reinforced polymer (CFRP) which plays an important role in the production of aerospace components. Testing methods have been chosen on the basis of the type of composite matrix. The article contains the most important mechanical properties and general characteristics of thermoplastics used as a matrix for CFRP type composites used in the aerospace industry. Individual test procedures which allow for the evaluation of mechanical properties of composite materials on a thermoplastic polymer matrix, have been described. Mechanical tests such as static tensile test and bending of short beams were carried out in order to examine CFRP composites.

Keywords: carbon fibre composites, PEEK, PPS, CFRP, thermoplastics, investigations of PEEK and PPS composites.

1. INTRODUCTION

The 40s of the last century became the beginning of a new era in the aviation industry. According to literature data, for the first time composite material was used as an element in aircraft construction [1,2]. A significant decrease in aircraft weight was achieved, which resulted in lower fuel consumption and better flight performance. It was a breakthrough moment for material engineering in the aerospace industry. Since then, composites have been gradually incorporated into individual structural components. Today, composite materials are in strong competition with traditional materials used in the aerospace industry.

In recent years there has been an intensive development of the aviation industry, largely related to the increased availability of this type of transport. According to Airbus' forecasts, the number of passengers using this type of transport is expected to double in the next 15 years. As a direct result of the dynamism in this area, a noticeable increase can be observed in the number of works devoted to the development of better and more comfortable aircraft allowing for further improvement of transport conditions.

Over the past 50 years, the aviation market has placed increasing emphasis on the development of new materials that can potentially be used in aircraft design. In recent years, there has been a particularly noticeable increase in the use of composite materials. Such materials, due to the combination of at least two different components, allow to obtain properties that would be extremely difficult to gain under different conditions. In aviation, it is extremely important to minimise the weight of the material, which translates, for example, into lower fuel consumption. The use of such materials in aircraft production began as early as the 1960s, when the weight of composite components accounted for several percent of the materials used in mechanical engineering. A breakthrough in aviation was the construction of the 787 (Dreamliner) by Boeing, which was designed so that about 50 percent of the materials used were composite materials. Commercial aircraft manufacturers are announcing a further increase in the use of composite materials.

The development of new materials is closely linked to the provision of appropriate properties that meet all design objectives. Reducing the weight of components, which is achieved by introducing composite materials with a lower density than traditional metallic alloys, is associated with giving them the appropriate mechanical properties. Components are loaded in different ways depending on their application. Changes in temperature and pressure are only examples of conditions that must be taken into account when designing machinery.

One of the basic criteria for classifying composite materials is their classification according to the type of matrix. There are three types of matrix: ceramic, metallic and polymer matrix [2]. The matrix performs very important functions in the composite material, such as transfer of external stresses to the reinforcement, which gives the products their shape and inhibits crack propagation [3,4].

Composites with polymeric matrix, due to their properties , i.e. high resistance to fatigue and stiffness, are materials more and more commonly used in aviation industry branches.

In the 70'÷80's of the last century, Airbus constructed a passenger airplane.

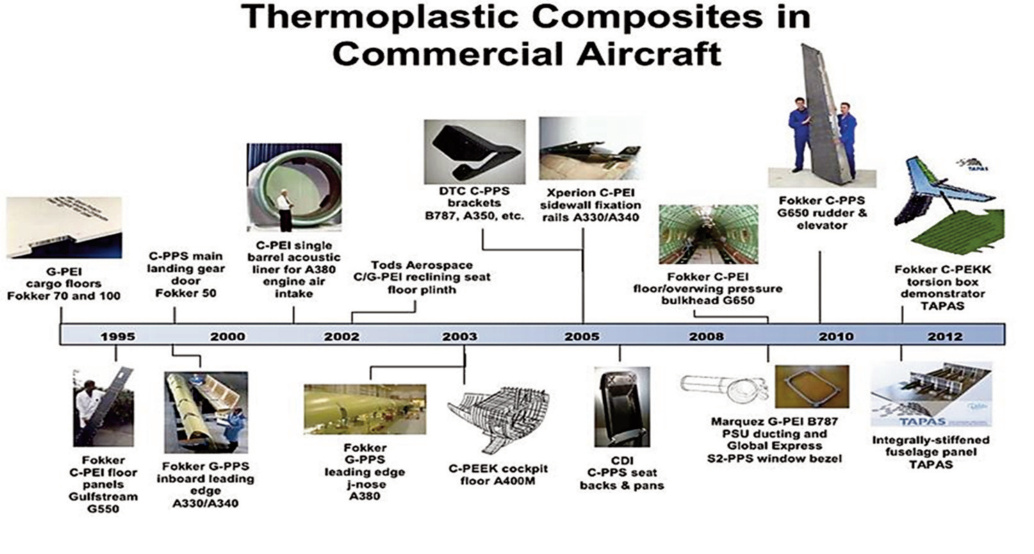

Figure 1. Thermoplastic matrix composites, CFRP used in the aviation industry [3]

A300-B2 consisting of approximately 6% by weight of polymeric matrix composite materials. In 2009, Boeing 787 - Dreamliner was constructed, consisting entirely of over 50% of fibrous composites [5÷8].

Literature data confirm the increasing importance of polymeric composites as construction materials which will dominate to a large extent in the aviation industry in the coming years [9].

Among composite materials used in aviation, we can distinguish more and more willingly used Carbon Fibre Reinforced Polymers (CFRP) composites. In this case, the matrix may be thermoplastics. For nearly a quarter of a century (Figure 1), these materials have been more and more commonly used in many branches of industry, especially in the aviation market. They are gaining popularity due to such properties as low specific weight, good corrosion resistance, ability to damp vibrations and resistance to fatigue [10]. The most popular thermoplastics used as a prepreg matrix include: poly ether ether ketone (PEEK), poly ether ketone ketone (PEKK) as well as poly phenylene sulphide (PPS) [10,11].

2. THERMOSTABLE POLYMERS

On the basis of the Marvel method, the thermostable polymer is the one which is not destroyed under the influence of high temperature (up to 300°C) and long-term use (max. 25 000 h). Moreover, according to the above classification, the material subjected to short-term heating (up to 300 h) at a temperature not exceeding 500°C, which does not melt and does not change its shape as a result of these factors [12,13], will also be a thermostable polymer.

In industry, especially aerospace, there is a considerable demand for thermostable materials. This is mainly due to the environment in which the given elements are operated, e.g. operation at temperatures above 800°C, as a result of which it is necessary to use ablative materials which through destruction in the surface layer will protect subsequent layers of parts [14].

The paper focuses mainly on thermoplastic high-temperature polymers such as: poly ether ether ketone (PEEK) and poly phenylene sulphide (PPS). Both PEEK and PPS are classified as partially crystalline polymers. This results mainly in high melting and glass transition temperatures.

PEEK combines good mechanical and thermal properties. In addition, it is distinguished by its high chemical resistance, as a result of which it belongs to the group of high-performance plastics. Poly ether ether ketone combines both good mechanical strength, sliding properties and high resistance to high temperatures. This material has good insulating properties [15,16].

PEEK has a number of good mechanical properties, thanks to which it is so widely used by various industries. The main mechanical properties of poly ether ether ketone primarily include: high elasticity modulus, low creep predisposition, stress cracks and very high resistance to abrasive wear [14]. Moreover, in high temperature range PEEK exhibits high plastic deformation resistance and high stability of strength properties – at 200°C and 10,000 h of operation, the tensile strength for PEEK almost does not change [15].

PEEK has very good chemical properties such as hydrolysis resistance as well as high resistance to many chemical substances (both organic and inorganic). In addition, PEEK is a flame retardant material with flammability class V0 according to UL 94. Of all thermoplastics, PEEK is the material that emits the smallest amount of gases and smoke during combustion. Compounds causing damage to poly ether ether ketone are: sulphuric acid, nitric acid and hydrocarbons, which contain halogens [16].

Owing to their unique combination of properties, PEEK matrix composites are currently used primarily by the aviation and marine industries, as well as for the construction of ammunition containers, fireproof fabrics and tanks [16, 17].

Another commonly used material is poly phenylene sulphide (PPS) which is a cheaper alternative to polymeric materials from the PEEK group. Like PEEK, it is classified as a semi-crystalline thermoplastic material. It shows very high dimensional stability even up to 200°C [18,19].

Composites based on poly phenylene sulphide, due to their very good thermal and mechanical properties, are used in many branches of industry, mainly in the automotive industry, engineering, chemical industries as well as electronic components [19].

Poly phenylene sulphide is characterised by highly desirable mechanical properties. These include high impact resistance with notch, which is stable even at high temperatures, and high dimensional stability, also at high temperatures. PPS is a material that has a low tendency to creep. Under the influence of high temperatures, poly phenylene sulphide exhibits low plastic deformation strength [19].

PPS exhibits high chemical resistance to both dilute and concentrated acids and bases. The exception is chloric acid and oxidizing acids. PPS has high resistance to hydrocarbons and boiling water and steam [19÷22]. The chemical properties of PPS also include its high resistance to oxidation. It is a material with low moisture absorption and shows high stability to hydrolysis with hot water or steam (Fig. 2) [20÷22].

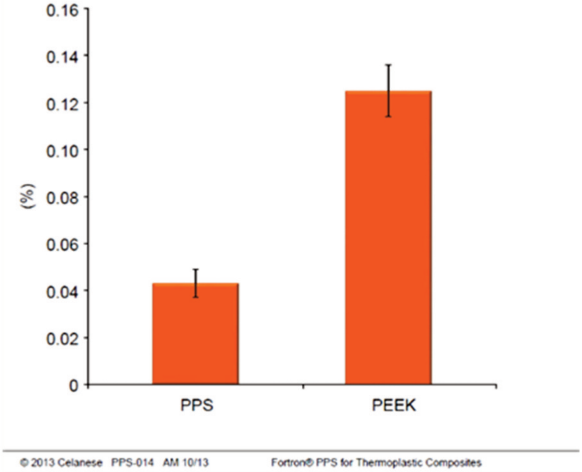

Figure 2. Comparison of water absorption for materials: PPS and PEEK [22]

3. USE OF THERMOPLASTIC MATRIX CARBON COMPOSITES IN THE AEROSPACE INDUSTRY

Constantly growing demand for civil and military services exerts a strong pressure to seek innovative solutions taking into account innovative materials. The main guidelines are: reduction of aircraft weight, maintenance of aerodynamic equilibrium of the vehicle [23]. This applies not only to the interior design of the aircraft, but also to its structure.

CFRP composites are the answer to the key requirements of engineers. These materials are not only much lighter than traditionally used ones, but also have very good mechanical properties and high resistance at high temperatures.

Both PEEK and PPS exhibit many beneficial properties for use in aircraft structures and internal components. Although the costs of materials used in the aerospace industry may be relatively higher than the prices of competing materials, the cost of the finished component is about 20÷40% lower. The result of this difference is a lower cost of service, processing and assembly [24].

PPS matrix composites combine a number of advantages, which are of great importance in the aerospace industry of mechanical properties (e.g. high hardness, impact strength and stiffness) with high chemical resistance. Moreover, these composites are dimensionally stable in the range of high temperatures exceeding 100°C and are flame retardant. As a result of such compilation of properties, it was only a matter of time when PPS matrix composites will enter the aerospace market. An example can be the use of PPS composite by one of the largest manufacturers in the aerospace industry as a substitute for many aluminum components (armrests, monitor housings, backrests and seats) inside aircraft. As a result, the weight of the component was reduced by as much as approx. 40÷50% [23]. For example, Tepex replaced the backrests in the lumbar part, in the base of the rear part of the seat, traditionally made of aluminium. Tepex is a carbon composite made of poly phenylene sulphide. Replacement of aluminium parts with PPS matrix composite reduced the weight of about 130 g per seat and 72 kg in the whole A380 aircraft [24]. This material gained recognition not only due to its lower weight, but also due to easier and cheaper ways of composite processing than aluminium which undergoes more processing stages. One of the global polymer manufacturers, Ticona, estimates that replacing aluminium elements with Tepex in the total calculation gives savings of 20÷25% [24÷25].

Aviation of the 21st century cannot exist without the use of composite materials. As shown in Fig. 2, it is slowly becoming a standard that composite materials replace traditionally used metals. In the case of the Boeing 787, the share of composites is 50% (Fig. 3) [26]. Composite materials are commonly used as elements for most modern aircraft. They are used not only in fuselage, wings, but also in engines and aircraft equipment.

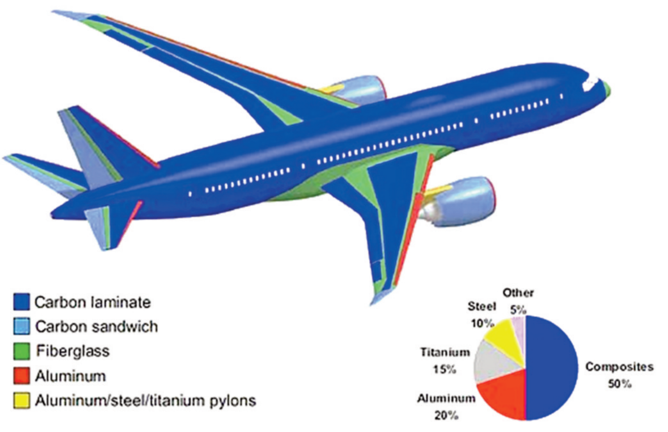

Figure 3. Materials used in Boeing 787 [26]

It is estimated that by 2020 the consumption of carbon composites, especially CFRP, will reach a result of about 89,000 t (Fig. 4) [27], which means an increase by almost 37% in relation to forecasts for 2017. This results in an increase of almost 37% in relation to the forecasts for 2017. The forecast of the consumption of carbon composites in the coming years proves how important materials they have become in industry.

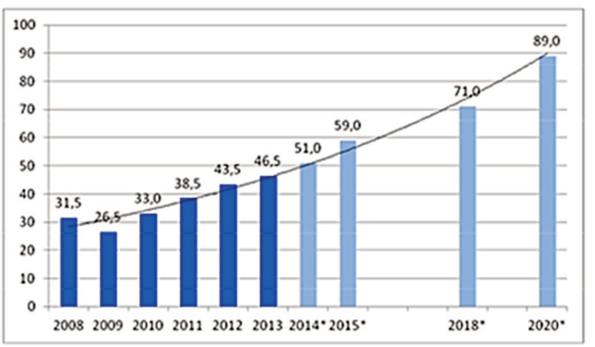

Figure 4. Estimated value of global demand for carbon composites in thousands of tons (forecast for 2008÷2020) [27]

4. TEST METHODOLOGY

4.1. Test material

The tests were carried out in the Composite Research Laboratory at the Institute of Aviation. Two composite boards made of unidirectional CETEX TC 1200 PEEK AS-4 preimpregnation with the use of an AFP (Automated Fiber Placement) robot were tested. Additionally, the second plate was consolidated with a PHBJ 250 hydraulic press. The layer system was quasi-isotropic: [0/45/90/-45]2S. The average thickness of the material layer was 0.15 mm. The samples were cut with a diamond disc 125 mm in diameter at a speed of 760 rpm. The tests were carried out under RTA (Room Temperature Atmosphere) conditions.

4.2. Strength tests

Two types of strength tests were performed:

1. Tensile testing in accordance with ASTM D3039,
2. Shear in a short beam bending test in accordance with ASTM D2344.

A static tensile test is carried out to test the strength of the material. The subject of the test is a thin strip of rectangular cross-section. The prepared material is assembled in the clamps of the testing machine. The load is then applied to the specimen gradually and recorded automatically. The maximum load carried by the specimen before failure is considered to be the limit of the tensile strength of the material.

The specimens to be tested for tensile strength should have a rectangular cross-section. This test method does not require the use of tabs (e.g. if there is a risk of specimen slippage in the grips). The thickness and width are selected in such a way that the specimen can be considered as a representative part of the material, i.e. the specimen can be used to perform a meaningful tensile test.
The ultimate tensile strengh was calculated using equation 1 [28].

$$F^{tu} = p^{\max} / A \tag{1}$$

A short beam bending test is carried out to determine the interlaminar shear strength of CFRP. This test is used during quality control of a given product and testing of technological processes. The test method consists in placing a short beam on sliding external supports. Bending is done by means of a loading nose, which is set in the axis of symmetry between two supports (Fig. 5).

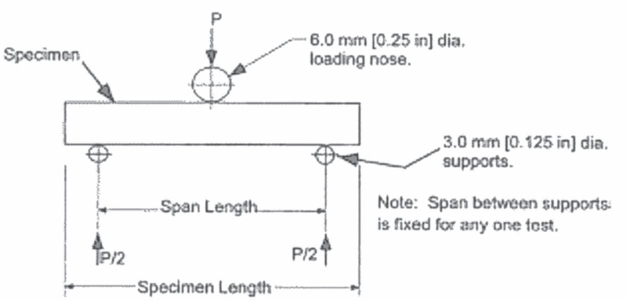

Figure 5. Short beam bending test scheme for flat specimens [28]

The dimensions of the specimens to be used in the interlaminar shear strength test are shown in Fig. 6. Longitudinal specimens are used for the tensile test. It is not necessary to use pads. Both the thickness and width of the material to be tested should be selected so that the specimen can be fully considered a representative of the material.

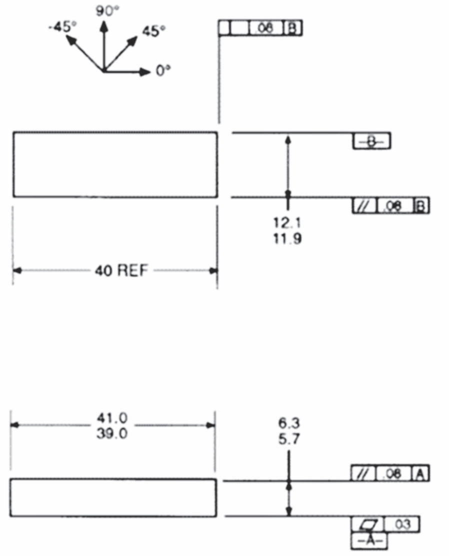

Figure 6. Short-beam shear bending test specimen model according to ASTM D2344 [28]

5. TEST RESULTS

Table 1 shows the results of the static tensile test carried out in accordance with ASTM D3039. The test speed was set at 2 mm/min according to the standard. The average tensile strength of the material tested was 659 MPa and the standard deviation was 18 MPa.

Table 1. Summary of results after the static tensile test

Coupon no.	Thickness, *d*, mm	Width, *W*, mm	Load at failure, P_{max}, kN	Tensile strength, F_{tu}, MPa
T-RTA-01	2.310	26.267	41.25	680.90
T-RTA-02	2.314	26230	40.46	666.71
T-RTA-03	2.354	26.207	41.11	666.52
T-RTA-04	2.358	26.207	41.07	664.70
T-RTA-05	2.358	26.127	39.40	639.68
T-RTA-06	2.334	26.143	38.67	633.74
Average	**2.338**	**26.197**	**40.33**	**658.54**
Standard deviation	**0.022**	**0.053**	**1.06**	**18**
Coefficient of variation	**0.94 %**	**0.20 %**	**2.63 %**	**2.71 %**

AzoMaterials has published the results of a PEEK-based carbon composite study. A static tensile test was carried out, resulting in a tensile strength of 750 MPa [29]. Almayid and co-authors [30] carried out a static tensile test under different temperature conditions for two fibre systems, i.e. 0° and 90°.

In the first case, the tests were carried out at room temperature. In the second series, the tests were carried out at 150°C. The results obtained (Figure 7), regardless of the temperature, clearly indicate that the tensile strength is much higher in the case of a composite of 0° fibre system. The results obtained by the Aymaide team for a fibre system at an angle of 0° at 23°C are similar to the results obtained from experimental work at the Institute of Aviation (Table 1).

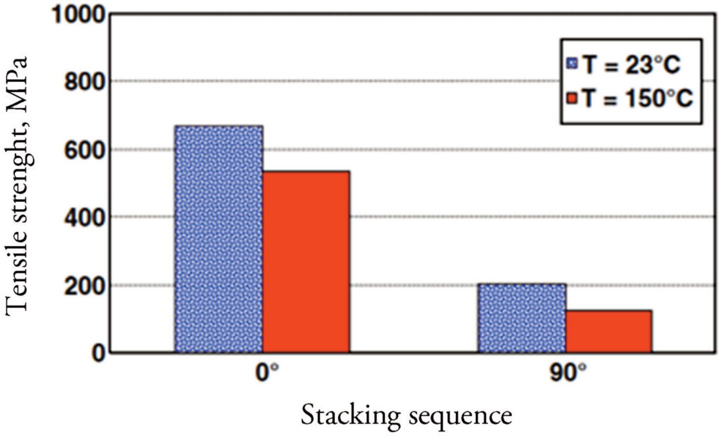

Figure 7. Results of tensile strength after a static tensile test for two fibre systems [30]

Table 2 shows the results of the shear strength tests carried out in the short beam bending test. The average shear strength for the tested composite was 69.01 MPa and the standard deviation was 1.15. In reference to the results of the tests carried out by Almajid and co-authors [30], the tested material at the Institution was the material tested at the Institute of Aviation obtained a higher shear strength of approx. 8 MPa. Both tests were carried out at room temperature: 23°C.

Table 2. Results of shear strength obtained after a short beam bending test

Coupon no.	Thickness, *d*, mm	Width, *W*, mm	Load at failure, P_{maxx}, kN	Interlaminar shear strength, F_{SBS}, MPa
SBS-RTA-01	2.417	5653	1.255	68.89
SBS-RTA-02	2.393	5.607	1.200	67.08
SBS-RTA-03	2.335	5.647	1.210	68.82
SBS-RTA-04	2.406	5.663	1.283	70.64
SBS-RTA-05	2.408	5.677	1.263	69.30
SBS-RTA-06	2.390	5.643	1.247	69.36
Average	**2.391**	**5.648**	**1.243**	**69.01**
Standard deviation	**0.030**	**0.024**	**0.032**	**1.15**
Coefficient of variation	**1.239%**	**0.420%**	**2.59%**	**1.67%**

Almayid and co-authors [30] additionally conducted shear strength tests in a short beam bending test at 150°C (Fig. 8). The average result of the test parameter was about 40 MPa, i.e. 20 MPa less than at room temperature for the Almayid test and 29 MPa less for the tests carried out at the Institute of Aviation. The lower result is the result of more aggressive environmental conditions that prevailed during the test.

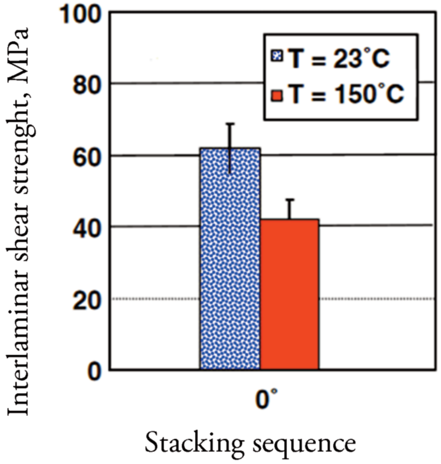

Figure 8. Results of shear strength after a short beam bending test, fiber system: 0 [30]

6. CONCLUSIONS

The use of modern composite materials with polymeric matrix allows to reduce significantly the weight of aircraft. The effect of weight reduction is to reduce fuel consumption, improve vehicle performance and increase vehicle life.

The estimated increase in demand for carbon composites in civil aviation will amount to nearly 37%, compared to data for 2017. This shows that CFRP composites are becoming an increasingly serious competitor to traditional materials used in the aerospace industry.

High wear resistance, tensile strength as well as resistance to plastic deformation at high temperatures make PEEK matrix composite material widely desired, especially in aviation. In the high temperature range of 150÷200°C, PEEK matrix composite exhibits high resistance to plastic deformations. During 10 000 hours of operation at 200°C, the tensile strength is almost unchanged.

The average tensile strength of PEEK matrix composite material was 658 MPa after a static tensile test. Compared to other scientific studies, the tensile strength of PEEK is about 14 MPa lower.

A static tensile test for a composite material with two different fiber systems of 0° and 90° showed more than 3 times higher tensile strength in the direction of 0° than for a composite with a fiber system of 90°.

The average shear strength obtained during the short beam bending test was 69.01 MPa. In reference to comparative tests from literature it was found that the material made of PEEK matrix composite at the Institute of Aviation has a higher shear strength by 8 MPa.

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PRZEGLĄD STOSOWANYCH BADAŃ MECHANICZNYCH DLA KOMPOZYTÓW WĘGLOWYCH O OSNOWIE Z POLIMERÓW TERMOPLASTYCZNYCH

Streszczenie

Niniejszy artykuł ma charakter teoretyczno-eksperymentalny. Przedstawiono w nim charakterystykę dwóch głównych termoplastów, używanych w przemyśle lotniczym – PEEK (polieteroeteroketon) i PPS (polisiarczek fenylenu. Wybrane materiały stanowią komponenty do wytwarzania kompozytów o osnowie z polimerów termoplastycznych. W artykule przeprowadzono przegląd literaturowy zastosowania materiałów kompozytowych na osnowie z polimerów termoplastycznych w lotnictwie. Dodatkowo, w pracy skupiono się na charakterystyce kompozytów polimerowych wzmacnianych włóknem węglowym – CFRP (Carbon Fibre Reinforced Polymers), które odgrywa istotną rolę w wytwarzaniu elementów lotniczych. Metody badawcze wybrano w oparciu o rodzaj osnowy kompozytu. Artykuł zawiera najważniejsze właściwości mechaniczne oraz ogólną charakterystykę termoplastów używanych, jako osnowy na kompozyty typu CFRP stosowanych w przemyśle lotniczym. Opisano poszczególne procedury badawcze, które pozwalają na ocenę właściwości mechanicznych materiałów kompozytowych na osnowie z polimerów termoplastycznych. Przeprowadzono testy mechaniczne takie jak statyczna próba rozciągania oraz zginanie krótkiej belki, w celu zbadania kompozytów CFRP.

Słowa kluczowe: kompozyty węglowe, PEEK, PPS, CFRP, termoplasty, badania kompozytów z PEEK i PPS.