Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

17: 3 (2017) 131-135

COMPOSITES THEORY AND PRACTICE

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Received (Otrzymano) 16.06.2017

FLAMMABILITY OF ELECTRICALLY CONDUCTIVE COMPOSITE DEDICATED FOR LIGHTNING STRIKE PROTECTION

Lightning strike protection is one of the crucial structural demands for aircraft composites addressed to their integrity and durability after a strike. When the lightning strikes a classic composite structure, the generated heat from electrical resistance as well as mechanical impulse resulting from acoustic wave propagation, might cause serious damage. Currently used metallic meshes and foils immersed in composite structures are effective in dissipating lightning charges and generated heat, however, such a solution has numerous disadvantages like increasing mass, problems with adhesion on the metal/polymer interface, complicated manufacturing technology, etc. Therefore, a fully organic conductive composite was developed as an alternative to current solutions. After a lightning strike the developed composite should not only effectively conduct and dissipate the electrical charge and generated heat, but also stop burning, which appears due to very high temperature values in the vicinity of the strike area. In this study, flammability tests were performed for a classic carbon fabric-reinforced composite as well as for the developed conductive polymer and carbon fabric-reinforced composite based on this polymer for comparative purposes, with measurement of the combustion temperature. The obtained results show that the developed composite is characterized by sufficiently low flammability, however, further studies will be focused on further improvement of flame retardancy.

Keywords: flammability, lightning strike protection, flame retardancy, carbon fabric

PALNOŚĆ KOMPOZYTU PRZEWODZĄCEGO PRĄD ELEKTRYCZNY DEDYKOWANEGO DO OCHRONY ODGROMOWEJ

Ochrona odgromowa jest jednym z ważniejszych wymagań strukturalnych stawianych kompozytom lotniczym, odnoszących się do ich integralności oraz trwałości po uderzeniu pioruna. Gdy piorun uderza w klasyczne struktury kompozytowe, ciepło generowane z oporu elektrycznego oraz impuls mechaniczny, wynikający z propagacji fali akustycznej, może spowodować poważne uszkodzenia. Obecnie stosowane metalowe siatki i folie zatopione w strukturach kompozytowych są efektywne w rozpraszaniu ładunków piorunowych i generowanego ciepła, jednak takie rozwiązanie posiada szereg wad, jak wzrost masy, problemy z adhezją na granicy ośrodków metal/polimer, skomplikowana technologia wytwarzania itd. Dlatego został opracowany w pełni organiczny kompozyt przewodzący jako alternatywa dla obecnych rozwiązań. Po uderzeniu pioruna opracowany kompozyt powinien nie tylko efektywnie przewodzić i rozpraszać ładunek elektryczny i generowane ciepło, ale także zatrzymać płonięcie, powstające w wyniku bardzo dużych wartości temperatury w otoczeniu miejsca uderzenia. W niniejszej pracy w celach porównawczych badania palności przeprowadzono dla klasycznego kompozytu wzmacnianego tkaniną węglową oraz opracowanego polimeru i kompozytu wzmacnianego tkaniną węglową na jego bazie z pomiarem temperatury spalania. Otrzymane wyniki wykazały, że opracowany kompozyt charakteryzuje się stosunkowo niską palnością, jednak przyszłe badania będą skupione na dalszej poprawie ognioodporności.

Słowa kluczowe: palność, ochrona odgromowa, ognioodporność, tkanina węglowa

INTRODUCTION

Since aircraft metallic elements such as elements of exterior fuselage, wings, stabilizers, etc., have been substituted by polymeric composites, lightning strikes constitute a serious operation problem, considering the fact that statistically each airplane can be struck by lightning two - three times a year. Lightning strikes can cause serious damage, like burnout, reinforcing fiber breakage, extended delaminations, etc., due to the high electrical and thermal resistance of polymers used as the matrix of aircraft composites. Following this, the problem of effective lightning strike protection (LSP) started to be crucial for leading aircraft manufacturers. The solutions in LSP of aircraft, already applied in the aircraft industry, are based on immersing highly conductive metallic meshes and foils in the composite structure, which catch the electrical charge and effectively conduct and dissipate it. Many experimental studies performed to date confirm the effectiveness of such a solution (see e.g. [1, 2]), however, it has several disadvantages which have pushed research groups around the world to develop alternative LSP solutions. Besides their superior electrical and thermal conductivity, composites with metallic meshes have numerous disadvantages: due to the necessity of immersing meshes in the composite structure, the manufacturing process of such structures is complex and expensive with respect to manufacturing traditional composite structures. Moreover, during the operation of such structures there are problems with adhesion on the metal/polymer interface, and in the case of contact with an aggressive environment (e.g. humid air), corrosion processes may initiate additional damage. Finally, the addition of metals causes an increase in the mass of an aircraft, which is undesired, especially in the aircraft industry.

In order to overcome these disadvantages various LSP approaches have been developed. Many of the currently developing LSP solutions are based on carbon nanostructures (see e.g. [3, 4]), which reveal good mechanical, thermal and electrical properties. Several promising solutions in structural LSP have been developed using a special type of nanostructures - buckypaper, which is obtained in the form of highly oriented carbon nanotubes in a magnetic field [5-8]. These solutions have been proven to increase electrical conductivity [9] and fire retardation [10], however, the current market prices of carbon nanostructures make their application in mass production impossible. An alternative approach developed by several research groups is based on the application of intrinsically conductive polymers (ICPs) as a conductive filler in such composites. The approach developed by the authors' team is based on a mixture of epoxy resin and polyaniline (being an ICP) doped with camphorsulfonic acid (CSA) [11] and a carbon fabric (CF) reinforcement [12]. The performed laboratory tests confirmed the good electrical conductivity of the developed composite at the level of semiconductors and good resistance to artificial lightning strikes [11, 12]. However, an additional consequence of a lightning strike is heating-up to extremely high temperature values, which may even reach thousands of centigrade [13]. In such a case, pyrolytic processes appear in the struck structure, which often causes ignition of the material.

The flammability of polymers and polymeric composites used for structural elements is an important parameter in aircraft design and operation, and therefore need to be investigated in terms of degradation kinetics, ignition and burning parameters, as well as fire spreading [14,15]. Two approaches are usually used for flammability testing depending on the measurement parameters need to be determined: in the case of estimating the released heat during combustion, calorimetric tests are performed [16-18], while in the case of estimating flammability and fire spreading, UL 94 burning tests are performed [19-21]. Considering the above-described requirements, UL 94 burning tests seemed to be suitable for the testing problem.

In this paper, the authors present the research results on a comparison of the flammability properties of a classic carbon fabric-reinforced polymeric (CFRP) composite, the developed polymeric mixture of CSA-doped polyaniline with epoxy (PANI-EP), and CSA-doped PANI-EP reinforced with carbon fabric (PANI-EP-CF). Besides the standard measurements performed according to the UL 94 HB test requirements, the combustion temperature was measured. The obtained results were compared to previously performed thermogravimetric (TGA) analysis in order to evaluate the burning properties of the developed materials. The performed tests allow a burning classification to be assigned to the material and investigation of the consequences of its ignition during a lightning strike.

EXPERIMENTAL STUDIES

The experiments were performed on the laboratory test rig presented in Figure 1. The tests were performed on CFRP, PANI-EP, and PANI-EP-CF specimens of the following dimensions: length of 125 mm, width of 12.5 mm, and thickness of 2.5 mm. The laboratory stand *1* with a testing specimen *2* fixed in a clamp *3* was placed in a laboratory fume hood. A metal foil *4* was placed 300 mm beneath the testing specimen *2*. Burning was performed using a burner *5* directed at an angle of 45° to the front edge of the testing specimen *2* with a 25 mm long soft flame. Temperature measurements were performed using an infrared camera *6* with a frame rate of 1 frame per second.

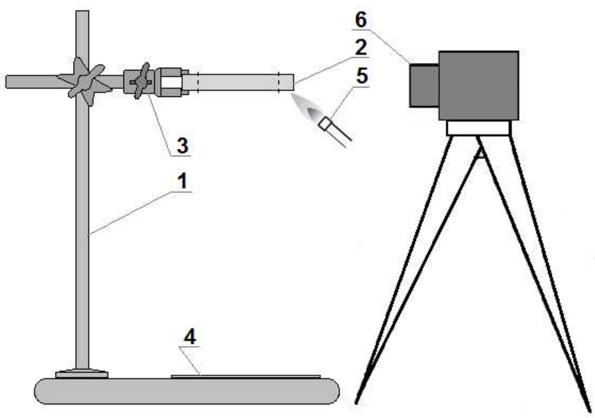

Fig. 1. Experimental setup for flammability tests
Rys. 1. Stanowisko badawcze do testów palności

The flame was applied to the free end of the specimen for 30 seconds or until the flame reached the 25 mm mark on the specimen. After that the flame was removed and the time until the flame extinguished was measured in order to evaluate the burning rate. Additionally, dripping of the burning material was monitored. Starting from applying the flame, thermograms were captured until the flame extinguished. Based on the measurements of the burn length and the time until the flame extinguished the burning rate was determined and the flammability of the specimens was classified according to UL 94 HB classifications.

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RESULTS AND DISCUSSION

The results of the performed tests are shown in Table 1. The developed polymer as well as the composite based on this polymer can be classified to the B class of the UL 94 HB classification, which means that the burning rate does not exceeded 76.2 mm per minute, considering the fact that the thickness of the specimens was less than 3.05 mm.

TABLE 1. **Results of flammability tests**
TABELA 1. **Wyniki testów palności**

Material	Flame extinguishing time [s]/ length [mm]	Burning rate [mm/ min]	UL 94 HB classification	Dripping	Average burning temperature [°C]
CFRP	15 / 0	self-extinguished	B	no	595.00
PANI-EP	54 / 33	36.67	B	yes	629.07
PANI-EP-CF	43 / 30	41.86	B	no	669.11

Nevertheless, compared to CFRP, the PANI-EP mixture exhibits high propagation of the flame with observed dripping (Fig. 2a). Less flame propagation was observed for PANI-EP-CF with no dripping (Fig. 2b).

a)

b)

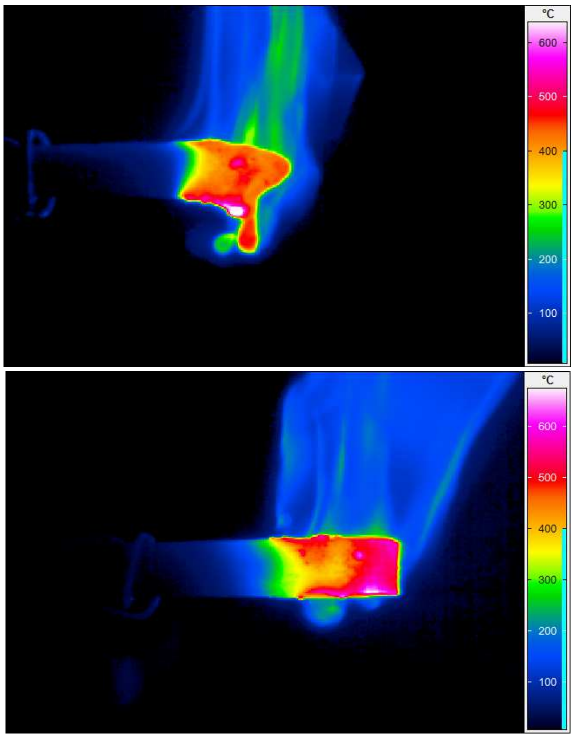

Fig. 2. Thermograms of PANI-EP (a) and PANI-EP-CF (b) specimens during flammability tests

Rys. 2. Termogramy próbek wykonanych z PANI-EP (a) i PANI-EP-CF (b) podczas testów palności

These observations lead to the conclusion that the addition of PANI to epoxy resin increases the flammability of such structures. The maximal burning temperature values observed during the whole process are presented in Figure 3. The burning phases can be easily determined from these temperature curves: after removing the flame at the 30th second, the tested materials burn by themselves and various values of burning temperature for the considered materials can be observed. The non-monotonicity of the PANI-EP temperature curve can be explained by dripping. Flame extinguishing can be also identified by a sudden temperature drop on the temperature curves. The determined burning temperature values can be compared to the TGA and DTA (differential thermal analysis) results obtained for PANI-EP [11] (see Fig. 4).

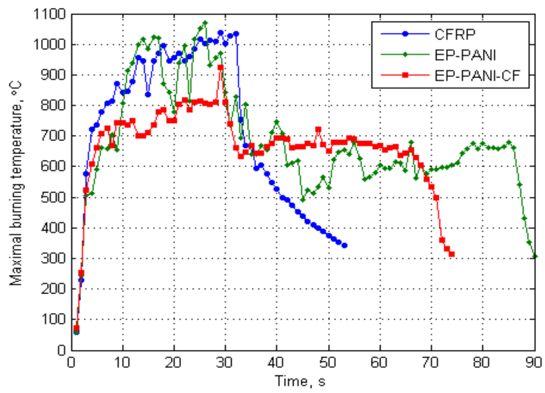

Fig. 3. Burning temperature curves for tested specimens

Rys. 3. Krzywe temperatury spalania dla badanych próbek

The TGA tests were performed using a Mettler Toledo TGA 851e thermogravimetric analyzer according to standard PN-EN ISO 11358-1:2014 in an oxygen atmosphere with a flow rate of 60 ml/min, a heating rate of 10°C/min in the temperature range of 25÷1000°C.

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The results observable on the TGA curve allow four regions of mass loss to be distinguished, which are connected with the decomposition of particular components of the polymeric mixture. This explains the complex shape of the TGA curve. The two main peaks, where the highest mass loss is observable, can be distinguished in the DTA curve in Figure 4. Since these peaks are below the burning temperature values of PANI-EP (see Table 1), piloted and auto-ignition can occur due to vaporization of the components of PANI-EP during burning. This means that the temperature values during a lightning strike [13] are high enough to burn up the structure, however, the PANI-EP-CF composite exhibits a self-extinguishing property after a certain period, which is enough to classify this material as slightly flammable. Full decomposition of the PANI-EP mixture occurs at 617.1°C, which was confirmed when analyzing the tested specimens after flammability tests. After burning of the CFRP and PANI-EP-CF specimens, only the carbon fabric remained (see Fig. 5).

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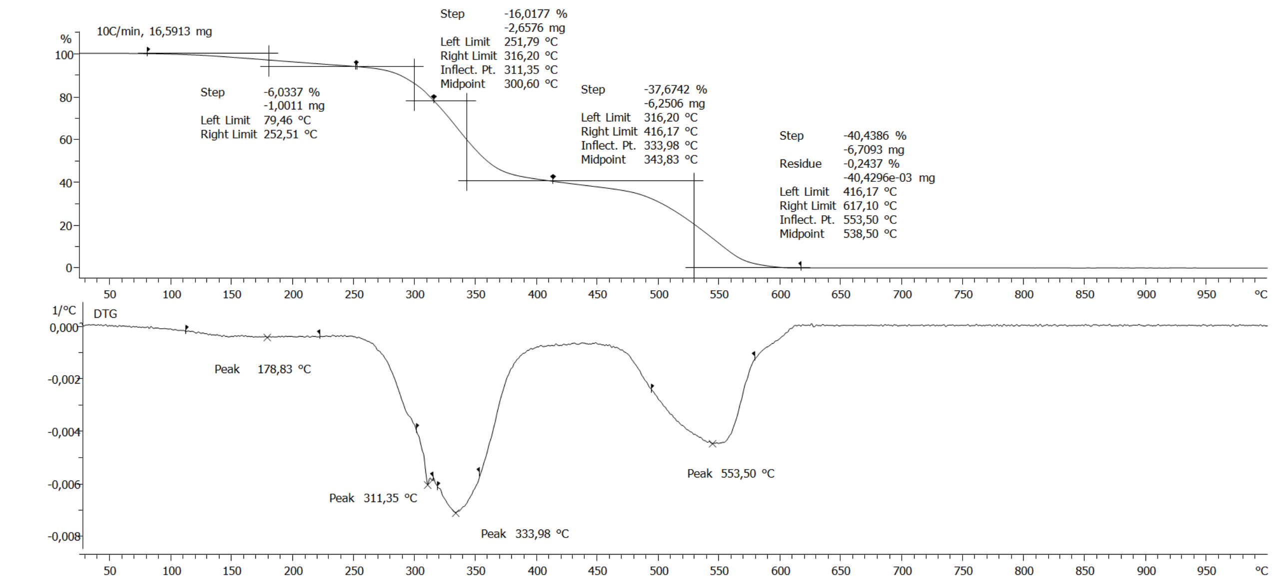

Fig. 4. TGA and DTA curves for PANI-EP

Rys. 4. Krzywe TGA i DTA dla PANI-EP

a)

b)

Fig. 5. Photographs of investigated composites CFRP (a)and PANI-EP-CF (b) after burning process

Rys. 5. Fotografie badanych kompozytów CFRP (a) i PANI-EP-CF (b) po procesie spalania

CONCLUSIONS AND FURTHER RESEARCH

The presented study focused on evaluating the flammability of the developed CSA-doped PANI-EP intrinsically conductive polymeric mixture and a carbon fabric reinforced composite based on this mixture. The standard UL 94 HB flammability test was performed with measuring of the combustion temperature during the burning process. The developed PANI-EP-CF composite passed the flammability test with a B classification. Self-extinguishing with no dripping was observed for this composite, however, the burning intensity was higher with respect to the CFRP specimen, which extinguished immediately after removing the flame. The application of popular flame retardants like those used in [20] might be effective, but may negatively influence the electrical and thermal conductivity of the composite, which are the key properties in LSP solutions. An original idea was described by the authors of [22, 23], who proved that PANI nanoparticles can be an excellent flame retardant without loss of the mentioned key properties. Modification of the morphology particles in the new electrically conductive composite, which has already been submitted for patent protection to the Patent Office of the Republic of Poland with patent application No. P.420282, can be a promising solution in terms of flame retardancy. The conducting particles have the shape of microspheres, which allows simultaneous improvement of the mechanical, electrical and thermal properties of the resulting composite. The effectiveness of this solution is planned to be reported in the further studies.

Acknowledgements

The authors would like to thank to Dr Katarzyna Krukiewicz and Dr Roman Turczyn from the Department of Physical Chemistry and Technology of Polymers, Silesian University of Technology for manufacturing the PANI-EP and PANI-EP-CF specimens for the performed tests.

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