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CONCEPT OF A CONDUCTING COMPOSITE MATERIAL FOR LIGHTNING STRIKE PROTECTION

ABSTRACT

The paper focuses on development of a multifunctional material which allows conducting of electrical current and simultaneously holds mechanical properties of a polymeric composite. Such material could be applied for exterior fuselage elements of an aircraft in order to minimize damage occurring during lightning strikes. The concept introduced in this paper is presented from the points of view of various scientific disciplines including materials science, chemistry, structural physics and mechanical engineering with a discussion on results achieved to-date and further plans of research.

Keywords: *conducting composite, aircraft materials, lightning strike protection*

INTRODUCTION

Currently, structural elements of the most of civil and military aircraft are manufactured mostly of polymeric composites. During the last three decades an unequivocal tendency of increase of application of polymeric composites in aircraft structures can be observed. This is mainly due to their superior properties in comparison with previously used metallic materials, namely polymeric composites have much better mechanical properties and simultaneously they are much lighter than metals, they are corrosion-resistant, and they are characterized, in general, by lower thermal expansion and better fatigue resistance. These statements are proven by the construction and materials solutions applied in the newest and biggest passenger airplanes: Boeing 787 Dreamliner and Airbus A350 XWB, where fuselage, wings, stabilizers and turbine housings are manufactured primarily from polymeric composites (see Fig. 1).

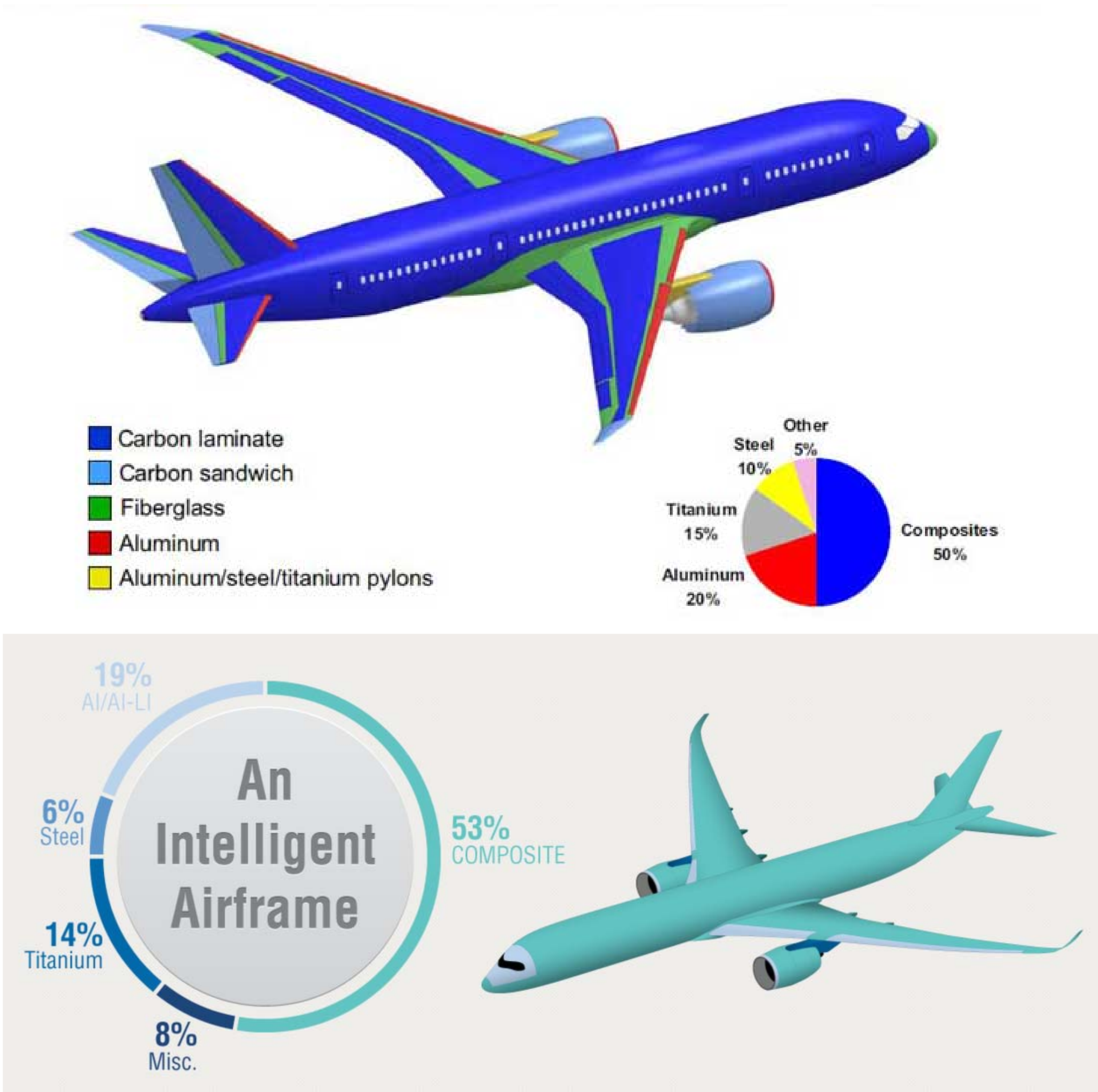

Fig. 1. Materials used in the outer skin of a) Boeing 787 Dreamliner [1], b) Airbus A350 XWB [2]

However, besides numerous advantages of polymeric composites in application to aircraft structural elements, they are essentially dielectric which limits their performance. These limitations result from specific demands to exterior aircraft structures, namely resistance to high electrical discharges and highly charged electromagnetic fields. Such phenomena occur during lightning strikes which happen quite often. Statistically, every passenger airplane being operated in USA is stroked by lightning more than once a year [3], another source reports that an airplane can be struck by lightning every 1000-3000 flight hours in average [4]. Modern lightning protection systems as well as processes of control and certification on lightning protection of airplanes, which should be performed before the release to service of each airplane, guarantee passenger safety. However, a lightning strike may cause serious structural damage of exterior skin of an aircraft which leads to expensive repair and certification processes. This is because industrial polymers (mainly epoxy resin) used in manufacturing of aircraft structures are inherently dielectric which means that electrical charge cannot be dissipated over the large area of a structure which, in turn, causes a rapid increase of temperature in the location of a lightning strike [5], and, as a consequence, causes burns in the structure. An example of such burns is presented in Fig. 2.

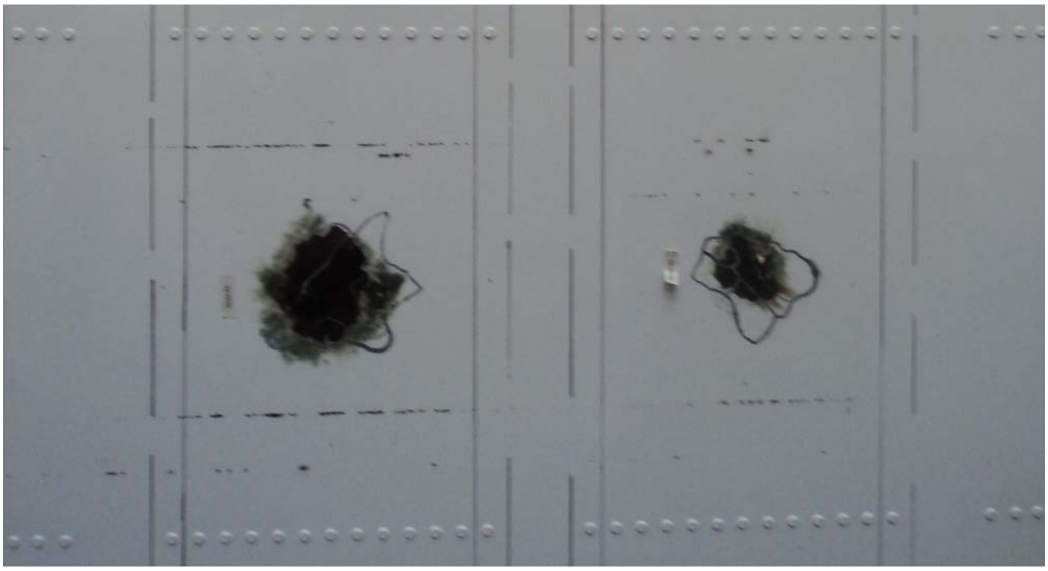

Fig. 2. Structural damage in the outer skin in the Airbus A400 M airplane after the lightning strike

The most serious danger during the lightning strike is connected with hot spot formation in components of fuel tanks. However, the actual aviation regulations on design and protection of aircraft fuel tanks [6] guarantee their protection from burning out and eventual fuel ignition. This is also confirmed by a fact that the last registered airplane crush in USA directly attributed to the fuel tank explosion caused by lightning happened in 1967 [7]. Consideration of statistical data from USA in above examples is justified by quite high lightning activity in this area (see annualized distribution of lightning activity in [8]).

Following this, it is highly desirable to provide the electrical conductivity properties in exterior composite aircraft structures. Such properties, among lightning protection, can ensure grounding and voltage reference of all electrical and electronic devices. Moreover, conducting fuselage of an airplane can be both a Faraday cage which protects passengers and electronic devices inside and a kind of screen to protect electronic devices from outside electromagnetic interferences. By introducing electrical conductivity properties in such structures, one achieves large dispersion area of electrical charge, and thus, reduction of temperature and damaged region in the location of a lightning strike. The conducting composite may solve the problem of lightning current arcing between metallic fasteners and composite structural elements which occurs during the lightning strike [9].

The aim of this study is to present the concept of a new multifunctional electrically conductive composite dedicated for exterior elements of aircraft in order to fulfill lightning strike protection (LSP) requirements. Such material has been currently developed by the team of authors of this paper.

OVERVIEW ON LIGHTNING STRIKE PROTECTION SOLUTIONS IN AIRCRAFT

According to SAE ARP 5414 [10], the exterior surface of a typical large aircraft can be divided into the so-called lightning strike zones which represent the areas likely to experience various types of lightning currents (see Fig. 3). A detailed description of these zones can be found e.g. in [12].

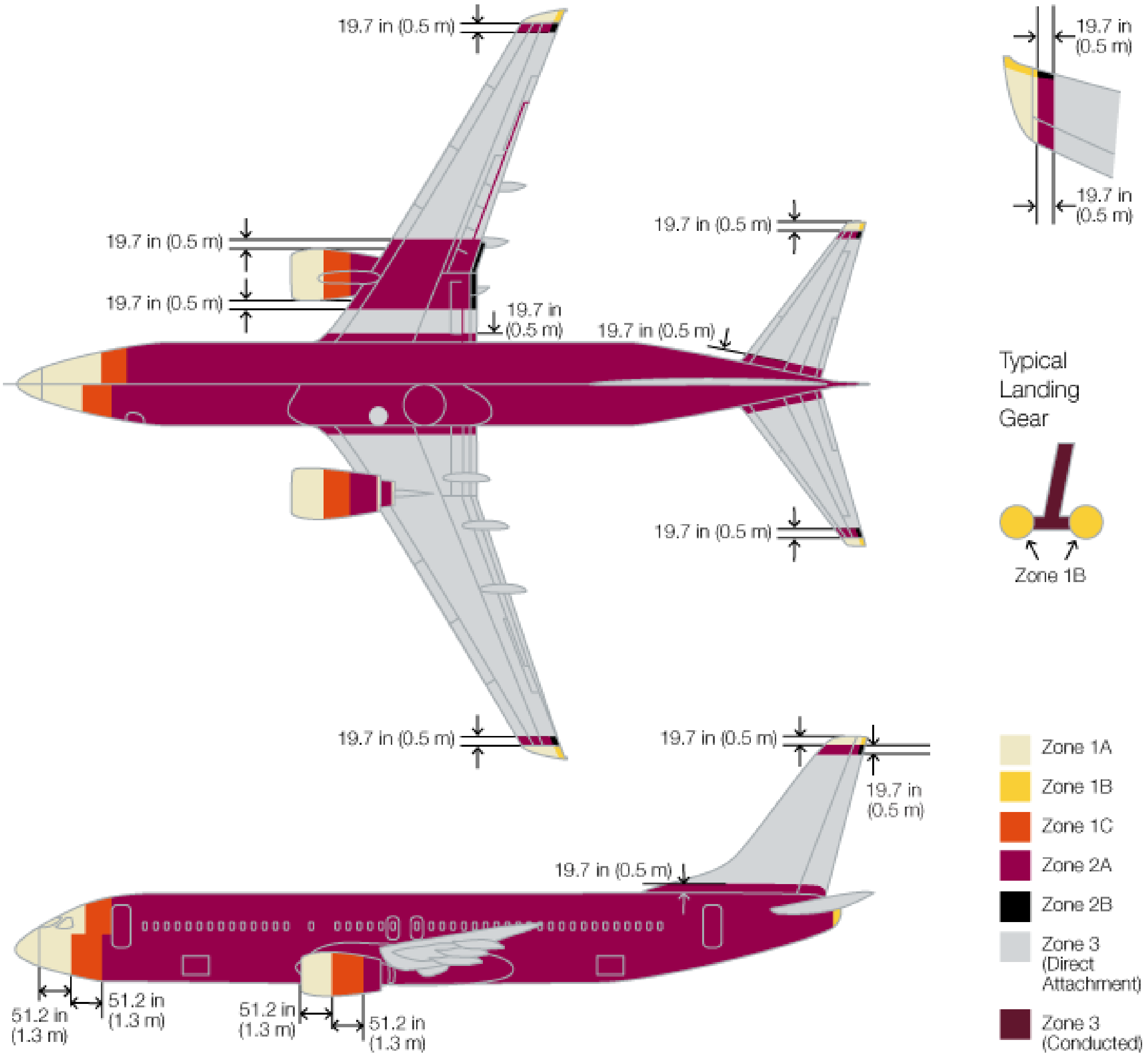

Fig. 3. Lightning zoning diagrams for a typical large airplane according to SAE 5414 [11]

The most of exterior composite elements of modern airplanes belonging to these zones are manufactured from carbon fiber-reinforced polymers (CFRP) which are weakly conductive due to the presence of carbon fiber, and, in some part, from glass fiber-reinforced polymers (GFRP) which are dielectric, as one can observe from the comparison of materials usage and lightning zoning diagrams (cf. Figs. 1 and 3). Both numerical and experimental studies of CFRP structures subjected to lightning strikes [12-16] proved that lightning still causes serious damage in such structures which extent dramatically increases when discharging occurs near metallic fasteners. In order to improve electrical conductivity of these materials various solutions of LSP of aircraft have been developed to-date. These solutions can be classified into two groups [7]: employment of diverter strips or bars on the exterior surface (this solution is usually applied for LSP of radomes and antenna fairings), and the application of electrically conductive material over the exterior surface of composite aircraft structures. Since we are interested in LSP of outer skin of airplanes the solutions of the second group are discussed further.

One of the common and already standard solutions of LSP of aircraft is an inclusion of metallic meshes or foils into a fuselage which are made of copper or aluminium. These solutions are the most frequently selected in LSP aircraft applications due to their high specific electrical conductivity, high heat of vaporization necessary to handle massive lightning strike current levels and relatively low prices [4]. Although the mentioned approaches are effective, there are several technological problems, e.g. metallic meshes and foils do not drape smoothly over surfaces with compound curves which may result in wrinkles and induce delamination processes which, as a consequence, may cause appearance of moisture, which, in turn, can lead to the mesh or foil corrosion [7]. In order to overcome this problem expanded metal foils were developed. Such foils are fabricated during the milling process that perforates and stretches a solid foil which allows for better draping over compound curves during bonding to a composite structure. According to the information available on the Boeing and Airbus websites, the wire mesh laminated into composite elements is a solution selected for Boeing 787, while the metallic foils embedded into composite structural parts is selected for Airbus A350. The results of experimental studies presented in [17] show that metallic mesh significantly improves LSP of a composite structure, i.e. damage is much less when the structure is protected this way. Nevertheless, application of metallic meshes and foils for LSP significantly complicates manufacturing process of elements and increases the overall mass of an airplane which, in turn, generates additional costs. The properties, dimensions and overview of existing commercial LSP solutions using metallic meshes and foils can be found in [18].

Another solutions of LSP are based on covering aircraft composite elements by metallized sprays or paints which allow formation of a layer of metal coatings (see e.g. [19,20]). The usage of metallized sprays eliminates a problem with surface matching (as in the case of metallic meshes and foils) and can be applied on the surfaces of arbitrary complexity. In order to obtain very thin conducting coatings on composite elements the Physical Vapor Deposition (PVD) approach of highly conductive metals is applied in some cases, e.g. for shielding aircraft from electromagnetic interferences [18]. Conductive paints have marginal applicability in LSP of aircraft [7], since they contain conductive particles which can make only random contact with each other. As a result, such coatings have much lower conductivity than above-presented LSP solutions.

The more advanced LSP solutions cover reinforced fiber metallization as well as dispersion of micro and nanoscale conducting particles in the dielectric matrix. The metallized fiber, such as aluminized glass fiber or nickel- and copper-coated carbon fiber is already commercially available. However, such solutions have found application mainly in aircraft electromagnetic shielding on internal composite panels within cockpits, rather than LSP of external fuselage composite structures [7]. As one can expect, such solutions increase manufacturing complexity of aircraft composite elements. Moreover, there are some difficulties during service life, e.g. there are problems with appropriate interphase adhesion between metal and polymeric matrix.

Actually, the most attempts are focused on novel LSP solutions that are based on dispersion of nanoscale conducting particles, primarily carbon nanostructures (CNS) with several modifications [18,21-25] which can provide light-weight but still expensive alternative to metallic meshes and foils. In the studies described in [22,25] the metallic foils are simply replaced by CNS-based paper which can conduct electrical current. However, experimental tests of lightning strike simulations presented in both studies show that electrical density of a typical lightning is much greater than the ability of CNS to conduct, thus the resulting damage is still extensive in such structures. The useful concept in LSP solutions is to consider a percolation theory during doping dielectric polymer by conductive particles. This allows predicting the volumetric (or mass) content of conducting particles in order to reach a percolation threshold at which the whole material changes his conductivity properties in a jump-wise manner. Such an approach allows obtaining effective percolation pathways between defined regions which is proven by experiments described e.g. in [21,26-29]. Such solution is very effective considering that numerous researchers reported the necessary content of conducting particles into dielectric matrix in order to obtain percolation cluster on level much lower than 1%vol. [27], however the problem with too low electrical density to carry on lightning charge still remains. The alternative solution of dispersion of metallic (aluminium, copper, nickel, silver and gold) nanowires into dielectric polymeric matrix solves this problem [30-32], however it does not indicate an improvement in conductivity over traditional metallic meshes [33], but the cost of manufacturing of such structures is much higher than for metallic meshes.

THE CONCEPT OF MULTIFUNCTIONAL CONDUCTIVE COMPOSITE

Motivation

Considering the above-presented overview, every group of presented LSP solutions has serious drawbacks. In several cases it is a complexification of manufacturing process and significant increase of manufacturing costs, in the other ones – too low electrical density to carry on lightning strike. However, each group has advantages which can be considered in a new LSP solution proposed in this paper.

The promising alternative to CNS is application of conducting polymers as a conductive filler of a dielectric matrix. Such a solution will increase overall electrical conductivity of a resulting material with respect to CNS, since some conducting polymers have a conductivity similar to metals. Using a mixture of conducting and dielectric polymers allows minimizing the complexity of manufacturing process which results in a macroscopically homogeneous light-weight conductive material obtained at low cost. The only problem of this solution is that conducting polymers have low mechanical properties in general. In order to ensure good percolation capabilities as well as appropriate mechanical strength it is planned to use percolation theory with further optimization for reaching the compromise and ensuring two mentioned properties at the same time. The carbon fiber reinforcement which is typical for aircraft composite structures will participate in conductivity processes which creates a new possibility to decrease a content of conducting material in a resulting composite.

Preliminary computational studies performed for mixtures of selected conducting polymers and dielectric polymers [34] reveal satisfactory results, e.g. in some cases a content of conducting polymer was less than 1%vol. This allows obtaining a conductive material with a strength enough for constructional applications for aircraft industry. Although one can find similar solutions of conducting/dielectric polymeric mixtures [35-38], none of them were dedicated for effective LSP solutions in aircraft. Moreover, multidisciplinary structured approach to the problem which includes advanced modelling of appropriate percolation systems with use of experimentally determined material properties, analytical and numerical thermo-electro-mechanical simulations of material behavior in various in-service conditions and during the lightning strike and further models updating will allow achieving and manufacturing of optimized material for LSP applications. The detailed description of a concept is presented below with emphasis on the mentioned stages of development as well as points of view of various scientific disciplines.

Modeling of percolation systems

The percolation theory is known as a branch of the probability theory, which have a wide application in natural and engineering sciences [39-42], as well as a discipline of a statistical physics which explores critical phenomena over the last half-century [43,44]. The percolation theory describes adequately specificity of occurrence and evolution as well as properties of connected regions in systems, where the geometrical phase transition takes place. It found an application in wide range of scientific problems, e.g. investigation of protein structures, porous media, development of filters, investigation of doped semiconductors, in analysis of epidemics propagation, investigation of polymerization processes, design of composite materials, and many others. At the same time, for the critical exponents of physical quantities which describe the processes and phenomena, one can specify a set with the dimensionality of which this indicator is connected. In turn, the study of the structure of these sets allows understanding of the critical behavior of a system and the relations between the indicators, and allows tracing the connection between the behavior of a system in its intermediate asymptotics and its geometry [43-46].

There exists a number of materials and processes for an adequate description of which a special percolation problems is required – the so-called "all-sides" percolation problems – which, in spite of a classical formulation of percolation between two points (or two boundaries), requires the existence of connection between all boundaries of an analyzed domain (see example in Fig. 4). Such materials include porous or cellular sponge rubbers, acoustic slabs of sound-absorbing microporous materials, porous concrete, solid and powder sinks and odor neutralizers, shell-rock and others. The all-sides percolation problems allow to describe the structure, properties and processes in such materials, and will also be useful in the design of materials with high thermal and electrical conductivity.

The investigation of properties of a random mixture of conductive and dielectric polymers using methods of percolation theory is possible within the problem of hopping conductivity of random nodes. The idea of hopping conductivity, introduced in [43] for the study of the properties of doped semiconductors, can be interpreted as the problem of the modified connectivity. Applying the latter to the problem of the mixture, this means that the conductive additive can form a cluster, however, not only in direct contact, but also at some distance between conductive particles. This distance depends on the specific properties of the constituents of the mixture, and, in turn, defines a set of characteristics of a percolation cluster. A priori, it is clear that increasing the allowable hopping distance can significantly reduce the percolation threshold and the degree of filling of a material by conductive additives, and, as a consequence, increase the correlation length and lacunarity, reduce the power of the percolation and finite clusters, etc. The hopping distance plays here the role of the control parameter [43,45].

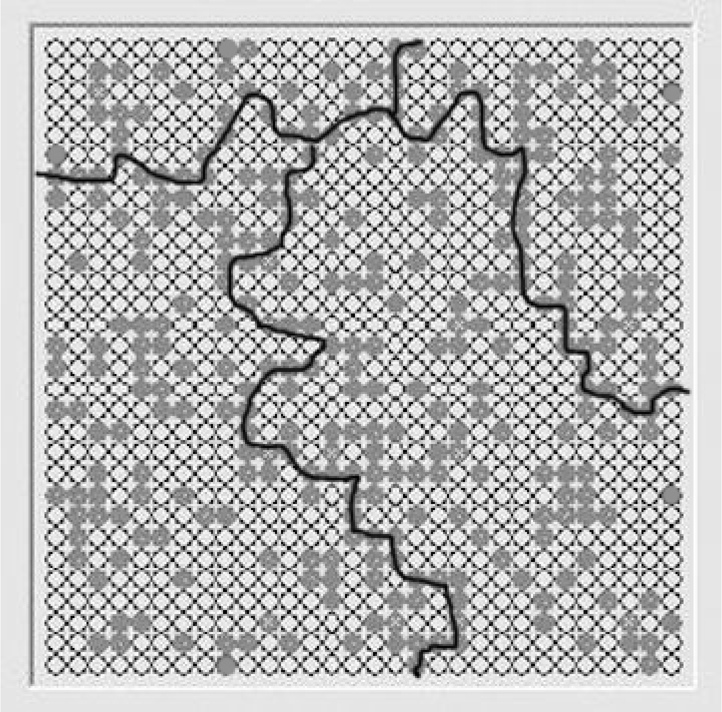

Fig. 4. An example of implementation of 2D percolation cluster within “all-sides” percolation problems definition: light grey cells – dielectric polymeric material; dark grey cells – conductive dopes; black line – a conductive trace of “all-sides” percolation cluster

For the proper modeling of percolation system, selected physicochemical properties of conducting polymer have to be determined experimentally. These are mainly the conductivity of polymer and the size of polymer’s particles.

There are two major methods used to determine the conductivity of polymeric films, i.e. two-point and four-point techniques. In the two-point approach, two metal electrodes are evaporated on a glass substrate prior to the deposition of polymer film. Usually a high work function metal, e.g. gold, is used to prevent the formation of Schottky barrier between the electrode and the polymer [47]. In the four-point approach, a constant current is applied between two outer probes and the voltage drop is measured in the inner probes (Fig. 5) [48]. These techniques give enough data to calculate so-called surface sheet conductivity:

$$\sigma = \left(\frac{V}{I}\right) \cdot CF\,, \qquad (1)$$

where: σ – surface sheet conductivity, V – voltage drop, I – current, CF – correction factor.

The size of conducting polymer’s particles and morphology of polymer film are highly influenced by the conditions of polymerization. It was shown that by the judicious choice of surfactant and polymerization environment, it is possible to obtain polyaniline particles in a range between 75 and 160 nm [49]. Besides, there is a great variety of achievable nanoscale structures including fibers, tubes, aligned wires, flowers, spheres and hollow spheres and plates [50]. This is why the characterization of size of polymeric particles is necessary for each individual process conditions. The most popular method for particle-size determination is the use of dynamic light scattering [51]. The morphology of conducting polymer film is usually determined with the use of microscopic methods, mainly AFM, SEM and TEM [52-54]. Having the fundamental properties and parameters of particular materials used for developed composite, the parametrization of a percolation problem is possible.

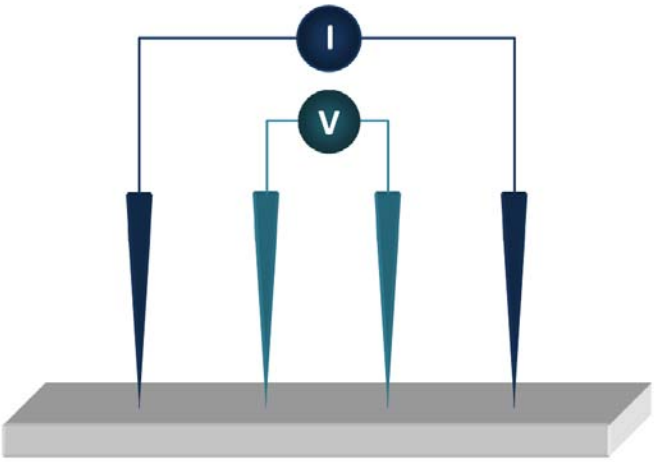

Fig. 5. The scheme of a four-point probe

Simulation of in-service conditions

The multifunctional material has to meet the structural and electrical requirements that are demanded in aeronautical structures. Because of its multifunctional nature its response to complex loadings (structural, thermal and electrical) needs to be assessed. In this perspective Multiphysics Modeling is the procedure that is used when estimating the response of the material subjected to complex combinations of loading of different nature. In particular, before the composite structure is manufactured, it is necessary to have a tool or set of tools able to predict if the structural and electrical requirements are satisfied during in-service conditions and, in particular, during lightning strike.

The Finite Element Method allows to gain an insight into the complex response of such multifunctional material using Representative Volume Elements (RVE) together with appropriate Periodic Boundary Conditions (PBC). The analyses performed on these RVEs will be multi-field analysis: the solution of the coupled thermo-electro-mechanical problem needs to be found.

It should be noted that the microstructure of the composite plays a fundamental role in determining its multifunctional properties. Therefore an accurate representation of the microstructure is not only desirable, but necessary. Conductive particles may have different shapes, nano-spheres or spheroids, for example, may have different dimensions and their characteristic sizes may vary following different statistical distribution. All these aspects need to be taken into account.

Very recently we have proposed a numerical algorithm to obtain random distribution of spherical particles for the generation of RVE-based Finite Element Model [55]. When the shape of the particle is not simple but, on the contrary rather more complex (spheroidal particles) the use of the Lubachevsky-Stillinger packing algorithm is the standard approach [56]. Once the RVE-based Finite Element model has been obtained, appropriate Periodic Boundaries Conditions are applied to the faces of the RVE taking into account the multi-field approach discussed above.

One of the question regards the modelling of the electrical percolation. Very recently we have proposed [57] a methodology to model the percolation networks inside the materials and we have used the model not only to estimate the percolation threshold but also to estimate the conductivity at a given volume fraction of the conductivity particles. Fig. 6 reports the percolation network obtained using the methodology proposed in [57], while in Fig. 7 the complete RVE is reported. In Fig. 7 the conductive particle are in red, the dielectric resin that become conductive because of tunneling is in ochre while the dielectric resin that is not interested by the tunneling is reported in white.

Fig. 6. Percolation network [57]

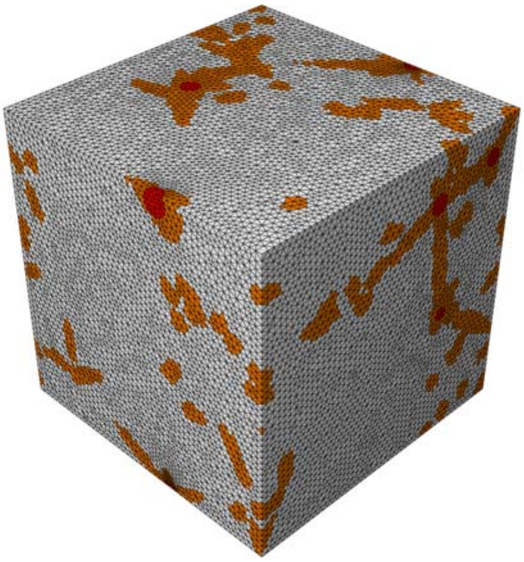

Fig. 7. RVE of PPy/epoxy blend [57]

Using this approach, the conductivity of a blend of Intrinsic Conductive Polymers with a dielectric blend can be estimated as a function of the particles volume fraction as reported in Fig. 8.

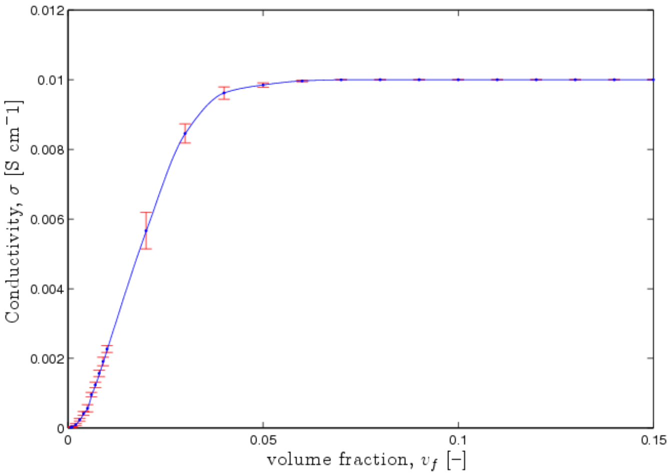

Fig. 8. Conductivity as a function of the volume fraction [57]

Of course, if the response of the final aeronautical structure is required, the multi-scale problem needs to be solved because it should be taken into account not only the nanoscale-problem (the conductivity of the blend) but also the meso-scale problem (conductivity of the composite plate) and the macro-scale problem (conductivity of the laminate). It is worth to mention here that carbon fibres are conductive (10^8 S/cm) but the matrix usually used (epoxy) is not (10^{-9} S/cm). Using a conductive matrix (10^{-2} S/cm) the composite obtained should have a high conductivity that would be less than metals (10^7 S/cm), but sufficiently high to provide:

static discharge, electrical bonding and grounding, and interference shielding, of the structure. The conductivity requirements for the structure are obtained using a multi-scale approach. Multi-scale analyses can also lead through the development of optimized structures. For some structure, for example, electrical isotropy would be the best solution. For example when static discharge or interference shielding are required. For other structures, electrical anisotropy/orthotropic would be desirable: for example, for the case of lightning strike, the use of highly orthotropic structures would facilitate the quick electrical discharge far from critical or weak points of the structures.

Manufacturing and tests

Among the wide range of conducting polymers, only several can be applied commercially, i.e. polypyrrole, poly(3,4-ethylenedioxythiophene) and polyaniline. Exhibiting high conductivities together with chemical and electrochemical stabilities makes them advantageous materials to be used in surface and coatings technology [58]. The lack of mechanical stability, low processability and flexibility, however, are the main limitations for the use of conducting polymers and the main reasons for the development of composite materials.

Because of easy synthesis, low cost of monomer and tunable properties, polyaniline (PANI) is frequently applied as the conducting filler for composite materials. There are many studies describing the synthesis of polyaniline composites with thermoplastics, e.g. polyamindes, poly(ethylene oxide), poly(vinyl alcohol), polystyrene, polyimides, and, last but definitely not least, epoxy resins [59-61]. Such composite materials can be synthesized by means of several methods, e.g. thermal and solution processing of PANI-blends or in situ polymerization of aniline within the insulating polymer [62]. Although useful for the production of fibers and thin films, the second method exhibits major drawbacks including conductivity restricted to substrate surface as a result of hindered diffusion of aniline. More homogeneous conducting composites are formed as a result of solution processing. This method can be applied only if a specific solvent, in which both the conducting polymer and the host polymer are soluble, is identified.

Conducting PANI/epoxy resin composites can be also prepared by blending doped PANI with epoxy resin in the presence of curing agent and plasticizer used to assist dispersion of the conducting polymer [63]. To avoid de-doping of PANI which would lower its conductivity, the careful selection of curing agent is necessary. Although the preparation of homogeneous PANI/epoxy composites remains a major challenge, Tiitu et al. [64] succeeded when they employed specific aminic hardeners to simultaneously dissolve PANI and crosslink with the epoxy resin. At low PANI concentrations (ca. 1 wt%), the resulting coating was sufficiently homogeneous.

CONCLUSIONS

The paper presents an overview and analysis of LSP solutions applied for elements of aeronautical vehicles made of polymeric composite materials. Based on the performed analysis the highlighting of the most important advantages and drawbacks of currently applied LSP solutions was possible. Considering these issues, a concept of the new conducting composite material which is based on a mixture of conducting and dielectric polymers and conductive reinforcement, and dedicated for LSP applications in aircraft, was proposed. The assumed multidisciplinary approach for this problem allows analyzing modeling and manufacturing of this material within different perspectives of scientific disciplines including physics, chemistry, mechanics, etc. An approach based on percolation modeling applied in this study allow predicting a volumetric content of various components in the resulting mixture, and thus, setting two most important physical properties of this material, namely high density with simultaneous high electrical conductivity. The numerical and experimental studies are currently in progress. After synthesis the new conducting material the experimental verification of LSP is planned.

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