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Investigation of dielectric and strength properties of organoplastics. Review

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ABSTRACT

Currently, the production and use of military UAVs in the direction of robotic complexes is actively developing. The purpose and use of military UAVs differ from civilian ones, based on two functions: reconnaissance purpose and a carrier of a warhead. The specifics of military UAVs are their invisibility to enemy radars and ensuring stable transmission of information from the command post. For these purposes, first of all, the UAV material must have the properties of radio transparency. For the production of UAV hulls, power elements, high-strength PCM are needed, which include organoplastics, carbon fiber, fiber glass. The choice of materials for parts of components and assemblies of aviation equipment depends on their operating conditions: operating loads, material properties. Organoplastics (OP) fully meets these requirements among polymer composite materials (PCM). OP have high strength properties along with low dielectric losses (radio transparency) compared to other fiber composites. This paper presents an overview of studies of dielectric and strength properties, as well as ways to improve the mechanical properties of organoplastics. The analysis of the work has shown that for radiotransparent organoplasty, the optimal frequency range of permittivity is 1kHz-12 GHz. The ultimate strength of organoplastics varies in the range from 320 MPa to 1 GPa. The possibilities of increasing the strength of aramid fibers and ways of modifying organoplastics epoxy resins are considered.

Keywords: unmanned aerial vehicles, fairing, organoplastics, permittivity, tensile strength.

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Introduction

One of the most important structural elements of an unmanned aerial vehicle (UAV), which determines the aerodynamic characteristics, the quality of radio signal transceiver with a command post, and the accuracy of targeting, is the nose antenna fairing [1].

A set of requirements is imposed on the materials of UAV antenna fairing: high radio performance, resistance to thermal shock, low thermal conductivity, high strength, high impact strength, low density – as a factor in weight reduction. For these purposes, more advanced radio-transparent and high-strength materials with

low dielectric permittivity, low dielectric losses, and high mechanical strength are required.

Organoplastic (OP) is the most promising radiotransparent material that meets these requirements. The use of organoplastic materials to protect transceiver antenna devices placed on board the UAV from external influences will ensure maximum radio transparency, which will not interfere with the transmission and reception of an electromagnetic wave of a certain frequency. The combination of high strength, fracture toughness with low density puts organoplastics into the category of materials that effectively work as protective shock-resistant PCM.

The relative permittivity of OP is much lower than that of metal alloys and carbon fiber, which are widely used in aircraft [[2], [3]].

Radio transparency is the ability of materials to transmit radio waves in a wide frequency range with low losses [4]. Radiotransparent materials (RM) include organic and inorganic dielectrics that provide transmission of electromagnetic radiation in the radio frequency range of $10^5 - 10^{12}$ Hz. [5]. RM is used mainly for the manufacture of antenna fairing for high-speed aircraft. The transparency of these materials for radio waves is ensured by the choice of dielectrics with low dielectric characteristics (dielectric loss tangent $\text{tg}\delta \leq 0,02$, dielectric constant $\epsilon = 1,1 - 9,0$) and the corresponding electrodynamic calculation of the layer thickness [[2], [3], [6]]. In other words, the lower the dielectric constant, the more radio transparent the material. Such RM provides minimal distortion of the electromagnetic field in a given spectrum of operating frequencies. For this reason, for epoxy composite structures used in the construction of military UAV, the dielectric properties of the materials are very important.

The study of the properties of radio transparency and strength properties of epoxy composites, as well as ways to improve the mechanical properties of organoplastics, is relevant for the scientific and military industries. This paper presents the results of scientific work on the study of the dielectric (radiotransparent) and strength properties of OP, as well as ways to improve the strength characteristics of the composite.

Dielectric (Radiotransparent) properties of organoplastics

In the aerospace industry, especially in UAV, lightweight materials are needed to increase flight time, namely composites of glass, aramid, carbon fibers. In particular, carbon fiber is the most suitable material for UAV due to its high strength to weight ratio. However, the use of carbon fiber composites can interfere with the transmission of radar signals during flight. This is due to its high dielectric constant, therefore, to achieve the radio transparency of the UAV body, the use of composites of aramid and glass fibers are more effective [[7], [11]].

In aviation and rocket and space technology, radiotransparent fairings are used as protection against external influences of transceiver antenna devices. Their shape when placed on aircraft is determined by the configuration of the antenna

devices and their location [12]. The operating range of the UAV antenna systems depends on the requirements for the communication channel between the UAV and the ground control complex. For communication systems of small UAV, the decisive factors in choosing the frequency range are the weight and dimensions of the airborne transceiver and antenna-feeder device. It is expedient to choose a range of microwave frequencies. One suitable frequency band is the 2,4 GHz band. Also, a promising direction in the development of communication systems with UAVs is the use of frequency bands above 5 GHz [13]. Therefore, the UAV antenna fairing must be radiotransparent at high frequencies and provide minimal distortion of the electromagnetic field in a given operating frequency spectrum, which can be approached with low parameters of dielectric properties. Therefore, for composite structures used in electrical and aerospace applications, the dielectric properties of materials can be important as they directly affect the speed and energy loss during signal transmission [14].

Over the past few decades, the dielectric properties of composites have been widely studied for layered composites [[8], [9], [15], [16], [17], [18], [19], [20], [21], [22]]. For example, in the work [15] the authors investigated the dielectric properties of aramid, glass, carbon plates in the range of 8 – 12 GHz with vertical and horizontal polarizations. A UHF sweep generator is used to generate the signal. Vertical polarization is when the direction of the electric field vector of the microwave signal is parallel to the direction of the fibers, and horizontal polarization is when the electric field vector is orthogonal to the direction of the fiber. The test results are shown in tables 1 and 2. As the test results showed, the dielectric constant (DC) of carbon composites is several times higher than that of aramid and glass plastic.

As can be seen from tables 1 and 2, the dielectric constant values of aramid plastic for vertical polarization are slightly higher than for horizontal polarization. The authors attribute this to the electric field. In the vertical case, it is parallel to the directions of the fiber, which results in more of the signal entering the sample and gives a higher permittivity. From a comparison of all composites, the aramid composite has the smallest DC, and carbon fiber has the largest DC. Organoplastic and glass plastic showed good results in terms of radio transparency.

Table 1 – DC results for composite materials (vertical polarization) [15]

Freq uency (GHz)	Dielectric constant of aramid plastic	Dielectric constant of glass plastic	Dielectric constant of carbon plastic
8.0	4.63	4.71	26.6
8.5	4.30	4.83	18.2
9.0	4.27	4.85	20.9
9.5	4.59	5.12	13.4
10.0	4.63	4.98	14.2
10.5	4.57	5.04	10.5
11.0	4.72	5.24	7.3

Table 2 – DC results for composite materials (horizontal polarization)

Frequ ency (GHz)	Dielectric constant of aramid plastic	Dielectric constant of glass plastic	Dielectric constant of carbon plastic
8.0	3.40	5.19	29.4
8.5	3.42	4.58	22.8
9.0	3.61	4.50	21.6
9.5	3.53	4.52	17.6
10.0	3.42	4.32	15.1
10.5	3.62	4.57	11.5
11.0	3.50	4.54	10.5

Table 3 – Results of testing the strength properties of composite materials

Compo site laying type	Reinforce ment content, %	Matrix conten t, %	Tensile strength, MPa	Impact strength, J	Dielectric constant at 1000 MHz
17C	61.5	38.5	504.2	1.76	4.9
3A11 C3A	57.5	42.3	540.4	1.67	4.4
5A7C 5A	56.1	43.9	472.8	1.63	3.9
7A3C 7A	51.4	48.6	673.3	1.19	3.95
17A	49.6	50.4	676.5	1.35	3.97

In the next work [16] were investigated for the dielectric properties of organoplastics, glass plastic and a hybrid of these composites (aramid/glass). For the manufacture of plates, aramid fabric (Twaron 1000) manufactured by Akzo and E-glass EDR14 300-778 manufactured by JushiGroup (Zhejiang, China) were used. The resin system was ER 618 and hardener Iminazole 5510 manufactured by Shanghai Resin Company (China). In the manufacture of composites, five types of three-dimensional reinforcement geometries with 8 base layers and 9 fabric layers were adopted – 17C, 3A11C3A, 5A7C5A, 7A3C7A and 17A. (A – AF and C – fiberglass). The research results are shown in table 3. The dielectric constant and dielectric losses of the composites were obtained in the frequency range from 1 MHz to 1000 MHz.

It can be seen from table 3 that the DC of the composites decreases as the AF content increases, when the volume fraction of AF was lower than that of 5A7C5A, then the opposite happened. This indicates the low dielectric parameters of the AF, which increases the radio transparency of the material. A good DC result was shown by the 5A7C5A composite, but with the lowest tensile strength of 472.8 MPa.

At present, there are various methods developed in practice for determining the dielectric properties of composites, including the waveguide method, the free space method, the resonator method and the coaxial method, etc. The waveguide method is based on measuring the parameters of the scattering matrix (S-matrix) of the waveguide in which the sample is placed of the material under study in the form of a plate filling the cross section of the waveguide [17]. The DC of basalt/ER and AF (Kevlar 129)/ER composites were studied in [18], as well as fabricated intralayer three-dimensional orthogonal fabric hybrid composites basalt/AF/ER and measured their dielectric properties by the waveguide method in the frequency range of 8-12 GHz. In the manufacture of composites, 4 geometries of reinforcement with six layers of base and seven layers of filler were adopted, namely, composites with intermediate hybrid, intralayer hybrid, with basalt and with aramid type. In the intermediate hybrids, AF or basalt yarn was placed in different layers, while in the intralayer hybrids, the two types of yarn were placed alternately in each layer of the warp or filler. Measurements of the dielectric properties were performed on an Agilent 8722ES vector network analyzer. The test results are shown in figure 1.

From the results, it was determined that the DC of the basalt composite increases with increasing frequency. The authors explain this as the phenomenon of achieving electronic resonance. The other three types of composites tend to slowly decrease as frequency increases, which may be in the range of dipole relaxation and electronic resonances. It has been observed that the DC of the AF composite exhibits a relatively faster downward trend than that of the hybrid types, showing unstable AF dielectric properties as previously reported [16].

The free space method makes it possible to measure the dielectric properties of a material under various external influences. For example, the authors of the study [[8], [19]] used this method to characterize the effect of a damaged AF/ER composite surface on the wave transmission characteristics of radomes. In work [20], the authors studied the dielectric parameters of a unidirectional and quasi-isotropic AF/ER composite at various strains. The tensile values of the composite are given as, initial stage (IS), 0,001 D, 0,002 D, 0,003 D. The resulting DC results are shown in figure 2. Figure 2a shows the DC of a unidirectional AF/ER composite that looks like a wavy line with different frequencies.

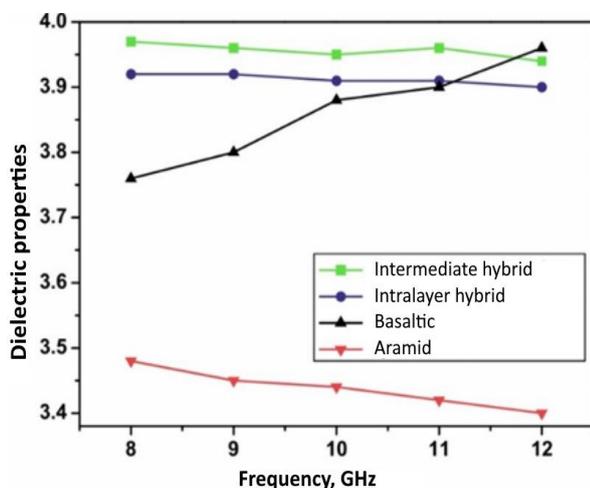


Figure 1– Dielectric constants of four types of composites [18]

in X-range up to the application of tensile loads, and the maximum change in DC with different frequencies is within 0,061. When tensile loads are applied, the shape of the DC curves practically does not change. However, it has been shown that the DC of the composite increases with increasing tensile strain. The electromagnetic parameters of the quasi-isotropic AF/ER composite were also measured under various strains, which are shown in figure 2b. It is seen, that the dielectric constants increase when the sample is stretched. According to the results of the authors, the DC increases by 0,045 per 0,001 strain. In addition, the DC of quasi-isotropic composites is lower than that of a unidirectional composite due to the different orientation of the fibers within the composite.

The DC of epoxy composites increases with increasing filler content (Kevlar 49) and temperature. This conclusion was reached by the authors of [21]. In their opinion, the permittivity and losses of composites are mainly affected by interfacial polarization, which occurs due to inhomogeneities at the interfaces introduced by the filler. In [22] compared the mechanical and dielectric properties of OP based on AF Kevlar 49, Kevlar 49, Kevlar 149 and ER with lamination geometry [0,90]. The best results were shown by an OP based on Kevlar 149 with a DC of 3,9 at a frequency of 10^6 Hz.

Tables 4 and 5 present the dielectric properties of the composites. Thus, according to the literature data, OP reinforced with AF have low dielectric constants in comparison with other fibrous composites. According to the analysis, the optimal frequency range for measuring dielectric properties (radio transparency) is 1 kHz – 12 GHz. Because, according to extensive studies in this range, they show the best results of DC.

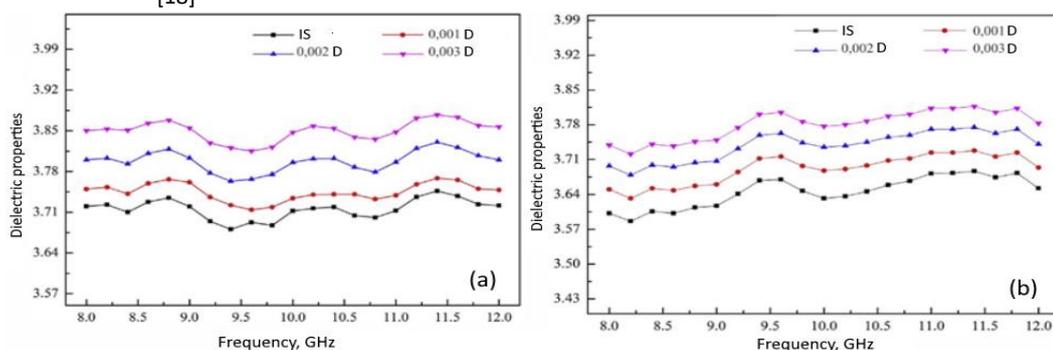


Figure 2 – Dielectric properties of the aramid-epoxy composite under various deformation conditions: (a) unidirectional and (b) quasi-isotropic AF/ER composite [20]

Table 4 – Dielectric properties of aramid fabric reinforced epoxy matrix composites at a frequency of 10^3 Hz [22]

Textile	The dielectric constant	Dissipation factor
Kevlar®29	4.51	0.0135
Kevlar®49	4.44	0.0131
Kevlar®149	4.14	0.0103

Table 5 – Dielectric properties of aramid fabric reinforced epoxy matrix composites at a frequency of 10^6 Hz [22]

Textile	The dielectric constant	Dissipation factor
Kevlar®29	4.19	0.0171
Kevlar®49	4.14	0.0170
Kevlar®149	3.90	0.0142

Table 6 – Tensile strength of the obtained composites [29]

Composite	Trial 1	Trial 2	Trial 3	Average value, MPa
30% AF + 70% ER	510	520	517	515
35% AF + 65% ER	545	547	548	546
45% AF + 55% ER	534	531	526	530

To achieve high dielectric parameters in the composite, the aramid fabric layer should be one layer larger than the base layer. In the above works, the smallest DC, which is equal to 3,4, has an ER/AF composite with six base layers and seven filler layers [18]. In addition, the DC of quasi-isotropic composites is lower than that of a unidirectional composite due to the different orientation of the fibers within the composite.

Strength properties of organoplastic

When designing UAV, the strength of epoxy composites plays an important role [[23], [24], [25], [26], [27]]. For ER reinforced AF is characterized by high strength, it is insufficient compared to metals. In a number of scientific papers [[28], [29], [30], [31], [32], [33], [34]], the results of work related to the change and increase in strength properties

depending on the composition of AF and ER, the type of AF, the type of reinforcement, the number of layers and the order of fabrics, as well as the direction of the fibers are presented.

BenniF. et al. [28] conducted a comparative study on the mechanical properties of the UAV skin for AF, glass fiber E and glass fiber S, as well as their hybrid arrangement, made using ER and a vacuum infusion process. The authors used Renlam LY 5138-2 and RenHy 5138 hardener (Huntsman, Indonesia) as ER. EW 130 E-glass fiber and SW220B-90A, AF S-glass fiber were used to reinforce the ER. In a typical experiment, eighteen layers of fibers were arranged and covered with a bag film that was connected to the inlet and outlet streams of the tube. The ER in the container was pumped through the tube to wet the entire laminate. The sample was placed at room temperature (25 ± 2 °C) for 3 hours to cure. As a result of complex analyzes, it was determined that the specific tensile strength and specific modulus of elasticity mainly depended on AF. However, AF had little effect on the specific compressive strength, while the E-glass excellently withstood the compressive stress. The best tensile strength result was shown by a sample with 9 layers of AF and 9 layers of S-glass fibers (321 MPa).

In [29], the mechanical properties of an AF reinforced ER composite are studied by varying the percentage composition. The three different compositions of AF are 30 %, 35 % and 45 % by weight. The aramid-epoxy composite was produced by the vacuum method. The resulting composites are then cured in a hot air oven for 180 minutes. The results of the work are shown in table 6. The composite with the composition of 35 % AF + 65 % ER demonstrated the maximum tensile strength and hardness due to the uniform distribution of ER and the best interface between AF and ER.

The authors of [30] studied polymer composites based on AF with increased shear strength for aircraft products. The main task of the work was to study the interlayer strength of aramid OP after transverse reinforcement. The volume fraction of reinforcing fibers in the cured OP was 52 – 55 %. OP was obtained by layer-by-layer deposition of prepregs, followed by compression of the package at elevated temperature and pressure. The results showed that the use of a unidirectional reinforcing filler or a three-dimensional six-layer fabric

Table 7 – Physical and mechanical properties of organotextolites [33]

Strength characteristics	Organotextolite based on fabric	
	Rusar NT	Ruslan
Density, kg/m ³	1380-1390	1340-1380
Tensile strength, MPa	930 / 900÷950	880 / 840÷900
Tensile modulus, GPa	42 / 41÷43	35 / 33÷37
Compressive strength, MPa	210 / 200÷230	210 / 190÷220
Bending strength, MPa	570 / 560÷590	470 / 450÷500
Modulus of elasticity in bending, MPa	34 / 32÷35	25 / 22÷27

increases the interlayer strength of PCM by 22 %. And the use of voluminous two-component fabrics doubles them compared to conventional single-layer fabrics. J. Wu and XH Cheng [31] prepared aramid-epoxy unidirectional composites, in which the content of AF F-12 was 65 % vol. for all composite samples. The ratio between ERE-51 and hardener 593 was 100: 25 by weight. The results of interlaminar shear strength showed 54-60 GPa, shear strength 3,8-4,0 GPa depending on the surface treatment AF. M. Goodarz et al. [32] studied the low-speed impact response of aramid-epoxy plastics containing nano-layers of various thicknesses (17,5, 35, and 70 μm) and various stacking configurations (reverse, central, and two-sided alternation). The best results were obtained on composites containing a 35 μm spacer. The results show that the inclusion of nanofibers at the interface allows the composite to absorb significantly higher impact energy compared to plates without any nanofibers.

The aim of the work [33] was the development and manufacture of experimental reinforcing fillers from Rusar NT aramid fiber, a textile thread with a linear density of 14.3 tex, fabrics of a typical satin weave, as well as evaluating the effectiveness of new Rusar NT AF for reinforcing aviation organotextolite. Table 7 presents the physical and mechanical properties of samples of organotextolite based on fabric from the Rusar NT thread.

The article presents the results of a study of the physical and mechanical properties and moisture resistance of experimental organotextolites reinforced with AF fabric. Organotextolites for research were made from prepregs by autoclave molding. For the manufacture of prepregs from a

solution of the binder EDT-69N(M), an impregnation unit UPST-1000 was used.

In [34], the mechanical behavior of an epoxy composite reinforced with unidirectional and fabric fibers was experimentally studied. Fabric glasses, aramid and carbon fibers, as well as unidirectional glasses and carbon fibers were used in the preparation of composite samples. Tensile, compression and shear tests were carried out to determine the mechanical properties of the composites (table 8). From the test results, it turned out that the mechanical properties of the reinforced AF composite are higher than those of glass and carbon fiber when we consider textile fiber types.

Thus, from the presented results it follows that the strength range of the OP starts from 320 MPa to 1 GPa. It is worth noting that the mechanical properties of the reinforced AF composite are higher than those of glass and carbon fiber, if we consider textile fiber types. High strength shows a composite with aramid fiber Rusar NT with a monolayer thickness in plastic of 0.11 – 0.12 mm, which is closer to 1 Gpa [33]. AF have a promising reinforcing effect on many resins, but the reinforcement mechanism needs further study. Therefore, the question of how to further enhance the interaction between the fillers and the matrix is of great importance for the application of this material in a wide industry, including military UAV.

The study of ways to improve the strength characteristics of organoplastic

Methods for modifying the surface of materials can be divided into four categories: mechanical,

Table 8 – Tensile strength of aramid epoxy composite [34]

Reinforcement type	Fiber volume V	Density [g/cm ³]	Modulus of elasticity [MPa]	Shear modulus [MPa]	Poisson's ratio [-]	Tensile strength [MPa]	Tensile strength / density	Shear strength [MPa]	Compression force [MPa]	Elongation at break
Glass fabric	30	1.55	14 352	4728	0.24	220	141.9	119	96	0.016
Aramid fabric	30	1.2	19 087	2585	0.38	357	297.5	53	64	0.019
Carbon fabric	30	1.31	42 000	12350	0.32	340	259.5	180	118	0.009
Unidirectional glass (0°)	30	1.55	18 300	3895	0.25	432	278.7	30	71	0.028
Unidirectional glass (90°)	30	1.55	7940	3895	0.17	52	33.5	30	16	0.0096
Unidirectional carbon (0°)	30	1.31	78 715	2195	0.4	826	630.5	20	118	0.0100
Unidirectional carbon (90°)	30	1.31	4 930	2195	0.25	37	28.2	20	27	0.0130

chemical, combustible and plasma. Since the diameter of conventional fiber is several micrometers, the use of mechanical methods and methods of burning on fibers becomes almost impossible to modify the surface of the fiber. Chemical surface treatment of fibers has long been widely used in industry. Another method that is mainly used is the surface oxidation of the fibers. However, chemical modification may have some disadvantages. When the fibers are oxidized in concentrated nitric acid, the equipment used must have good corrosion resistance, and the acid adsorbed on the surface of the fiber must be properly removed. This takes a long time and in most cases is accompanied by a decrease in fiber strength [11].

In the modern literature, many works are reported on the study of ways to improve the strength characteristics of the OP, and at present, the search for optimal technologies is underway. As is known from practical work, the main task in the manufacture of OP is to increase the strength characteristics. Strength characteristics directly depend on interfacial adhesion between fillers and matrices [36]. To improve interfacial adhesion between AF and ER matrices, various methods of fiber surface modification are used, such as chemical treatment (using binding agents and chemical grafting methods), plasma treatment, and others. The purpose of these surface modification methods is to increase the concentration of reactive functional groups or to roughen the fiber surface to

increase physical contact with the resin matrix [35], [36], [37].

The formation of the fiber-resin interface is largely influenced by the polarity and total surface energy of the fiber surface. Thus, the addition of polar groups has been proposed to increase adhesion [38]. Various types of oxidative treatment constitute the basic fiber surface modification methodology, and these procedures cover: (1) gas oxidative treatment; (2) treating the solution with oxidation; and (3) electrochemical or electrolytic oxidation treatment. These treatments simply change the surface morphology of the fiber and may also change the surface energy and chemical composition. Naturally, changing the surface roughness also affects the chemical composition of the surface of the fibers. Lin J.S. [39] studied the use of bromination and metalation to change surface roughness and chemical composition. Very often, an effective and severe surface treatment leads to a deterioration in quality and a decrease in the strength and stiffness of the fibers, although the macroscopic properties of the composite may remain at an acceptable level or even at a high level. A typical surface treatment with solutions, namely AF sizing, is the use of emulsified solutions. Dimension based aqueous solutions of epoxy piperazine were studied by deLange et al. [40] and they reported improved adhesion.

In ways to improve the strength characteristics of OP, the most common method is chemical grafting. For example, Wu et al. applied the method

of graft modification of AF in [31], [41]. In the works, two types of fiber surface treatment were used to improve the strength characteristics: solutions of the modifier of rare earth elements (REE) and epoxychloropropane (ECP). For the modified ECP grafting treatment, F-12 aramid fibers were immersed in a KOH (0,7 %)/alcohol solution at 30 °C for 2 hours, then washed and dried. After that, these fibers were grafted into ECP at 90 °C for 6 h, then washed with distilled water and dried. For treatment in REE solutions, F-12 aramid fibers were immersed in a REE/alcohol solution at room temperature for 1 hour and dried in a vacuum oven at 110 °C for 4 hours. The results of [41] show that that both of these methods can improve interfacial adhesion. The REE surface treatment is superior to the ECP grafting treatment in providing interfacial adhesion between AF. The interfacial shear strength for the REE treated sample is 30.2 MPa, while the ECP grafted sample has 28.9 MPa. Meanwhile, the treatment of REE had almost no effect on the tensile strength of individual fibers.

The strength of the OP is increased by chemical grafting of AF with amino-functionalized graphene oxide [42] and supercritical carbon dioxide [[43], [44]]. In the first case [42], in order to functionalize the surface, AF 2 mm long was immersed in a buffer solution (pH = 8.5), and then dopamine was added. The above mixture was sonicated for 10 minutes and kept under constant stirring for 24 hours at room temperature. The coating was formed on the surface of the AF by dopamine self-oxidative polymerization. To obtain AF modified with amino-GO/dopamine, fibers from self-polymerized polydopamine-aramid were added to the amino-GO solution at 15 – 50 °C for 12 – 24 h. Next, a mixture of ER E-51 and m-xylylenediamine in a mass ratio of 100: 18.32 was applied to one AF with the formation of a resin microdroplet. The resin microdroplets were then cured at 60 °C for 1 hour and at 100 °C for 2 hours. The above process is shown in figure 3. The prepared resin microdroplets were used to test the interfacial properties of the modified fibers. As a result, at a higher reaction temperature of 60 °C, composites based on modified AF and ER showed an interfacial strength of 35.21 MPa, which is 34 % higher than that of composites based on pure AF/ER (26.31 MPa).

In [43] the mechanical and surface properties of AF were simultaneously improved by grafting with 1,4-dichlorobutane in supercritical carbon dioxide (scCO₂). For this purpose, the AF was placed in a stainless steel pressure vessel (1 l) where the

treatment was carried out. An appropriate volume of 1,4-dichlorobutane was added to the vessel and the ratio of mass to volume of fiber and reagent was 1:60. When the vessel reached the desired temperature, CO₂ gas was injected through a high pressure syringe pump. Thus, seven samples were prepared in accordance with three conditions; the details are presented in table 9.

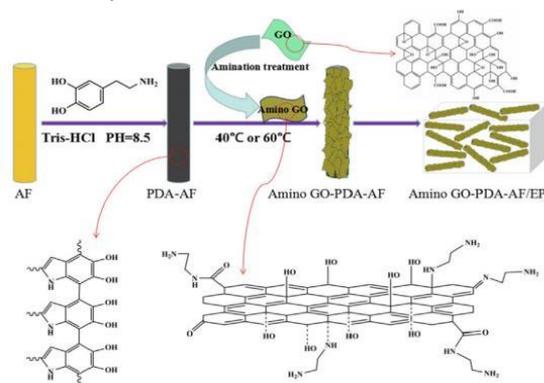


Figure 3. Illustration of the production process of modifying AF [42]

Thus, the authors developed a new strategy for improving the mechanical and surface properties of AF by treatment with 1,4-dichlorobutane in scCO₂. After the modification, the interfacial strength of the OP increased by 24.3 % from 51.29 to 63.91 MPa due to improved surface roughness and surface energy (figure 4b). In addition, the tensile strength of AF increased by 15.3 % from 3.14 to 3.62 GPa (figure 4a), which was attributed to improved crystallization of AF under tensile forces. In a similar work [44], the results show that the surface modification of AF in scCO₂ was an effective method for improving the adhesion characteristics between fibers and vinyl epoxy resin. The flexural strength of AF treated with scCO₂ vinyl epoxy composites was 18.1 % higher than that of untreated AF. Also, after treatment in scCO₂ with liquid isocyanate-terminated nitrile rubber, the interlayer shear strength increased from 42.5 MPa to 54.8 MPa.

Table 9 – Treatment conditions with supercritical carbon dioxide (scCO₂) for modification of AF [43]

Sample	Pressure (MPa)	Time (min)	Temperature (°C)
1	9.0	90	40
2	9.0	90	60
3	9.0	90	80
4	7.5	90	60
5	10.0	90	60
6	9.0	40	60
7	9.0	60	60

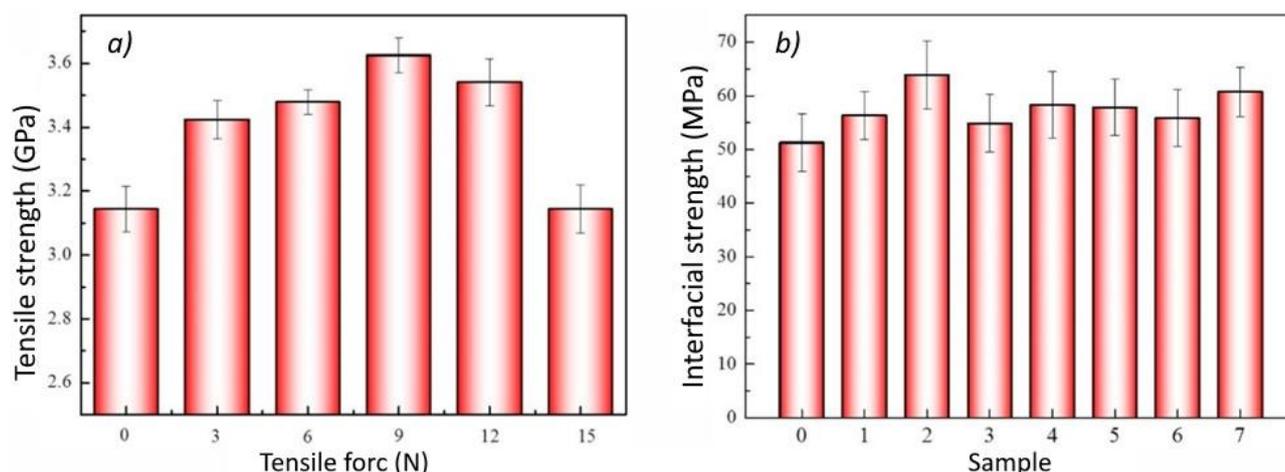


Figure 4 – Tensile strength of the fiber at tensile forces up to 15 N (sample 2 in table 2) (a) and interfacial strength of the OP before and after treatment with scCO_2 1,4-dichlorobutane at a static tension of 9 N. (0): untreated fiber; (1-7): modified fibers of samples 1 – 7 in table 2 (b) [43]

Kevlar fiber was functionalized with phosphoric acid of various concentrations in [45]. The authors functionalized the fiber at room temperature with 10, 20, 30 and 40 wt.% phosphoric acid at 40 °C for 2 hours. It has been found that functionalization significantly increases the bond strength between Kevlar fiber and ER. The amount of surface oxygen and hydroxyl groups in Kevlar fiber can be significantly increased by functionalizing it with 40 wt.% phosphoric acid. As a result, the interfacial shear strength of composites reinforced with Kevlar fibers treated with phosphoric acid increases significantly up to ~35 MPa.

The authors of [46] studied the effect of modified aluminosilicates, including bentonite from armenia modified with quaternary ammonium salts (BAQAS) and phosphonium salts (BAQPS), on the mechanical properties and morphology of Kevlar/ER composites. Kevlar/ES composites containing 1.0 or 3.0 wt % modified bentonites were made using a hand layup technique. Mechanical properties were tested, including tensile strength, bending and in-plane shear. The results showed that the mechanical properties improved with increasing bentonite, as shown in table 10. The best results were obtained for composites containing 3 wt.% BAQAS, since most of the mechanical properties were significantly improved (tensile strength 302,9 MPa (+ 30 %), Young's modulus 16.3 GPa (+ 17 %), flexural modulus 23,4 GPa (+ 12.5 %), in-plane shear strength 22.8 MPa (+ 24.5 %) and in-plane shear modulus 677.2 MPa (+ 42 %)).

The next group of scientists use plasma treatments to improve the strength characteristics of OP. In particular, Brown and Mathys [47] applied ammonia and oxygen plasma treatment and

reported improved performance of textolites in terms of interlaminar shear strength. Shaker et al. [48] used radio frequency (RF) plasma to modify aramid fibers and achieved improved textolite properties. The use of surface modifications to provide mechanical interlocking has been proposed by Palola et al. [49] and Wu et al. [50]. In [51], the authors increased the interfacial adhesion of epoxy composites reinforced with AF III due to low-temperature plasma treatment. Three technological regimes of low-temperature plasma treatment have been studied. Plasma treatment was carried out using a low-temperature DC glow-discharge plasma system (model HPD-280, Nanjing Suman Electronica Co. LTD, China) with an interelectrode gap of 30 mm, a reactor temperature of 20 °C, and a resonant frequency of 20 kHz. Sixteen treatment groups with various combinations of treatment power, treatment time, and treatment pressure were performed as shown in table 11.

Obviously, plasma treatment has an adverse effect on the tensile properties of AF III, and the detailed rates of reduction in tensile stress of AF III treated under different conditions. The results showed interfacial adhesion increased by 35.5 % to 30.44 MPa under optimal conditions, which were found to be a treatment power of 67.5 W, a treatment time of 11 minutes and a treatment pressure of 2500 Pa. After plasma treatment, the interfacial adhesion of the AF III/ER composites was improved, as shown by fragmentation testing of the monofilament composite material, but the tensile stress of a single strand of AF III was reduced. By surface morphology, chemical composition, AF III wettability, and fractured monofilament composite cross - sectional morphology, the interfacial

Table 10 – Tensile strength of composites reinforced with Kevlar [46]

Material	Tensile strength, MPa	Young's modulus, GPa	Elongation at break, %
ER/Kevlar	233.9 ± 12.5	13.9 ± 1.2	1.6 ± 0.2
ER+1% BAQAS/Kevlar	303.1 ± 11.8	13.1 ± 0.9	1.9 ± 0.4
ER+3% BAQAS/Kevlar	302.9 ± 17.7	16.3 ± 3.0	1.6 ± 0.5
ER+1% BAQPS /Kevlar	260.3 ± 9.0	12.8 ± 1.0	1.8 ± 0.3
ER+3% BAQPS /Kevlar	285.7 ± 19.6	15.5 ± 0.2	1.7 ± 0.3

Table 11 – Results of fiber tensile and fragmentation tests for various processing conditions [51]

No.	σ_0 (MPa)	β	σ_f (MPa)	l_c (μ m)	τ_{IFSS} (MPa)
0	4724.70	17.02	5466.06	2092.00	22.47
1	4673.06	15.70	5476.22	2072.67	22.72
2	4593.64	15.02	5433.28	2008.67	23.26
3	4465.58	13.18	5492.79	1632.53	28.94
4	4354.59	12.08	5468.55	1595.60	29.47
5	4638.23	16.41	5431.13	1876.00	24.90
6	4500.38	15.29	5364.76	1703.33	27.09
7	4330.79	14.43	5254.64	1535.20	29.44
8	4351.82	16.69	5136.90	1569.47	28.15
9	4573.80	13.14	5586.19	1803.07	26.65
10	4451.74	11.09	5700.61	1610.53	30.44
11	4435.38	13.68	5419.92	1610.40	28.94
12	4283.74	16.97	5061.05	1475.73	29.49
13	4523.26	14.28	5443.86	1774.40	26.38
14	4498.71	11.59	5684.69	1660.27	29.45
15	4113.07	15.63	4939.56	1428.93	29.73
16	4071.60	11.42	5217.84	1471.33	30.50

reinforcement mechanism of plasma-treated AF III reinforced epoxy composites can be summarized as four aspects:

- 1) van der Waals binding due to increased surface area of AF III;
- 2) mechanical adhesion of the rough surface AF III with the matrix;
- 3) good wettability of the AF III surface by the polymer;
- 4) chemical bond between oxygen-containing groups on the surface of AF III and the matrix.

In the literature, the work [52] is reported, where the authors developed a fast and economical surface treatment with a flame and treatment with a silane binder in order to improve the adhesive characteristics of light multilayer hidden fairing structures. The flame treatment was performed

using propane gas, and the silane treatment was performed with c-methacryloxypropyltrimethoxysilane (c-MPS) and c-aminopropyltriethoxysilane (c-APS) under various processing conditions. The results of all treated composites are shown in figure 5. Flame treatment for 5 s and treatment with a silane coupling agent with a silane concentration of 0,5 wt.% on the surface of the OP had the highest bond strength of 10,9 MPa among all treatments.

Strength characteristics can be increased by incorporating multi-walled carbon nanotubes into aramid fabric-reinforced epoxy composites. The results obtained showed that the addition of 0,3 wt. % of multi-walled carbon nanotubes in aramid-epoxy composites is the optimal value, which significantly improves its mechanical properties [53].

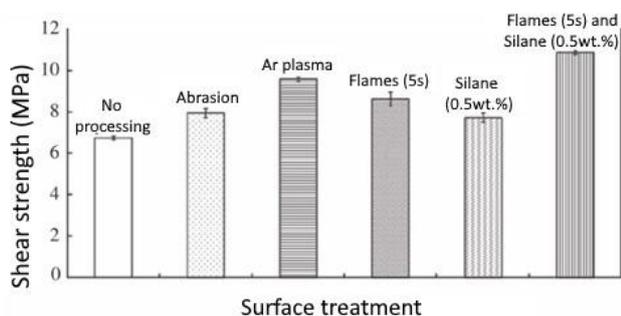


Figure 5 – Shear strength in relation to the surface treatment of the aramid-epoxy composite [52]

The authors in [54] studied the properties of epoxy compositions based on epoxy diano resin brand ED-20 and PEPA hardener with the addition of tricresyl phosphate (TCP) plasticizer. When using the composition of 70 % ED-20 + 30 % TCP + 15 % PEPA, the most optimal strength properties were obtained. The physical and mechanical properties are as follows: the impact strength increased from 9 to 14 kJ/m² compared to the composition without TCP modification, the bending stress increased to 98 MPa. The study [55] developed compositions based on ED-20 resin with TCP modifiers. PEPA hardener was used as the resin hardener. The samples were obtained in the form of compressed tablets with a thickness of 1 mm containing 70 % by weight of ED-20, 15 % PEPA, 30 % TCP. The tests were carried out for strength characteristics and for gelation time, epoxy curing time and temperature. The results of the study showed that the introduction of the TCP plasticizer into the resin composition improves impact strength by 3 times (10 kJ/m²), bending by 3 times (57 MPa), and hardness by 59 % (197 MPa). It also increases the gelation time from 24 to 60 minutes, the curing time from 39 to 115 minutes and reduces the curing temperature from 125 to 44 °C.

Based on all of the above, we can conclude that it is expedient to process AF and ER. Among the above works, the AF/ER composite modified by treatment with 1,4-dichlorobutane in scCO₂ (63,91 MPa) has a high interlaminar shear strength [43].

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The use of methods for increasing the strength characteristics of OP when creating PCM is an important and significant process for improving the interaction between the polymer matrix and the filler. This, in turn, increases the strength of the fairing material in UAV hulls, which brings it closer to the stringent requirements for the design of aerial vehicle.

Conclusions

According to the literature data, aramid fiber-reinforced organoplastics have low dielectric constants and high mechanical characteristics compared to other fiber composites. According to the analysis, the optimal frequency range for measuring dielectric properties (radio transparency) is 1 kHz – 12 GHz. To achieve high dielectric parameters in the composite, the aramid fabric layer should be one layer larger than the base layer. Based on the results of the work, it follows that the strength range of organoplastics starts from 320 MPa to 1 GPa. Mechanical properties of the composite, reinforced aramid fiber higher than glass and carbon fibers. Also, it can be concluded that it is reasonable to aramid fiber and epoxy resin. In many studies, surface treatment is achieved by increasing interfacial adhesion, which greatly increases the strength characteristics of the organoplastic. Using these methods, it is possible to improve the strength of epoxy composites by more than 30 %.

Thus, ways to improve the strength characteristics of OP is currently an area of active research and a topic for further study.

Conflict of interests. There is no conflict of interest.

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Органопластиктердің диэлектрлік және беріктік қасиеттерін зерттеу. Шолу

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ТҮЙІНДЕМЕ

Қазіргі уақытта роботты кешендер бағытында әскери ҰҰА өндіру және қолдану белсенді дамып келеді. Әскери ҰҰА мақсаты мен қолданылуы азаматтық функциялардан екі функцияға байланысты ерекшеленеді: барлау мақсаты және соғыс зарядының тасымалдаушысы. Әскери ҰҰА ерекшелігі олардың жау радарларына көрінбейтіндігінде және командалық пунктпен ақпараттың тұрақты берілуін қамтамасыз етеді. Осы мақсаттар үшін, ең алдымен, ҰҰА материалы радио мөлдірлігінің қасиеттеріне ие болуы керек. Корпустарды, ҰҰА қуат элементтерін өндіру үшін жоғары беріктігі бар ПКМ қажет, олардың қатарына органоластик, көмірластик, шыныластик кіреді. Авиациялық техниканың тораптары мен агрегаттарының бөлшектері үшін материалдарды таңдау олардың пайдалану шарттарына: қолданыстағы жүктемелерге, материалдың қасиеттеріне байланысты болады. Бұл талаптар композициялық Полимерлі композициялық материалдар (ПКМ), органоластик (ОП) арасында толық жауап береді. ОП басқа талшықты композиттермен салыстырғанда төмен диэлектрлік шығындармен (радио өткізгіштік) бірге жоғары беріктік қасиеттеріне ие. Бұл жұмыста диэлектрлік және беріктік қасиеттерін зерттеуге шолу, сондай-ақ органоластиктің механикалық қасиеттерін арттыру әдістері келтірілген. Жұмысты талдау көрсеткендей, радио өткізгіш органоластик үшін диэлектрлік тұрақтылықтың оңтайлы жиілік диапазоны 1кГц-12 ГГц құрайды. Органоластиктің беріктік шегі 320 МПа-дан 1 ГПа-ға дейін өзгереді. Органоластиктің эпосид шайырының модификациялаудың тәсілдері және арамидтік талшықтарының беріктігін арттыру мүмкіндіктері қарастырылады.

Түйін сөздер: ұшқышсыз ұшу аппараттары, ағын, органоластик, диэлектрлік тұрақты, беріктік шегі.

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Исследование диэлектрических и прочностных свойств органоластика. Обзор

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АННОТАЦИЯ

В настоящее время активно развивается производство и применение военных БПЛА в направлении роботизированных комплексов. Предназначение и применение военных БПЛА отличаются от гражданских, исходя из двух функций: разведывательное назначение и носитель боевого заряда. Специфика военных БПЛА заключается в их невидимости для радаров противника и обеспечения устойчивой приемопередачи информации с командным пунктом. Для этих целей, в первую очередь, материал БПЛА должен обладать свойствами радиопрозрачности. Для производства корпусов, силовых элементов БПЛА нужны высокопрочные ПКМ, к числу которых относятся органоластик, углепластик, стеклопластик. Выбор материалов для деталей узлов и агрегатов авиационной техники зависит от их условий эксплуатации: действующих нагрузок, свойств материала. Этим требованиям полно отвечает среди композиционных полимерных материалов (ПКМ) органоластик (ОП). ОП обладают высокими прочностными свойствами наряду с низкими диэлектрическими потерями (радиопрозрачность) по сравнению с другими волокнистыми композитами. В данной работе представлен обзор исследований диэлектрических и прочностных свойств, а также способы повышения механических свойств органоластиков. Анализ работ показал, что для радиопрозрачного органоластика оптимальный диапазон частот диэлектрической проницаемости является 1кГц-12 ГГц. Предел прочности органоластиков варьируется в интервале от 320 МПа до 1 ГПа. Рассмотрены возможности увеличения прочности арамидных волокон и способы модификации эпоксидных смол органоластика. **Ключевые слова:** беспилотные летательные аппараты, обтекатель, органоластик, диэлектрическая проницаемость, предел прочности.

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