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STUDY OF RADIO TRANSPARENCY AND DIELECTRIC PERMITTIVITY OF GLASS- AND ARAMID EPOXY COMPOSITES

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Aramide- epoxy-filled composites are widely used for manufacturing in the structures of modern aerospace vehicles. Not only do they have excellent mechanical properties, but they are also radio-transparent materials for wave transmission. In this work, an epoxy-filled composite and a fibreglass were made by vacuum infusion for a comparative study on radio transparency and dielectric permittivity. The radio transparency of the materials analyzed has been evaluated by measuring in free space in the frequency ranges of 1-6 GHz. According to the results of radio transparency, aramide- epoxy-filled composite suffers less electromagnetic wave losses than in fibreglass. When measuring the dielectric permittivity of the aramide- epoxy-filled composites, a low average value of 2.874 has been set, whereas for the fibreglass is defined at 4.

Keywords: aramide-epoxy-filled composites, fibreglass, epoxide resin, radio transparency, frequency,dielectric permittivity.

Introduction

Radio transparency is the low loss capacity of radio materials to transmit radio waves across a broad frequency range [1]. The radio-transparent materials include organic and inorganic dielectrics that allow transmission of electromagnetic radiation of the radiofrequency range of 10^5 - 10^{12} Hz. [2]. The transparency of these materials for radio waves is ensured by choosing dielectrics with small values of dielectric characteristics (dielectric dissipation factor $tg\delta \leq 0.02$, dielectric permittivity $\varepsilon = 1.1$-9.0) and relevant electrodynamic calculation of layer thicknesses [3]. In other words, the lower the dielectric permittivity, the more radiotransparent the material is. The reducing the dielectric permittivity and dielectric dissipation factor can reduce the capacitance and time delay of a signal to improve signal transmission in antenna, fairing. The selection of materials for manufacturing the fairing makes necessary the maximum optimization of mechanical and electrical properties for the effective functioning of radar systems of supersonic aircraft [4].

The polymer composites with fibers, which have low extended defects [5], are very promising as radio-transparent materials. One such material is polymer composites reinforced with aramid fiber that is the aramide epoxy-filled composite (AEC). They have low dielectric permittivity, low dielectric absorption losses, and outstanding mechanical characteristics, this is why they are widely used for manufacturing of fairings, stabilizers and vertical fins in the modern airplane industry [6-8]. The dielectric properties of AEC are important parameters since they directly affect the speed and loss of the wireless power during signal transmission. The precise measurements of the dielectric properties of AECs can provide engineers and researchers with valuable information that can be used to optimize the performance and characteristics of its designs [9-11].

Over the years, numerous papers [12-18], have been reported on the study of the dielectric properties of AEC. The authors' efforts apply various methods to improve the radio transparency of composites (dielectric performance degradation). According to the authors of the review paper [12], there are two simple ways to reduce the dielectric permittivity (DP) of composites. The first is to reduce the number density of the dipole by inclusion of air, and the second - to alloy with fluorine element in order to reduce the polarizability of the dipole in the composite material.

A group of several researchers believe that combining aramid fiber (AF) with fibreglass results in lower dielectric characteristics. L. Yao et al. [13,14] have investigated the dielectric properties of composites, reinforced AF, and three-dimensional hybrid composites by the rectangular waveguide method. They found that the hybrid composite 5A7C5A (A – aramid fiber and C – fibreglass) had the lowest DP, which is even lower than 17A pure aramid composite. Under the charge of Choi and Chin [15,16], authors have used the free space method, to characterize the effect of a damaged faceplate from the AEC on the wave transmission characteristics of the fairings. The hybrid composite nearly invisible fairings were designed as a composite sandwich construction consisting of E-glass/aramid/epoxy. The hybrid composite low-visibility fairing with HF2 face has met the requirements for transmission characteristics of electromagnetic waves with transmission coefficient of 81 % at the resonance frequency of 8.50 GHz and bandwidth of 0.84 GHz. The following article [17] has considered a combined dielectromechanical test method based on the free-space method and a mechanical testing machine. DPC of aramid/epoxy, epoxide resin (ER) and fiberglass/epoxy composites were measured under different deformation conditions. It was found that the DP of composites increases with increasing strain, while the tangent of the angle of dielectric losses remains unchanged. In [18] paper, nearly invisible fairing was made with an AEC face and a foamed core for low-observability. The dielectric constant and AEC dielectric dissipation measured by free space measurement were 3.742 and 0.018, respectively. The maximum transmission rate was 83 % at a bandwidth of 0.99 GHz for the transmission rate greater than 80 %. As it turned out, the composite with aramid fiber was superior in dielectric characteristics. Despite these and other high-quality studies, hardly anything is known about the dielectric properties and radio transparency of AEC, and more experimental research in this area is required.

The purpose of this work is a comparative study of radio transparency and dielectric permittivity (DP) of aramid epoxy-filled composite and fibreglass (FG) samples obtained by measuring in free space.

1 Materials and methods

For the manufacture of AEC and FG, ER of L grade was used as a binding substance (PoxySystems, Germany) with EPH hardening agent. The 3300 dtex aramid fabric has been used as reinforcing filler (Teijin, Netherlands) and Ortex 360 - 300 g/m^2 fibreglass (OOO Altair M, Russia). AEC and FG has been made by vacuum infusion method. The detailed description of the methodology is presented in our previous paper [19]. The dimensions of the AEC and FG have been designed specifically for measuring radio transparency in the approximate A3 format, which is shown in Figure 1.

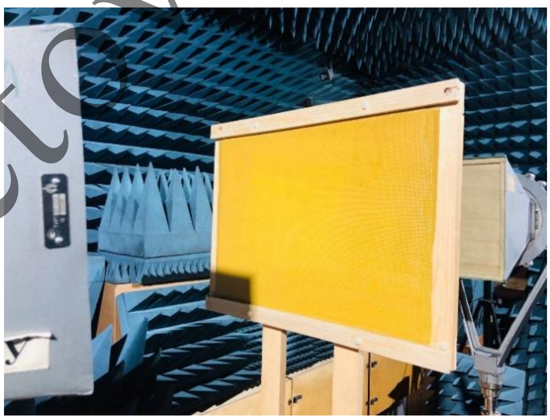

Fig.1. Sample of AEC with A3 size

The dielectric properties of AEC and FG samples were measured using measuring equipment of the SLLP “Institute of Space Engineering and Technology” (ISET) in an anechoic shielded chamber (ASC) by free-space measurements. The measurements of radio transparency of the material sample (electromagnetic wave transmission coefficient) have been performed by comparing the levels of electromagnetic radiation between the transmitting and receiving horn antennas in the presence of sample and without it according to Figure 2. The configuration of equipment used to measure the radio transparency of a material sample: N9010B Keysight spectral analyzer with measuring receiver of electromagnetic radiation, Signal Generator type waveform generator, P6-23M/2 horn antenna. The measurements were taken in the anechoic screened chamber.

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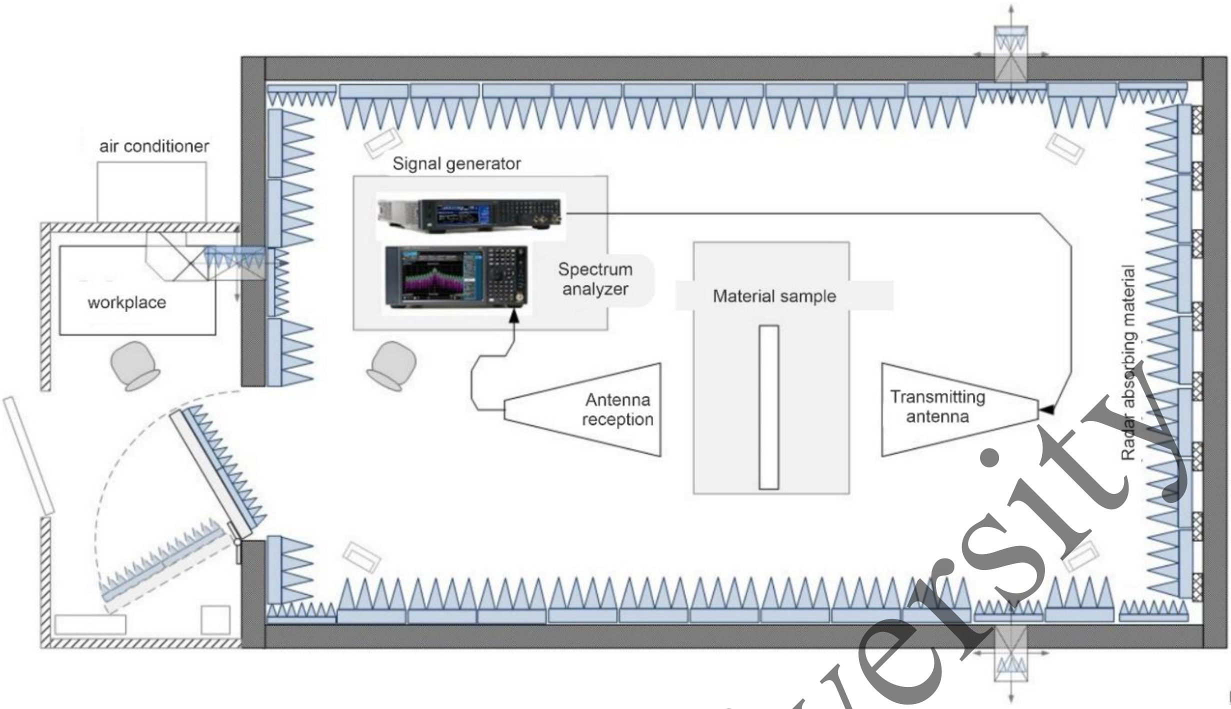

Fig.2. Diagram of measuring the material sample radio transparency in the ASC

The radio transparency is measured in the frequency band of measuring horn antenna and devices 1÷6 GHz. The measured material sample in the diagram has no contact with the antennas. A3 format sample area exceeds the aperture area of horn antenna by 20-25 %, which is in good agreement with measurement method, when the maximum electromagnetic energy in the antenna directivity diagram passes through the sample, rather than flowing between the antennas by passing the sample. When measured in the frequency range from 1 to 6 GHz, there was unevenness in the intrinsic transmission characteristic of the horn antennas in the range from 4.5 to 6 GHz approximately. In this respect, during measurements the whole range was divided into two sections: 1÷4 GHz and 4÷6 GHz, for a more accurate presentation of the results. For each section, measurements were taken three times.

2 Results and discussions

2.1 Results of materials radio transparency measurements

Figure 3 demonstrates one of the three measurements of the electromagnetic field attenuation of the AEC sample in the 1÷4 GHz band - trace 2 in blue, against the background of the antenna transmission coefficient in air (without sample) – trace 1 in yellow. 1, 3, and 5 markers correspond to yellow trace 1, and markers 2, 4, and 6 correspond to blue trace 2 with the pattern. The numerical values of frequencies and attenuations are given in the Marker Table at the bottom of the pictures (screenshot).

The comparison should be made by markers located at the same or close frequency: 1 and 2, 3 and 4, 5 and 6. For example, in Figure 2, marker 1 corresponds to the frequency f=1.230 GHz and attenuation 23.18 dB/mW, and marker 2 has a frequency of 1.240 GHz and attenuation – 23.53 dB/mW. The difference in attenuation due to losses in the material: 23.53 – 23.18 = 0.35 dB/mW. Therefore, electromagnetic energy loss in the AEC at this frequency was 0.35 dB/mW. For the other frequencies, the calculation was performed in the same way. According to the results of averaging of three measurements of AEC radio transparency, it was determined that in the 1÷4 GHz range the attenuation is ~ 0.201 dB. Table 1 demonstrates the results of calculations for determination of attenuation, followed by subtracting the average value.

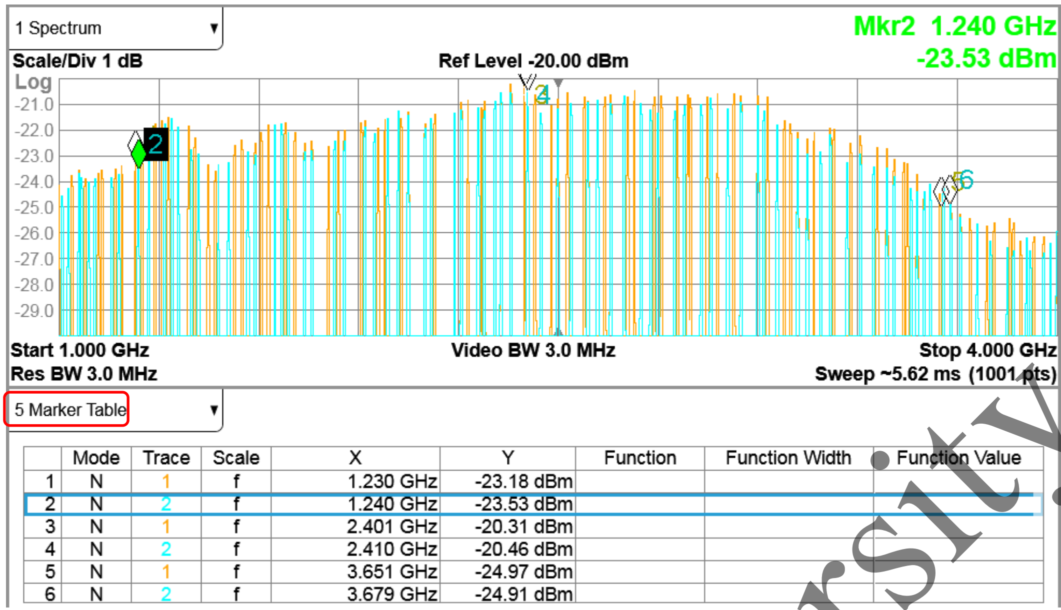

Fig.3. Measurement 1, field attenuation in the AEC

Table 1. Indicators of field attenuation in AEC in the 1÷4 GHz frequency range

Measurement	Blue marker frequency, dB/mW	Yellow marker frequency, dB/mW	Difference of attenuation, dB/mW	Averaging, dB/mW	Total loss of electromagnetic energy, dB/mW
1	23.53	23.18	0.35	0.147	0.21 (at 1÷4 GHz range frequency)
	20.46	20.31	0.15		
	24.91	24.97	-0.06		
2	23.47	23.18	0.29	0.103	
	20.40	20.31	0.09		
	24.90	24.97	-0.07		
3	23.49	23.18	0.31	0.353	
	21.12	20.31	0.81		
	24.91	24.97	-0.06		

The resulting average attenuation value of (minus) 0.21 dB can be converted to times using the decibel table [20]. Since decibels can be added (times - multiplied), then: 0.21 dB = 0.2 dB + 0.01 dB. According to the voltage, current, power conversion table, 0.2 dB corresponds to a power ratio of 0.955 (part of the power that has passed through the material), 0.01 dB corresponds to a power ratio of 0.9977. As a result 0.955 × 0.9977 = 0.9528 is that part of the power that has passed through the material (95.28 %). Therefore, capacity loss in the material in the 1÷4 GHz range is defined as follows: 100% - 95.28 % = 4.72 %.

Figure 4 below demonstrates one of the three measurements of the electromagnetic field attenuation of the AEC sample in the 4÷6 GHz range. Table 2 demonstrates the results of calculations for determination of attenuations, followed by subtracting the average value.

The capacity loss of 0.73 dB can be represented as 0.7 + 0.03 dB. Then 0.7 dB corresponds to power ratio of 0.8511 (part of the power that has passed through the material), 0.03 dB corresponds to a power ratio of 0.9931. As a result 0.8511 × 0.9931 = 0.8452 is that part of the power that went through the material is 84.52 %. Therefore, capacity loss in the material – 15.48 % in the 4÷6 GHz range.

Figure 5 below demonstrates one of the three measurements of the electromagnetic field attenuation of the FG (A3 format, H=1.5 mm). Table 3 demonstrates the results of calculations for determination of attenuations, followed by subtracting the average value of the FG sample.

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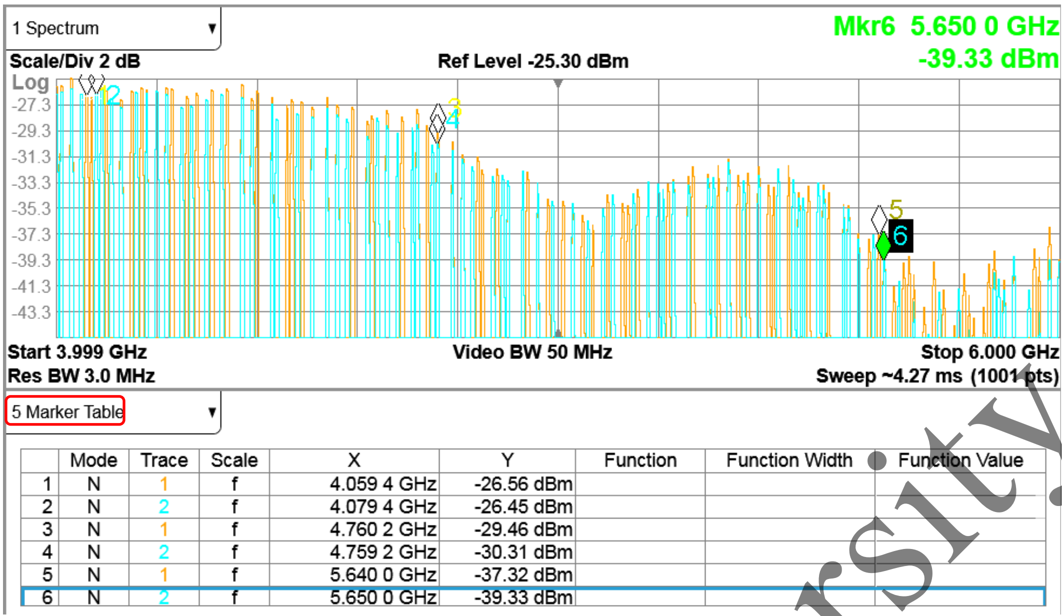

Fig.4. Measurement of 1 field attenuation in AEC in the 4÷6 GHz range

Table 2. Indicators of field attenuation in AEC in the 4÷6 GHz frequency range

Measurement	Blue marker frequency, dB/mW	Yellow marker frequency, dB/mW	Difference of attenuation, dB/mW	Averaging, dB/mW	Total loss of electromagnetic energy, dB/mW
1	26.45	26.56	-0.11	0.917	0.73 (at 4÷6 GHz range frequency)
	30.31	29.46	0.85		
	39.33	37.32	2.0		
2	26.74	26.56	0.18	0.36	
	29.81	29.46	0.09		
	37.87	37.32	0.55		
3	26.64	26.56	0.08	0.917	
	30.21	29.46	0.75		
	39.24	37.32	1.92		

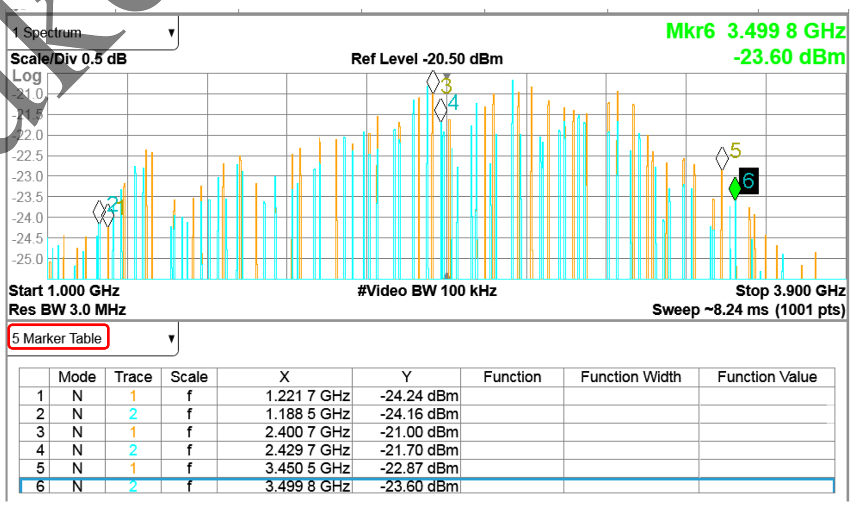

Fig.5. Measurement of 1 field attenuation in FG in the 1÷4 GHz frequency range

Table 3. Indicators of field attenuation in the FG in the 1÷4 GHz frequency range

Measurement	Difference of attenuation, dB/mW	Averaging, dB/mW	Total loss of electromagnetic energy, dB/mW
1	-0.08	0.45	0.173 (at a frequency range of 1÷4 GHz)
	0.70		
	-0.73		
2	0.01	0.25	
	0.13		
	0.65		
3	-0.24	-0.18	
	-0.70		
	0.40		

The average value of radio wave attenuation in FG in the 1÷4 GHz frequency band (+0.45+0.25-0.18)/3 = 0.173 dB. Therefore, in the FG capacity loss – 2.51 % in the 1÷4 GHz range. Figure 6 demonstrates a similar measurement only in the 4÷6 GHz range. Table 4 shows the results of calculations to determine the attenuations, followed by subtracting the mean value of the FG sample.

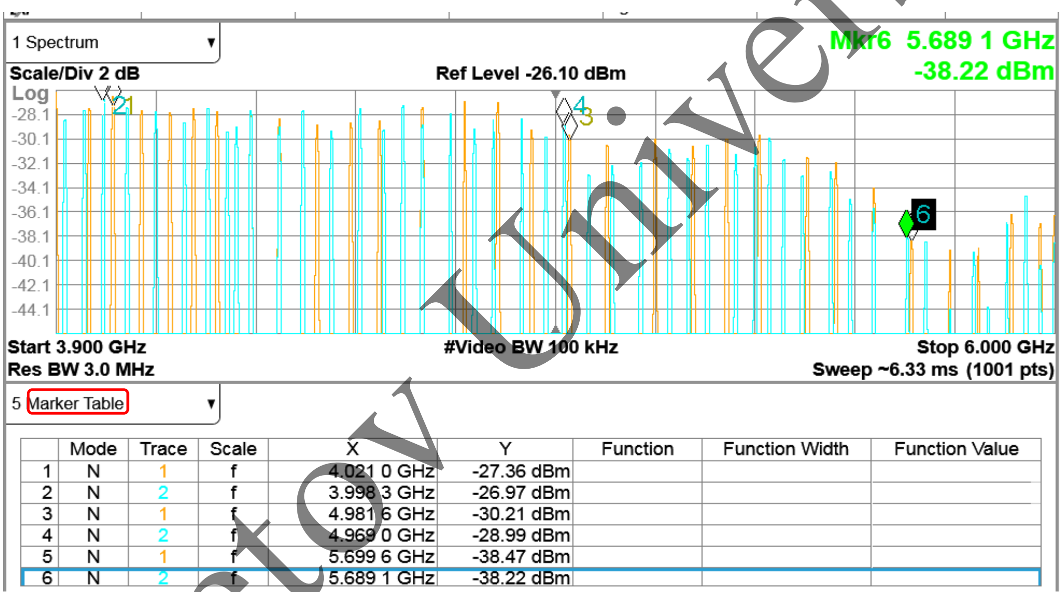

Fig.6. Measurement of 1 field attenuation in the 4÷6 GHz frequency band in FG

Table 4. Indicators of field attenuation in the FG in the 4÷6 GHz frequency range

Measurement	Difference of attenuation, dB/mW	Averaging, dB/mW	Total loss of electromagnetic energy, dB/mW
1	-0.39	-0.36	0.94 (at the range frequency 4÷6 GHz)
	-1.22		
	-0.25		
2	1.82	1.67	
	0.40		
	2.81		
3	0.87	1.53	
	1.23		
	-0.57		

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The average value of radio wave attenuation in FG in the frequency range 4÷6 GHz (-0.36 +1.67 +1.53)/3 = 0.94 dB. Therefore, in the FG capacity loss – 19.47 % in the 4÷6 GHz range.

Summarizing the above results of the analysis of radio transparency of AEC and FG, final comparative table 5 demonstrates the comparative data on the radio transparency of samples. As the Table shows, average values of electromagnetic wave attenuation in the 1÷6 GHz range for AEC and FG are very close. According to the averaged values, transmission coefficient for AEC was 89.9 % and for FG 89.01 %. A possible reason for the fact that the transparency of the AEC is higher than the FG may be the low DP of the AEC compared to the FG. Since it is known that the wave transmission characteristics of wave-transparent composites with a polymer matrix are usually estimated by DP [21-22]. In contrast to the AEC, FG is made of glass fiber, which has a higher dielectric constant than the polymers used in AEC. This means that FG absorbs more radio waves, which results in decrease of its radio transparency compared to the AEC. AEC sample was close to the FG - 0.17 dB at the beginning of the 1÷4 GHz section in attenuation values - 0.21 dB, and at the end of the section it was even better. Therefore, based on the results of radio transparency, it may be concluded that the losses in AEC are less than in the FG.

Table 5. Comparison of radio transparency of AEC and FG samples

Material	Deamplification, dB/% 1÷4 GHz	Deamplification, dB/% 4÷6 GHz	Averaging
AEC	0.210 dB / 4.72 %	0.73 dB / 15.48 %	0.47 dB / 10.1 %
FG	0.173 dB / 2.51 %	0.94 dB / 19.47 %	0.55 dB / 10.99 %

2.2 Measurements of dielectric permittivity of samples

The dielectric permittivity of the samples is measured using the condenser-type method since the dielectric permittivity of the insulator material affects the capacitance of low-profile capacitor.

For the mechanical clamp of AEC and FG sheet between the plates (electrodes) of the capacitor, a stand was made with D16 aluminum electrodes (170 × 138 mm) on the basis of precision milling machine vise with minimum microscrew backlash according to Fig. 7. The capacitor capacitance in the presence of organic plastic and without it is measured with APPA701 LCR-meter. In the stand the electrode insulators from the vise mechanism are made of caprolon material with a small intrinsic DP, to minimize the stray capacitance of the stand that affects the result. The dielectric permittivity was measured according to the methods set out in [23].

Fig.7. Mechanical clamp of the AEC sheet between the plates (electrodes) of the capacitor

Table 6 shows the results of three measurements of the AEC and FG sample. As shown by the results, AEC has average DP 2.874, whereas the FG - 4. The obtained results of the FG measurement coincide with the reference data given in [23-24]. Due to the lower DP of aramide fibre than the DP of fiberglass, AEC indicates a low value. One of the reasons for the difference in DP between the AEC and FG is its structure.

Table 6. Results of DP of the AEC and FG materials

Sample 1	C diel, pF	C	d_0, mm	ε	Averaged value ε
AEC	273	99.1	2	2.754	2.874
AEC	286	97.6	2	2.930	
AEC	289	98.3	2	2.939	
FG	600	150	1.5	4	4

FG consists of the fibreglass, which have a higher DP than the polymeric materials used in AEC. Furthermore, an important factor affecting the DP is the content of moisture and other impurities in the material. FG can be more sensitive to moisture than AEC, which can lead to an increase in its DP. However, it should be realized that DP depends on many factors and can vary over a wide range depending on the specific material and operating conditions.

Conclusion

In this work an aramid-epoxy-filled composite and fiberglass are produced by vacuum infusion method. The comparative studies of radio-transparency and dielectric permittivity of the listed composites have been performed. The radio transparency of the studied materials was evaluated by measuring in free space in the frequency ranges of 1-6 GHz. According to the results of radio transparency, it may be concluded that the losses in the aramid epoxy-filled composite are less than in the fiberglass due to the high dielectric permittivity of the latter with the previous one. According to the averaged values, the transmittance for the aramid epoxy-filled composite was 89.9 %, and for fibreglass it was 89.01 %. When measuring the dielectric permittivity, the aramid epoxy-filled composite has demonstrated a low average DP value of 2.874 due to the lower dielectric constant of the aramid fiber, whereas fibreglass is defined at 4. Our results suggest that the differences in the composition and structure of the aramid-epoxy-filled composite and fibreglass result in different physical properties, including its radio transparency.

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