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Original paper

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JUSTIFICATION OF BINDER MATERIAL SELECTION FOR CARBON PARTICLES INCORPORATION INTO FIBROUS ELECTROMAGNETIC RADIATION ABSORBER

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Abstract. The paper presents justification of a binder material for incorporating carbon particles into the inter-fiber space of electromagnetic radiation absorber. A method for carbon particles incorporation into a fibrous material has been developed. It is based on applying a carbon-containing nanocomposite to the fibrous material's surface. Previously, the research of carbon particles incorporation into a synthetic material by using an aqueous solution were carried out, which ensured a uniform distribution of carbon particles in the material structure. However, the properties of the material have changed significantly upon mechanical deformation. Therefore, the carbon particles incorporation process was investigated using various nanocomposites obtained on the basis of mixtures of vinyl acetate polymer, or epoxy polymer, or surface-active substance with carbon black. Based on the results of electron microscopic analysis and the reflection and transmission coefficients frequency dependences in the frequency range 0.7–17 GHz, the efficiency of using a nanocomposite based on a mixture of surface-active substance and carbon black to create electromagnetic radiation absorbers was justified. Such electromagnetic radiation absorbers have the transmission coefficient value about –18 dB and reflection coefficient value about –12 dB in the frequency range 7–13 GHz. Carbon-containing electromagnetic radiation absorbers based on fibrous material have thickness less than 3 mm, properties of flexibility and resistance to mechanical deformation. It can be used in various fields, in particular for hiding objects from radio frequency reconnaissance or protecting equipment from external interference.

Keywords: carbon black, electromagnetic radiation absorbers, nanocomposite, reflection coefficient, transmission coefficient.

Conflict of interests. The authors declare no conflict of interests.

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Foreword

To date, various binder materials are used to create absorbers and screens of electromagnetic radiation. It is known that paint and varnish materials are widely used to create composite coatings with the addition of powdered conductive materials [1, 2], characterized by low values of reflection coefficients (up to –15 dB) and transmission coefficients (up to –20 dB) in the frequency range of 8–12 GHz. At the same time, such composite coatings do not retain their electromagnetic radiation shielding properties during deformation.

There are also methods for creating electromagnetic radiation screens based on gypsum and concrete composite materials [3, 4], characterized by low transmission coefficients (up to –20 dB) and reflection coefficients (up to –15 dB) in the frequency range of 0.7–17 GHz. However, such materials have significant weight and size parameters and do not have the properties of elasticity and flexibility.

It is known that hydrophilic polymers are utilized to create composite materials [5, 6] with the transfer coefficients ranging from –20 to –40 dB in the 8–12 GHz frequency range. At the same time, such composite materials have not only the property of flexibility, but also resistance to variations in ambient temperature.

During the research work of the State Scientific Inspection program for 2016–2020 "Photonics, Optoelectronics and microelectronics", the task was set to select the optimal binder for fixing carbon particles in the fibrous structure of the electromagnetic radiation absorber. Thus, we studied the properties of several samples of electromagnetic radiation absorbers made using various binders that differ in the properties of adhesion, density, strength, elasticity and flexibility, and resistance to mechanical deformation.

Earlier [7], studies were conducted on the use of water-based and adhesive composites (solutions of sodium silicates or polyvinyl acetate emulsions) for incorporation of carbon particles into foamed and fibrous materials. The reflection coefficient of such materials is –14 dB, the transmission coefficient varies up to –20 dB in the frequency range of 8–12 GHz. The use of an aqueous solution to incorporate carbon particles does not solve the problem of their fixation in the structure of the material, but the particles penetrate deep into the material and are distributed throughout its volume. The use of a solution of sodium silicates helps to fix the particles only on the surface of the material. Based on these results, it was decided to create nanocomposites based on a vinyl acetate polymer, an epoxy polymer, and a solution of surfactants with the addition of carbon black.

A fibrous material consisting of chaotic polyester fibers (70 %) and polypropylene fibers (20 %) was selected as an electromagnetic radiation absorber material for incorporating carbon particles. It should be noted that this material has the properties of density (from 100 to 1000 g/m^2), strength, flexibility, elasticity, shape stability, heat and noise insulation. The thickness of the fibrous material is not more than 2 mm.

The choice of carbon black for incorporation into the fiber structure of the electromagnetic radiation absorber is due to its physical and chemical properties: dispersion, highly developed surface (5–150 m^2/g), particle density (1.76–1.9 g/cm^3), low transmission coefficient (up to –40 dB in the frequency range of 8–12 GHz), carbon Black is a collection of spheroidal particles (the primary structure of carbon black), the coalescence of which leads to the formation of a secondary structure (Fig. 1, *a*), called the aggregates, up to 90 nm [8]. Also, in the structure of carbon black, a tertiary structure, agglomerates, is isolated, resulting from the physical connections of a set of aggregates (Fig. 1, *b*). Thus, carbon black is characterized by a disoriented particle structure, surface organophilicity, nanoscale primary and secondary structures (from 10 nm), and a variety of particle distribution forms (spheroidal, branched, linear, ellipsoidal).

a

b

Fig. 1. Carbon black structural units: *a* – aggregate; *b* – agglomerate

Routine of experiment

For the production of samples of electromagnetic radiation absorbers, a method was developed for fixing allotropic carbon particles in a fibrous material, which includes the following steps.

1. Preparation of a carbon-containing nanocomposite: mixing a binder composite (vinyl acetate polymer, epoxy polymer, and surfactant) and carbon black powder in a ratio of 1: 0.5.
2. Cutting the fibrous material into fragments of the required size and shape.
3. Application of a carbon-containing nanocomposite to the surface of a fragment of a fibrous material.
4. Retention of fibrous material fragments for 24 hours under standard conditions.

In accordance with the developed method, the following samples of electromagnetic radiation absorbers were obtained:

– synthetic fibrous non-woven material with a nanocomposite based on a mixture of vinyl acetate polymer and carbon black (sample No. 1);

– synthetic fibrous non-woven material with a nanocomposite based on a mixture of epoxy polymer and carbon black (sample No. 2);

– synthetic fiber non-woven, on the surface of which a nanocomposite based on a mixture of surfactant and carbon black is applied (sample No. 3);

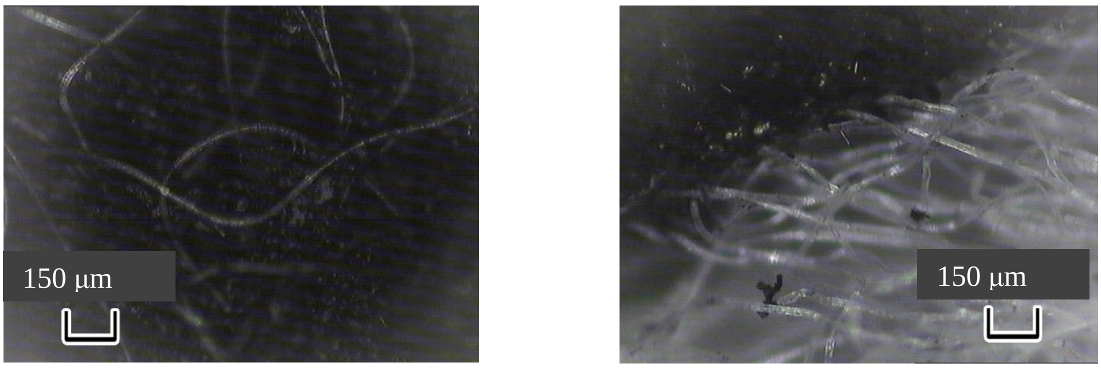
– synthetic fibrous non-woven material with a nanocomposite based on distilled water and carbon black (sample No. 4).

To determine the level of penetration of carbon particles into the internal structure of the fibrous material, an electron microscopic analysis was performed using a non-contact video measuring microscope Norgau NVM-2010, equipped with a color camera CCD 1/2'. The Norgau NVM-2010 video measuring microscope has extensive capabilities in measuring linear-angular values of surfaces of various materials and processing the measured data with an error of $\pm(3.0+L / 200)$ microns, where L is the measured length, mm, and magnification of the optical system from 0.7 to 4.5 times.

Studies of the shielding properties of the obtained samples of electromagnetic radiation absorbers were based on measuring the transmission coefficients (S_{21}) and reflection coefficients (S_{11}) of electromagnetic radiation in the range of 0.7–17 GHz, for which a panoramic transmission and reflection coefficient meter SNA 0.01–18 was used [9]. The reflection coefficient was measured in two modes: matched load (S_{11}) and short-circuit (S_{11ME}), i. e. a metal reflector was located behind the test sample. The choice of this range is due to its use for information exchange in mobile communication systems, between radar stations and computer equipment, etc.

Results and discussion

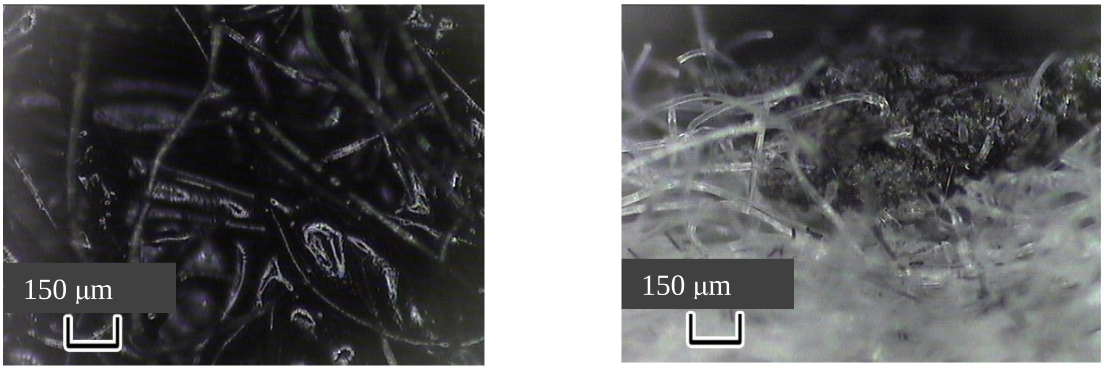
Based on the results of microscopic analysis of the surface and cross-section of the obtained samples of electromagnetic radiation absorbers, it was found that carbon black particles do not penetrate deep into the material of sample No. 1, on the surface of which a nanocomposite based on a mixture of vinyl acetate polymer and carbon black was deposited (Fig. 2, *a*). A layer of carbon-containing nanocomposite 500 microns thick is fixed on the surface of the fibrous material of sample No. 1 (Fig. 2, *b*).



a *b*

Fig. 2. Micrograph of sample No. 1: *a* – surface; *b* – cross section

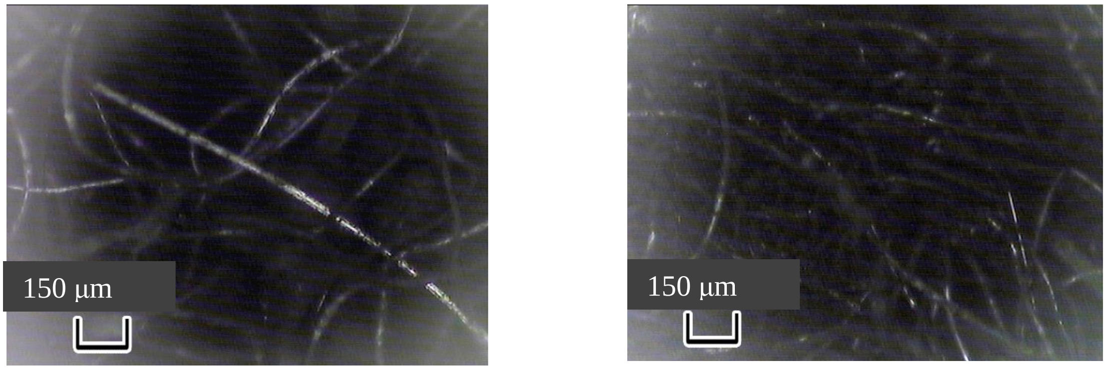
The thickness of the layer of carbon-containing nanocomposite from a mixture of epoxy polymer and carbon black deposited on the surface of sample No. 2 is 300 microns. Fig. 3, *b* shows that the boundary between the carbon-containing nanocomposite layer and the fibrous material is clear, which indicates that carbon particles do not penetrate into the depth of the material.



a *b*

Fig. 3. Micrograph of sample No. 2: *a* – surface; *b* – cross section

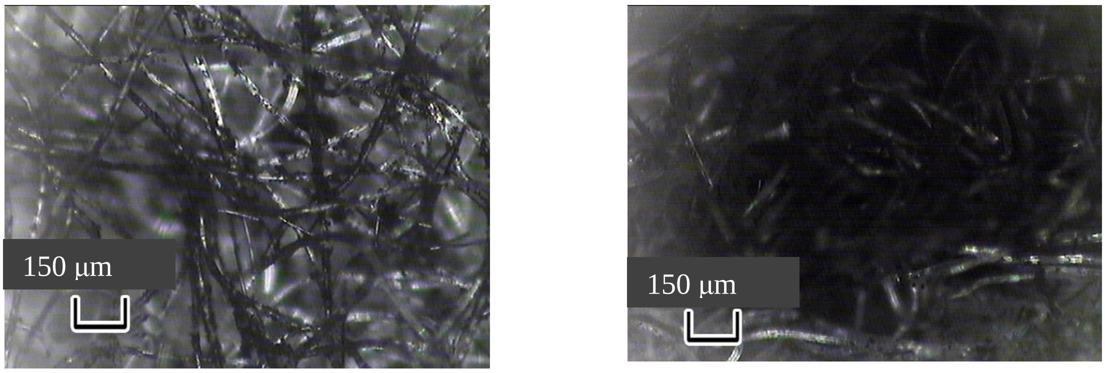
Fig. 4, *a*, *b* show that the mixture of surfactant and carbon black deposited on the surface of sample No. 3 contributed to the uniform distribution of carbon particles over the entire thickness of the sample, as well as their fixation on the material fibers and in the inter-fiber space.



a *b*

Fig. 4. Micrograph of sample No. 3: *a* – surface; *b* – cross section

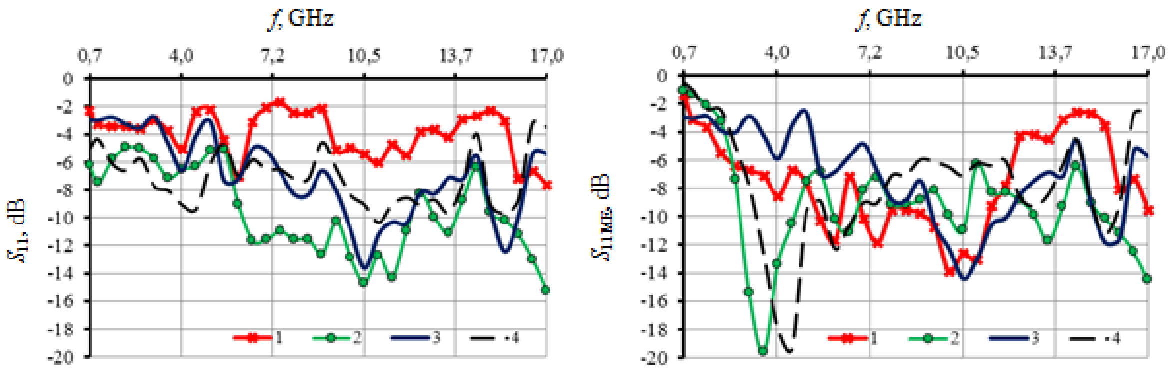
As already mentioned in [8], an aqueous carbon-containing solution contributes to the uniform distribution of carbon particles in the structure of the material. In this work, to compare the efficiency of penetration of carbon particles deep into the material, sample No. 4 was also made, on the surface of which a nanocomposite based on distilled water and carbon black was applied. Fig. 5 makes it clear that carbon particles actually penetrate deep into the material. With that, it should be noted that their distribution in the structure of the material is similar to the distribution of particles in the structure of sample No. 3.



a *b*

Fig. 5. Micrograph of sample No. 4: *a* – surface; *b* – cross section

The results of the analysis of frequency dependences of the reflection coefficients of manufactured samples obtained during measurements in the modes of matched load and short circuit (Fig. 6) show that the values of the reflection coefficients for sample No. 3 do not differ significantly when measured in the two modes and are –2.6 ... –14.4 dB in the frequency range of 0.7–17 GHz. The frequency dependences of the reflection coefficients of sample No. 3 confirm the results of electron microscopic analysis, since the uniform distribution of carbon particles throughout the structure of the fibrous material reduces the power of the electromagnetic wave due to its repeated re-reflection in the inter-fiber space and absorption when interacting with each fiber with carbon particles fixed on their surface. The transmission coefficient of sample No. 3 is –2.9 ... –19.9 dB and is minimal in comparison with the values of the transmission coefficients of other samples, which also confirms the above assumptions and proves the effectiveness of sample No. 3 for shielding electromagnetic radiation in the frequency ranges of 0.7–17 GHz (Fig. 7).



a *b*

Fig. 6. Reflection coefficients frequency dependences of samples, obtained by measurements in modes matched load (*a*); short circuit (*b*)

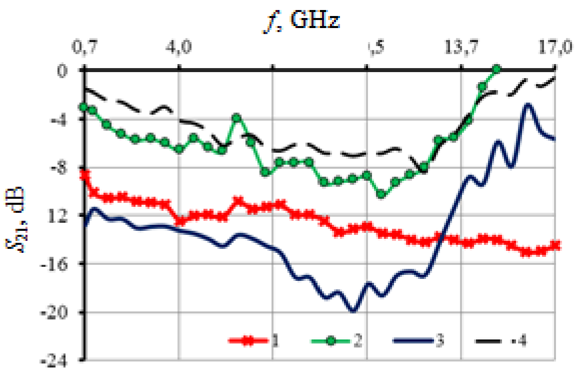


Fig. 7. Transmission coefficients frequency dependences of samples

Conclusion

The presented results of the study of the internal structure of samples of electromagnetic radiation absorbers with incorporated carbon particles and the frequency dependences of the reflection and transmission coefficients in the frequency range of 0.7–17 GHz show that an effective binder material for creating such absorbers is a nanocomposite based on a mixture of surfactant and carbon black. Electromagnetic radiation absorbers based on synthetic fiber material, on the surface of which a nanocomposite based on a mixture of surfactant and carbon black is deposited, are characterized by a uniform distribution of carbon particles in the fiber base, which provides a transmission coefficient of the order of –18 dB and a reflection coefficient of –12 dB in the frequency range of 7–13 GHz. Such electromagnetic radiation absorbers can be used to shield radar equipment from external interference or hide objects from radar reconnaissance. It should also be noted that these absorbers also have insignificant weight and dimensions, possess flexibility properties and are resistant to mechanical deformation.

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Authors' contribution

Belousova E.S. identified the purpose and objectives to be solved during the research, developed a method to produce the samples of absorbers, took part in the experiments, and in interpretation of the results.

Dumchev B.I. produced the samples of electromagnetic radiation absorbers, took part in the experiments and interpretation of the results, carried out a comparative analysis of the reflection and transmission coefficients frequency characteristics.

Al-Mahdawi M.S.Kh. produced the samples of electromagnetic radiation absorbers, took part in the experiments and interpretation of the results.

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