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FLEXIBLE DOUBLE-LAYERED MICROWAVE ABSORBERS BASED ON FOILED MATERIALS WITH MECHANICALLY TREATED SURFACE

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Abstract. The article presents the results of experimental substantiation of new technology for the manufacture of flexible double-layered microwave absorbers. This technology is based on the mechanical micromachining of electrically conductive sheet materials surfaces (in particular, foil polymer materials). In the course of experimental substantiation of the technology, regularities of changes in the of electromagnetic radiation absorption characteristics in the frequency range 2.0–17.0 GHz of foiled materials fixed on metal substrates, depending on the average size of their surface irregularities, were obtained. Based on the obtained regularities, the following features was established: 1) electromagnetic radiation absorption coefficient values in the frequency range 2.0–17.0 GHz of the studied materials reach 0.95; 2) the boundaries and width of the effective absorption band of the studied materials depend on the average size of the irregularities formed on their surfaces. The substantiated new technology is described in the article. Microwave absorbers, manufactured in accordance with this technology, seem promising for providing electromagnetic compatibility of radioelectronic equipment.

Keywords: *foiled polymer material, micromachining, microwave absorber, surface irregularity.*

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1. Introduction

Modern materials, providing the absorption of electromagnetic radiation in the microwave range, as a rule, are characterized by a layered structure (Gao *et al.*, 2021; Marra *et al.*, 2018; El-Hakim & Mahmoud, 2019; Pozdnyakova *et al.*, 2021; Wu *et al.*, 2019). Electromagnetic radiation absorption is provided by such materials due to the following phenomena:

1) multiple re-reflection of electromagnetic radiation at the interfaces between layers of materials (Fionov *et al.*, 2022; Pimenov & Rudenko, 1995);

2) ohmic, magnetic and/or dielectric energy losses of electromagnetic radiation propagating inside of the materials layers (Bychanok *et al.*, 2016; Qin *et al.*, 2013; Chen *et al.*, 2013; Pang *et al.*, 2021);

3) multiple scattering of electromagnetic radiation on the surface irregularities of the materials outer layers (Soltanmoradi *et al.*, 2016; Zhao *et al.*, 2022).

It follows from the presented list of phenomena, that in order to increase the electromagnetic radiation absorption coefficient values of materials, one or more of the following approaches should be implemented:

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1) to increase in the number of layers included in the materials structure;

2) to increase in the specific electrical conductivity and / or relative dielectric and magnetic permeability of the inner layers included in the materials structure (to increase in the values of the listed parameters of the outer layers included in the materials structure doesn't seem rational, since this increases the value of their electromagnetic radiation reflection coefficient due to increase in the wave resistance of the materials surfaces (Sahoo *et al.*, 2023);

3) the formation of irregularities on the materials surfaces, the size of which is comparable to the length of electromagnetic waves in the microwave range.

In works Bychanok et al. (2016); Soltanmoradi et al. (2016); Sahoo et al. (2023); Xie et al. (2021) it is shown that the third of the presented approaches is more efficient than the first and the second ones. In particular, it was shown in Bychanok et al. (2016) that by forming irregularities on the outer surfaces of electrically conductive materials, the dimensions of which are comparable to the length of electromagnetic waves in the microwave range, it is possible to increase, on average, by 50.0% the electromagnetic radiation absorption coefficient values of such materials.

In Grinchik (2014); Potapov (2018); Aliseyko *et al.* (2020), it is theoretically substantiated that the phenomenon of multiple scattering of electromagnetic radiation in the microwave range is observed when such radiation interacts not only with materials whose surface irregularities size is comparable to the length of electromagnetic waves in the indicated frequency range, but also with materials whose surface irregularities size is much less than the length of such waves. The aim of the study, the results of which are presented in this paper, was to confirm the experimental results of studies presented in Grinchik, (2014); Potapov, (2018); Aliseyko *et al.* (2020), and at the same time to substantiate by the experimental way new technology for the manufacture of microwave absorbers, based on mechanical micromachining of the surfaces of electrically conductive sheets materials (in particular, foiled polymer materials).

To achieve this aim, the following tasks were set:

1) the method for manufacturing the experimental samples in the form of electrically conductive sheet materials, the surfaces of which are characterized by the presence of irregularities of a certain micron size, was developed, and in accordance with the developed method, the experimental samples were manufactured;

2) electromagnetic radiation reflection and transmission coefficients values (S_{11} and S_{21}, respectively) of the manufactured experimental samples were measured in the microwave range;

3) based on the performed measurements results, electromagnetic radiation absorption coefficient values in the microwave range of the manufactured experimental samples were calculated;

4) the regularities of changes in the characteristics of electromagnetic radiation absorption coefficient values in the microwave range of the manufactured experimental samples were established depending on the value of the average size of the surface irregularities of these samples;

5) comparative analysis of electromagnetic radiation absorption characteristics in the microwave range of the manufactured experimental samples and electromagnetic radiation absorption characteristics of absorbers based on electrically conductive materials was carried out.

The choice of foiled polymer materials as an object of study is due to its following advantages compared to foil and other electrically conductive sheet materials:

– increased mechanical strength;
– low cost;
– elasticity.

The listed advantages can be typical for microwave absorbers, manufactured on the base of foiled polymer materials.

2. Materials and Methods

Based on the results of solving the first of the tasks set to achieve the aim of the study, the method for the manufacturing experimental samples was developed. This method includes the following stages.

Stage 1. Cut the roll of foiled polymer material into fragments, the length and width of which is not less than the length and width of the antenna aperture, which is part of the apparatus, planned for use in order to measure of S_{11} and S_{21} values. The number of fragments should be equivalent to the number of similar experimental samples to be obtained.

Stage 2. Mechanical micromachining of one of the surfaces of each of the fragments obtained as a result of the stage 1 implementation, using abrasive paper, characterized by a certain grain size.

The experimental samples were manufactured in accordance with the developed method. Fig. 1 presents self-explanatory schematic of the experimental samples manufacturing.

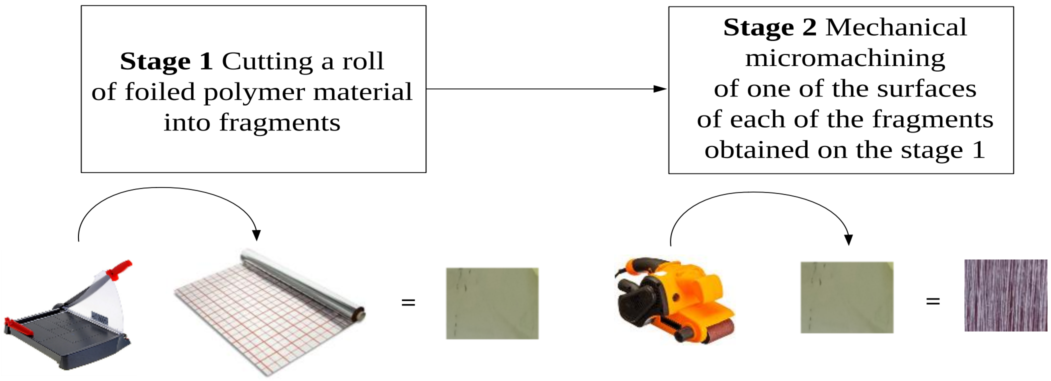


Fig. 1. Self-explanatory schematic of the experimental samples manufacturing

Three types of the experimental samples were manufactured. The experimental samples of each type differed in the average size of the irregularities formed on their surfaces. Table 1 presents the characteristics, as well as images of surface fragments of the manufactured experimental samples of each type.

10 experimental samples of each type were manufactured. The average value of the size of the surface irregularities of the experimental samples of each type (s_{av}) was determined as follows.

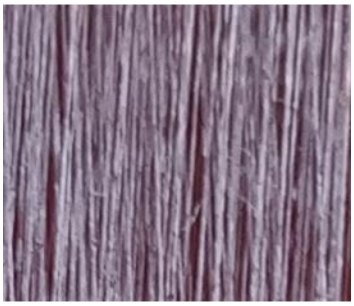
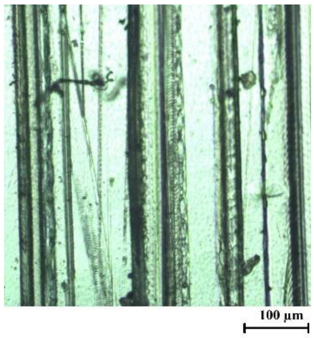
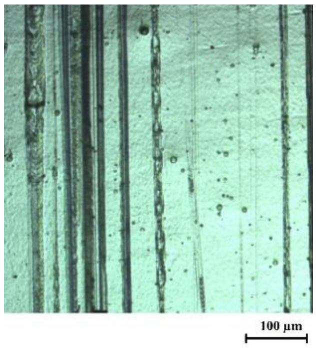
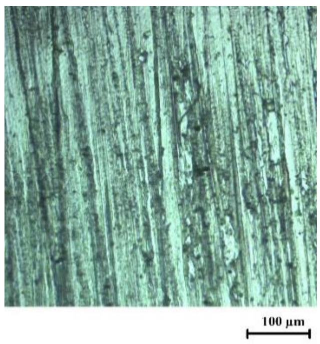
1. Measurement of the irregularities size at 100 points on the surface of each of the samples using a FOM-2-16 photoelectric ocular micrometer and an optical microscope of a metallographic aggregate METAM-R1 (the points of the surface at which the measurements of the irregularities were measured were located with the same step).

2. Calculation s_{av} according to the following formula:

$$s_{av} = \frac{\sum_{j=1}^{10} \frac{\sum_{i=1}^{100} s_{ij}}{100}}{10}, \ \mu\text{m},$$

where s_{ij} is irregularity size at a certain point on the surface of the sample of the certain type; i is order number of the sample surface point, in which the measurement of the surface irregularity size is carried out, $i \in [1; 100], i \in Z$; j is order number of the sample of the certain type, $j \in [1; 100], j \in Z$.

Table 1. Characteristics and images of surface fragments of the manufactured experimental samples

Name of the experimental sample	Average size of sample surface irregularity, µm	Zoom photo of 1×1 cm^2 fragment of the sample surface	Micrograph of the sample surface fragment (×100)
Sample of the type 1	80,0		
Sample of the type 2	50,0		
Sample of the type 3	20,0		

Measurements of S_{11} and S_{21} values in the microwave range of the manufactured experimental samples were made in the course of solving the second of the tasks set to achieve the aim of the study. The apparatus including the following devices was used to perform the measurements:

– panoramic meter of electromagnetic radiation reflection and transmission coefficients SNA 0.01–18;

– two horn-type broadband measuring antennas P6-23M.

The used panoramic meter includes the following devices:

– personal computer including sweeping frequency generator and a measurement signal processing unit;

– signal detectors;

– waveguides.

Measurements of S_{11} and S_{21} values were performed in the frequency range of 2.0–17.0 GHz, since the operating frequencies of most modern devices used to transmit signals over wireless lines belong to the specified range (Anand & Pauline, 2020).

The process of measuring of S_{11} values in the frequency range 2.0–17.0 GHz of the experimental samples of the certain type included the following stages.

Stage 1. Selecting the first experimental sample of the certain type as the measurement object.

Stage 2. Calibration of the apparatus, when metal sheet is located close to the transmitting measuring antenna (metal sheet acts as a short circuit in this case).

Stage 3. Location of the measurement object between the transmitting measuring antenna and the metal sheet.

Stage 4. Registration of the values of S_{11kj} (f) function (k = 1; j = 1), where k is the order number of the measurement, f is electromagnetic radiation frequency.

Stage 5. Repeat of the stages 1–4 until the value of the order number of the measurement reaches the value 5.

Stage 6. Selection another experimental sample of the same type as the experimental sample selected at stage 1 as the measurement object.

Stage 7. Repeat of the stages 2–5.

Stage 8. Selection as the measurement object the another experimental sample of the same type as the experimental samples selected in stages 1 and 6.

Stage 9. Repeat of the stage 7.

Stage 10. Repeat of the stages 8 and 9 until S_{11} values of all ten samples of the certain type have been measured.

Stage 11. Calculation the average values of S_{11kj} (f) function (S_{11av} (f)) according to the following formula:

$$S_{11av}(f) = \frac{\sum_{j=1}^{10} \frac{\sum_{k=1}^{5} S_{11kj}(f)}{5}}{10}, \text{ dB.}$$

The process of measuring of S_{21} values in the frequency range 2.0–17.0 GHz of the experimental samples of the certain type included the following stages.

Stage 1. Selecting the first experimental sample of a certain type as the measurement object. Fixing the selected sample on a metal substrate.

Stage 2. Calibration of the apparatus, when the transmitting and receiving measuring antennas are located closely.

Stage 3. Location of the measurement object between the transmitting and receiving measuring antennas.

Stage 4. Registration of the values of $S_{21mj}(f)$ function ($m = 1$; $j = 1$), where m is the order number of the measurement.

Stage 5. Repeat of the stages 1–4 until the value of the order number of the measurement reaches the value 5.

Stage 6. Selection as the measurement object the another experimental sample of the same type as the experimental sample selected at stage 1. Fixing the selected sample on a metal substrate.

Stage 7. Repeat of the stages 2–5.

Stage 8. Selection as the measurements object the another experimental sample of the same type as the experimental samples selected in stages 1 and 6. Fixing the selected sample on a metal substrate.

Stage 9. Repeat of the stage 7.

Stage 10. Repeat of the stages 8 and 9 until S_{11} values of all ten samples of the certain type have been measured.

Stage 11. Calculation the average values of the function $S_{11mj}(f)$ ($S_{21av}(f)$) according to the following formula:

$$S_{21av}(f) = \frac{\sum_{j=1}^{10} \frac{\sum_{m=1}^{5} S_{11mj}(f)}{5}}{10}, \text{ dB.}$$

In the course of solving the third of the tasks set to achieve the aim of the study, the average values of electromagnetic radiation absorption coefficient ($A_{av}(f)$) of the experimental samples were calculated. The following formulas were used for the calculation (Geetha *et al.*, 2009):

$$R_{av}(f) = 10^{\frac{S_{11av(f)}}{10}}, \text{ relative units},$$

$$T_{av}(f) = 10^{\frac{S_{21av}(f)}{10}}, \text{ relative units},$$

$$A_{av}(f) = R_{av}(f) – T_{av}(f), \text{ relative units},$$

where $R_{av}(f)$ and $T_{av}(f)$ are respectively, the average values of electromagnetic radiation reflection and transmission coefficients.

3. Results and their discussion

Based on the results of the performed calculations, the frequency dependences of the average value of electromagnetic radiation absorption coefficient of the experimental samples of every type were plotted. These dependencies are shown in Fig. 2. They were used to solve the fourth of the tasks set to achieve the aim of the study.

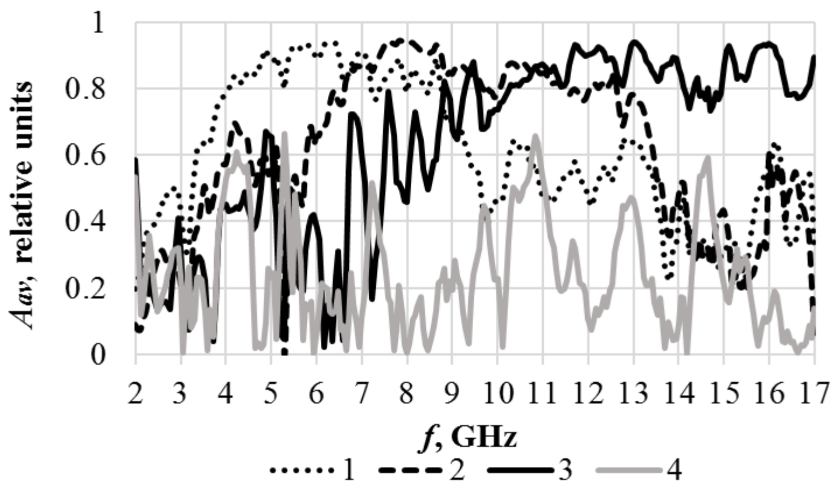


Fig. 2. Frequency dependences of the average value of electromagnetic radiation absorption coefficient in the range of 2.0–17.0 GHz of the samples of types 1, 2 and 3 fixed on metal substrates (curves 1, 2 and 3, respectively) and a fragment of foiled polymer material, used for these samples manufacturing and fixed on the metal substrate (curve 4)

As it seen from Fig. 2, as a result of the formation of 80.0 μm irregularities on the surface of the foiled polymer material, it is possible to increase from 0.01–0.65 to 0.3–0.95 the electromagnetic radiation absorption coefficient values of such material in the frequency range 2.0–17.0 GHz (when such material is fixed on a metal substrate). As a result of the formation of 50.0 μm and 20.0 μm irregularities on the surface of the specified material, it is possible to increase from 0.01–0.65 to 0.1–0.95 and 0.02–0.95 respectively the electromagnetic radiation absorption coefficient values in the frequency range 2.0–17.0 GHz of such material (when such material is fixed on a metal substrate). Thus, as a result of the formation of micron-sized irregularities on the surface of the foiled polymer material, it is possible to increase by 2.0–30.0 times the minimum value of electromagnetic radiation absorption coefficient in the frequency range of 2.0–17.0 GHz. At the same time, it's possible to increase by 1.5 times the maximum value the electromagnetic radiation absorption coefficient in the frequency range 2.0–17.0 GHz. Such an increase is due to the scattering of electromagnetic radiation interacting with the indicated material on the protrusions of its surface irregularities (Grinchik, 2014; Potapov, 2018; Aliseyko *et al.*, 2020).

The studied experimental samples fixed on metal substrates provide the electromagnetic radiation absorption due to the following mechanisms, observed when this radiation interacts with them:

– multiple reflection of electromagnetic wave in the air gap between the sample and metal substrate, on which the sample is fixed;

– scattering of electromagnetic wave, passed through the experimental sample, on its surface irregularities.

The explained mechanisms are presented in Figure 3. Other mechanisms, observed when electromagnetic radiation interacts with the studied experimental samples fixed on metal substrates are also presented in the Figure.

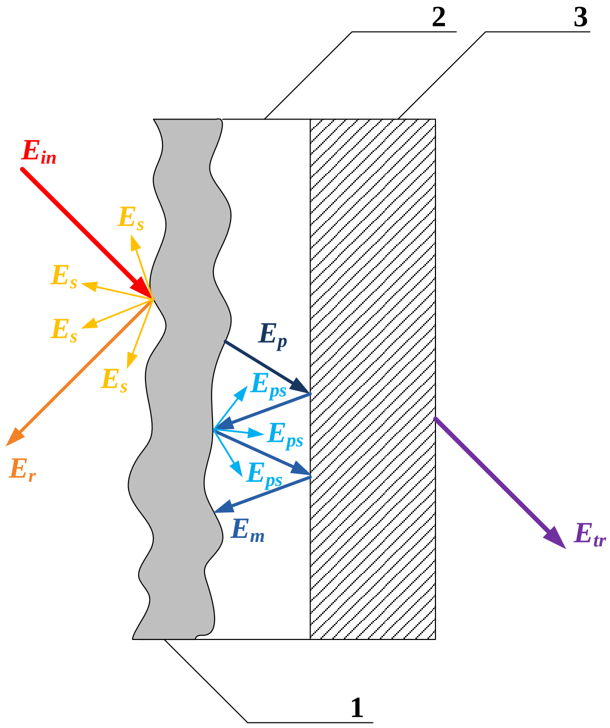


Fig. 3 Schematic illustration of mechanisms of electromagnetic radiation interaction with studied experimental samples

The following designations are used in Fig. 3: 1 – schematic illustration of the experimental sample; 2 – schematic illustration of the air gap between the experimental sample and metal substrate, on which the sample is fixed; 3 – schematic illustration of the metal substrate, on which the experimental sample is fixed; E_{in} – incident electromagnetic wave; E_r – reflected electromagnetic wave; E_s – electromagnetic wave scattered on the irregularities of outer surface of the experimental sample; E_p – electromagnetic wave, passed through the experimental sample; E_{ps} – electromagnetic wave, passed through the experimental sample and scattered on the irregularities of its inner surface; E_m – electromagnetic wave multiple reflected from the metal substrate surface and inner surface of the experimental sample; E_{tr} – electromagnetic wave transferred through the metal substrate.

Table 2 presents the characteristics of the effective absorption bands of the studied experimental samples fixed on metal substrates. This table also presents the characteristics of the effective absorption bands of a fragment of the foiled polymer material, used for these samples manufacturing and fixed on the metal substrate. Effective absorption bands correspond to the frequency range (frequency ranges), where the value of electromagnetic radiation absorption coefficient exceeds 0.5 (Hwang *et al.*, 2022).

Table 2 shows that samples of types 1, 2, and 3 fixed on metal substrates are broadband microwave absorbers, since the width of their effective absorption band is comparable to the value of the center frequency of this band (more than 65.0% of this band center frequency value). A fragment of the foiled polymer material fixed on the metal substrate is essentially a narrow-band microwave absorber. It’s because the width of its effective absorption bands is much less than these bands central frequency values (less than 11.0% of these bands center frequency value).

Table 2. Characteristics of the effective absorption bands of the studied samples

Experimental sample name	Effective absorption band, GHz	The value of the center frequency of the effective absorption band, GHz	Effective absorption band width, GHz
Sample of type 1 fixed on a metal substrate	3.5–9.5	6.5	6.0
Sample of type 2 fixed on a metal substrate	5.5–13.5	9.5	8.0
Sample of type 3 fixed on a metal substrate	8.0–17.0	13.5	9.0
Fragment of the foiled polymer material fixed on a metal substrate	4.0–4.5; 10.5–11.0; 14.2–15.0	4.25; 10.75; 14.6	0.5; 0.5; 0.8

It can also be seen from Table 2 that if the average size of the surface irregularities of the foiled polymer material decreases from 80.0 to 50.0 μm or to 20.0 μm, then the boundary values of the effective absorption band of such material fixed on a metal substrate, and the width of this band increase. An increase in the width of the effective absorption band with a decrease in the size of surface irregularities is due to the combination of the following features:

1) the pitch of irregularities with a size of 80.0 μm is smaller than the pitch of irregularities with a size of 50.0 or 20.0 μm, i.e., irregularities with an average size of 80.0 μm are less densely distributed over the surface of the foiled polymer material than irregularities with an average size 50.0 or 20.0 μm (see micrographs of surface of manufactured samples fragments, presented in Table 1);

2) the largest value of the amplitude of electromagnetic radiation in the microwave range, reflected from the material, the surface of which is characterized by the presence of irregularities, is recorded in the depressions of such a surface, and if the width of these depressions is greater, then the amplitude of such radiation is also greater (the indicated feature is established by the simulation results presented in the work (Aliseyko *et al*., 2020)).

Based on the above features, it can be concluded that the surface of the sample of type 1 reflects electromagnetic radiation interacting with it to a greater extent in the frequency range of 2.0–17.0 GHz than samples of types 2 and 3. Due to this fact the effective absorption band width of this sample smaller then effective absorption band width of the samples of types 2 and 3.

Based on the results of solving the fifth of the tasks set to achieve the aim of the study, it was found that the width of the effective absorption band in the frequency range of 2.0–17.0 GHz of the studied samples exceeds by 2.0–4.0 times the value of a similar parameter, typical for absorbers of electromagnetic radiation based on anodized foil, considered in (Boiprav *et al*., 2018). Electromagnetic radiation absorption coefficient value of the studied samples is comparable with electromagnetic radiation absorption coefficient value of microwave absorbers considered in (Bychanok *et al.*, 2016).

4. Conclusion

Based on the presented results of solving of five tasks, we can conclude that the aim of the study has been achieved. In privacy:

– the results of the theoretical justification presented in (Grinchik, 2014; Potapov, 2018; Aliseyko *et al.*, 2020) have been experimentally confirmed;

– experimental justification of new technology for manufacturing microwave absorbers has been carried out.

New technology should include the following stages.

Stage 1. Formation of the absorber outer (relative to the electromagnetic radiation propagation front) layer by successive implementation of the following actions.

1.1. Cutting a roll of foiled polymer material into fragments, taking into account the following requirements:

– the length and width of the fragments are equal to the length and width of manufactured absorbers;

– the number of fragments is equal to the number of absorbers to be manufactured.

1.2. Mechanical micromachining of one of the surfaces of each of the fragments obtained as a result of the implementation of stage 1.1, using abrasive paper, the grain size of which depends on the requirements for the size of the irregularities of these surfaces and, as a result, for the characteristics of the effective absorption band of manufactured absorbers.

Stage 2. Formation of the absorber inner (relative to the electromagnetic radiation propagation front) layer, by repeating action 1.1.

Stage 3. Adhesive pairing of the formed outer and inner layers in such way that the outer layer is oriented outward by the surface that has undergone mechanical micromachining during the implementation of action 1.2.

Microwave absorbers, manufactured in accordance with this technology, seem promising for providing electromagnetic compatibility of radio electronic equipment (in privacy, equipment units of the nanosatellites based on radio frequency communication, considered in the paper (Hasanov & Atayev, 2022)).

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