Bulgarian Society for NDT
International Journal "NDT Days"
Volume 1, Issue 5, Year 2018 ISSN: 2603-4018

Interaction of Radiowaves with a Polymer Composite Electromagnetic Screen

Vadim KOVTUN[1], Victor BANNYI[2], Mitko MIHOVSKI[3], Yordan MIRCHEV[3]

[1] Gomel Branch University of Civil Protection of the Ministry for Emergency Situations of the Republic of Belarus; Gomel, Belarus; e-mail: vadimkov@ya.ru
[2] Gomel State Medical University, Gomel, Belarus
[3] Institute of Mechanics at the Bulgarian Academy of Sciences, Block 4, Acad. G. Bonchev Str., 1113 Sofia, Bulgaria
Phone: +359 2 9797120; e-mail: nntdd@abv.bg, mirchev@imbm.bas.bg

Abstract
The present work is devoted to elaboration of representations on the mechanism of super high frequency radiation interaction with heterogeneous systems based on condensed media. The aim was to develop a systematized approach to creation of polymer composite electromagnetic screens. In this connection, a physical model of the polymer composite electromagnetic screens has been developed and its mechanism has been analyzed. Polymer composite absorbers of super high frequency radiation are proposed with reflectance and energy attenuation of electromagnetic waves optimized via choosing the required composition, dimensions and structural parameters.

Keywords: electromagnetic screens, radioabsorbing materials, electromagnetic radiation, radiowaves, physical models, polymer composite, thermoplastic binder, physico-chemical interactions.

1. Introduction

To the best of our knowledge, there is not as yet [1] any reliable theoretical approach able to forecast electromagnetic parameters of composite radioabsorbing materials (RAM), particularly ferroplastics, within a wide range of concentration of components and frequency of the outer electromagnetic field. In spite of availability of a series of theoretical methods for computing electromagnetic waves (EMW) absorbers [2–4] ready to define the desired limits of the magnetic, dielectric and Joule losses, there still exists a paradox in this physical domain of using the cut and try method in creating RAM and electromagnetic screens (EMS). Nevertheless, there have been elaborated the basic elements of a systematized approach to the development of the broadband EMS on the base of filled thermoplastics. Research workers in the physics of condensed state have established the mechanism by which the microwave radiation interacts with the matter. Moreover, the interaction schemes of electromagnetic radiation (EMR) with the screens and physical models of EMS based on certain condensed substances are proposed.

The aim of the work was to develop the notions on interaction of super high frequency radiowaves with the polymer heterogeneous systems. It is evident that the development of the physical model of thermoplastic-based EMS along with optimizing the composition and structure of the polymer solid and fibrous RAM by the criteria of reflectance and energy attenuation of radiowaves can solve a number of problems in protection of electronic facilities from harmful radiation and provision of electromagnetic ecological safety.

2. Physical models of polymer composite EMS

Some single-layer, structurally isotropic EMS fail to ensure sufficiently low EMW reflectance factor within a given frequency range [1, 2]. This is mainly because of a poor matching of the impedances of these EMS and the free space. The single- and multilayered EMS of the gradient type are devoid of this drawback owing to either smooth (Fig. 1 *a*) or stepwise (Fig. 1 *b*) increase of the electric and magnetic losses in direction of EMW propagation when the dielectric and magnetic permittivity values of the air and absorber are brought to a minimum at the interfaces [2, 5]. In the first case (Fig. 1 *a*), the gradient of losses is conditioned by the filler content increment across thickness of the composite EMS. The original processes are employed to produce mentioned EMS, particularly, the ones with sedimentation effects in the polymer melt. The gradient of electromagnetic properties in the laminated inhomogeneous systems is dependent on the number of RAM layers, their thickness and functional filler (FF) content in each layer.

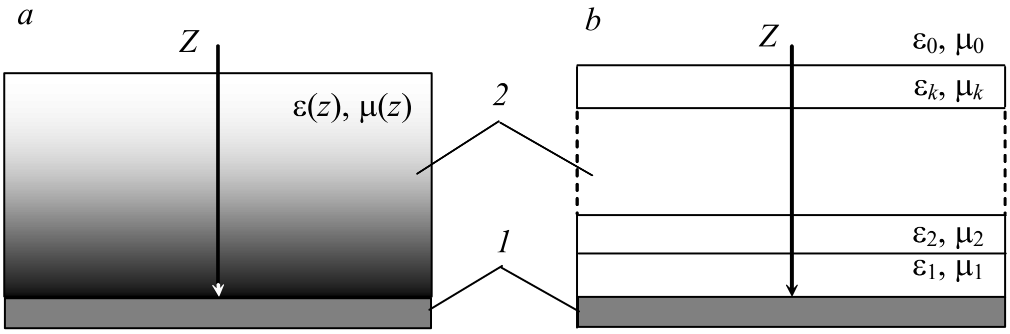

Fig. 1. Cross-sections of single-layer (*a*) and multilayer (*b*) EMS with gradient of electric and magnetic losses in direction *Z* of EMW propagation:
$\varepsilon_0 \approx \varepsilon_k < \varepsilon_{k-1} < \ldots < \varepsilon_2 < \varepsilon_1$; $\mu_0 \approx \mu_k < \mu_{k-1} < \ldots < \mu_2 < \mu_1$;
***1* – reflecting substrate;**
***2* – polymer material with dispersed filler ensuring electric and magnetic losses**

Figure 2 presents a diagram illustrating the performance of the gradient EMS based on a polymer binder and FF particles with increasing across thickness concentration in direction of EMW propagation. Let us take the following assumptions: the polymer binder is radioparent; FF particles of one origin are spherical; EMW propagates normal to the screen surface.

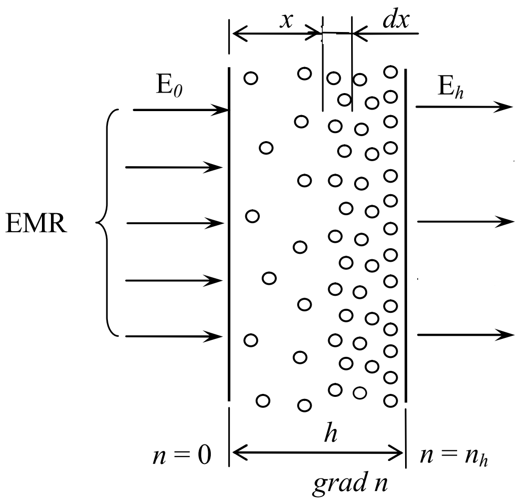

Fig. 2. Scheme of a model of polymer gradient EMS

Energy losses of EMR in the gradient screen are equal to the difference of the incident E_0 and having passed radiation energy E_h through the EMS, which present a sum of EMR energy constituents contributing to absorption E_A, scattering E_S and reflection E_R.

$$\Delta E = E_0 - E_h = E_A + E_S + E_R. \quad (1)$$

With account of the gradient distribution of FF particles in the sample,

$$\Delta E = \sum_{i=1}^{N} E_{Ai} + \int_0^h [E_S(x) + E_R(x)] \frac{dn}{dx} dx + E_\xi , \quad (2)$$

where N – total number of FF particles in the sample; h – sample thickness; dn – number of FF particles within the layer of dx thickness; E_{Ai} – EMR energy value absorbed by one particle; E_S, E_R – values of EMR energy scattering and reflection at a distance x from the screen surface; E_ξ – energy attenuation by the screen owing to radiation absorption at the boundaries of thermoplastic binder and FF particles.

The value of E_ξ is conditioned by physico-chemical interactions of the polymer binder with FF material, which alter essentially the composite structure and properties [6]. This constituent should be accounted for when forecasting the efficiency of the polymer composite EMS.
The experimental investigations [7, 8] have made grounds for determining an optimum filling degree (40-60 mass %) of the outer PE-based layer of the screen by ferromagnetic particles, for which value the reflectance factor of the screen is the minimal. If met, this condition eliminates the necessity of the external radioparent coatings on the radioabsorbing elements aimed at the impedance matching of the element and atmosphere.
Figure 3 shows a physical model of a laminated EMS whose layers realize consecutively the chief mechanisms of the EMR energy transformation.

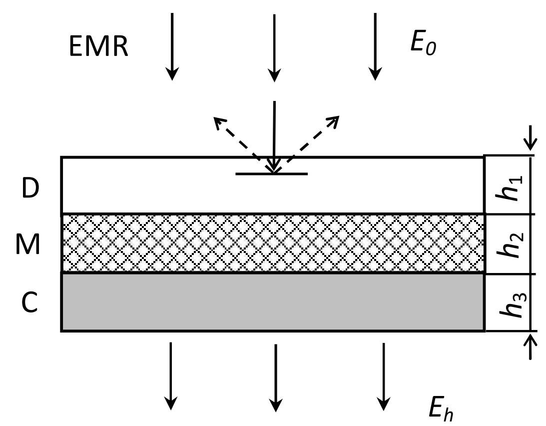

Fig. 3. EMS model consisting of matching dielectric (*D*), magnetic (*M*) and conducting (*C*) layers

The screen is modeled by three layers: the external dielectric (*D*) that allows for matching impedances of the screen and atmosphere, the magnetic layer (*M*) and the conducting one (*C*). Energy losses of the EMR penetrated through the screen present a sum of the losses in the layers, namely dielectric E_D, magnetic E_M and the ones generated by electric conductivity E_C, plus the energy attenuation at the interfaces E_{DM} and E_{MC}.

$$\Delta E = E_0 - E_h = E_D + E_M + E_C + E_{DM} + E_{MC}. \quad (3)$$

If to take into account physical parameters of the layers (ε and μ - dielectric and magnetic permittivity, γ - specific conductance), their thicknesses (h) and interfacial behavior in the contact zones, relation (3) can be presented as a sum of the functions:

$$\Delta E = F_D(\varepsilon_D, h_D) + F_M(\mu_M, h_M) + F_C(\gamma_C, h_C) + F_{DM}(\varepsilon_{DM}, \mu_{DM}) + + F_{MC}(\mu_{MC}, \gamma_{MC}). \quad (4)$$

3. Optimizing of composition and technique of polymer RAM and EMS.

The models of EMS set forth above have stipulated a series of experimental investigations fulfilled by the authors for optimizing the composition and the process of RAM formation. Herein below the investigation results are cited for the RAM based on a polymer binder and containing conducting and magnetic fillers in different amounts and dispersion degree. RAM samples were obtained by hot pressing from the mixtures of powder polyethylene (PE) (URSS GOST 16803-070) and fillers, including carbonyl iron (CI) (URSS Techn. Spec. 6-09-300-78), magneto-soft ferrite (MSF) (URSS Techn. Spec. 6-09-5111-84, grade 2500 HMC) and nickel (URSS GOST 9722-78). The reflectance factor (R) and energy attenuation (S) of the microwave radiation were recorded by the method of scatterometry in the 2-27 GHz frequency range at normal incidence of EMW on the object under study in the waveguide tracts (R2-50; R2-60, R2-61, R2-65, R2-66) for the standing wave ratio and attenuation. The dependencies of R for the normal incident plane EMW (ν = 8-12 GHz) versus sample thickness, filler concentration and dispersivity have been determined. The dependence of $R=f(h)$ (Fig. 4) for RAM samples with 50 mass % filling degree is in the form of degenerating sinusoids with a $\lambda/4$ period. The minimal R values correspond to thicknesses (h) till a 15 % accuracy of the samples described by next equation [7, 9]:

$$h = \lambda/K + z\lambda/4, \quad (5)$$

where K – the factor interrelated with magnetic permittivity values of ferromagnetic fillers, while z – equals to zero or a positive integer.

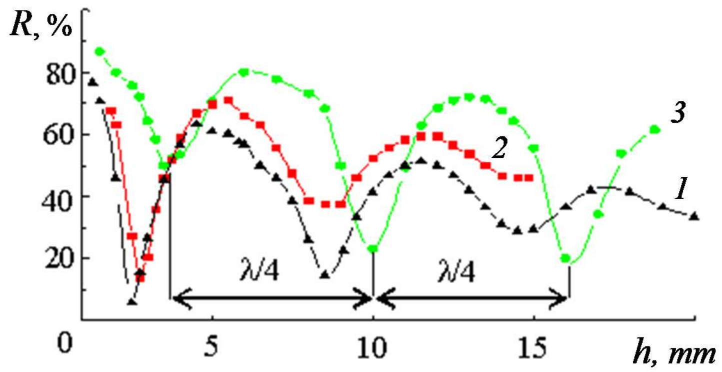

Fig. 4. Reflectance factor (*R*) of 12 GHz frequency EMW depending on sample thickness (*h*) and kind of FF: *1* – carbonyl iron, *2* – magneto-soft ferrite, *3* – nickel.

The concentration of the ferromagnetic components in the subsurface layer of the sample at the interface with the atmosphere affects *R* magnitude. Concentration (*C*) of ferromagnetic components in the surface layer of the sample at the interface with the atmosphere effects *R* value. For all studied fillers the dependencies *R=f(C)* show a minimum at 40-60 mass % at a similar sample thickness and fixed EMR frequency in the 8-12 GHz range. This is related to a competing effect of some processes. Firstly, introduction of the ferromagnetic filler in the radioparent PE binder results in a growth of magnetic losses in the material and reduction of *R*. Secondly, as the filling degree increases $C > 60$ % mismatching of impedances of the sample and atmosphere increments leading to *R* growth.

Radiophysical characteristics of the composite samples were found to depend upon the dispersion of FF as well as physico-chemical interactions of the filler particles with the polymer binder. PE-based 3 mm thick samples filled by MSF (50 mass %) differed in the filler dispersivity. The dependence of *R* on the filler dispersivity (Fig. 5) confirms that the optimal filler particle size providing for a strongest radioabsorption, all other conditions being equal, depends on the EMR frequency [9, 10]. This is because: 1) the ferrites of different dispersivity acquire different parameters of electromagnetic losses in the EMR field; 2) the conditions of EMW scattering change depending on the ratio of the filler particle size to the incident wavelength. Proceeding from the above, it follows that to create a wideband screen one should employ the polydispersed FF particles.

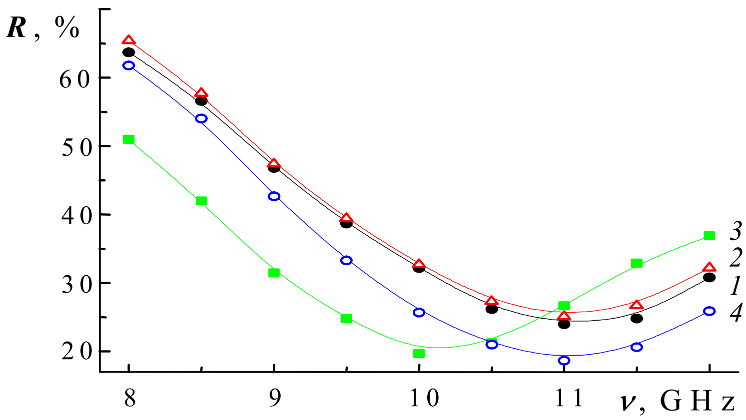

Fig. 5. Reflectance factor (*R*) of a normal incident plane EMW from RAM samples depending on frequency (*ν*) and filler dispersivity. Sample composition – PE + magneto-soft ferrites (50 mass %), *h* = 3 mm. Filler particle size, μm: *1* – below 50; *2* – 63…100; *3* – 100…160; *4* – 160…200

It has been shown on the example of PE filled by MSF of two fractions (50-63 μm and 160-200 μm) that the reflectance factor of EMW can be regulated within 30 % limits by altering the ratio of coarse and fine filler particle content (*l/s*) in the polymer matrix of RAM (Fig. 6). Keeping all other conditions equal, the minimal reflection shifts along the *l/s* scale as a function of EMR frequency and the ratio of dispersion values of the coarse and fine particles. The non-monotonous behavior of EMR attenuation curve depending on *l/s* can be explained by the varying relation of the EMW scattering intensity versus that of the EMR energy absorption by the samples.

The effect of the new phases arising at thermal forming of filled polymer composites has been studied by varying time and temperature regimes, all other conditions being equal. A correlation between the forming temperature and radiophysical parameters of the samples has been established for the PE–CI composite. This is because named parameters (*R*, *S*) are dependent on the oxidation degree of iron particles being, in its turn, a function of RAM formation temperature (Fig. 7).

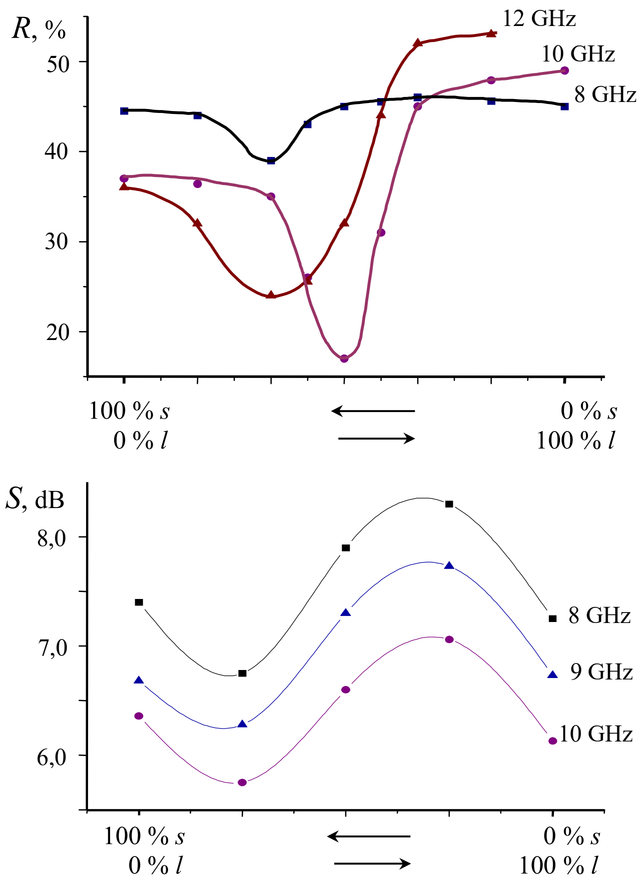

Fig. 6. Reflectance factor (*R*) of a normal incident plane EMW from RAM samples and attenuation (*S*) of EMR energy passing through the sample depending on frequency (*ν*) and ratio of coarse (*l*) to fine (*s*) FF particle concentrations. Sample composition: PE + 50 mass % MSF, *h* = 3 mm. Filler particle size, μm: *s* – 50…63; *l* – 160…200

The minimal value *R*~7 % and EMR attenuation down to *S* = 5-6 dB are observed at *T* = 210°C corresponding to a maximal adhesion of PE to iron [11] in 3 mm thick samples and 10 GHz EMR frequency. This is evidently, caused by the dependence of the stoichiometric composition of iron oxides (FeO, Fe_2O_3, Fe_3O_4) on the heating temperature of the composition during sample formation and by different structure of the newly formed metal-polymer phases appearing at PE–CI boundaries. Consequently, different oxides and metal-polymer phases are characterized by different radiophysical parameters. The experimental results show the necessity of considering the interaction at the binder-FF interface presented within the models of the gradient and laminated composite EMS (formulas 2 and 4).

Hence, there must be some optimal thickness, filling degree, dimensions and coarse to fine FF particle ratio for the composite PE-based RAM in whose polymer matrix different-nature FF particles are distributed in the isotropic manner so as to attenuate EMW energy to the utmost. When optimizing dimensional, composition and structural parameters of the screens aiming at EMR energy attenuation, it is important to ensure not only high dielectric and magnetic losses but also impedance matching of the RAM with the free space and intensified scattering effect of EMW at the interfaces in the bulk.

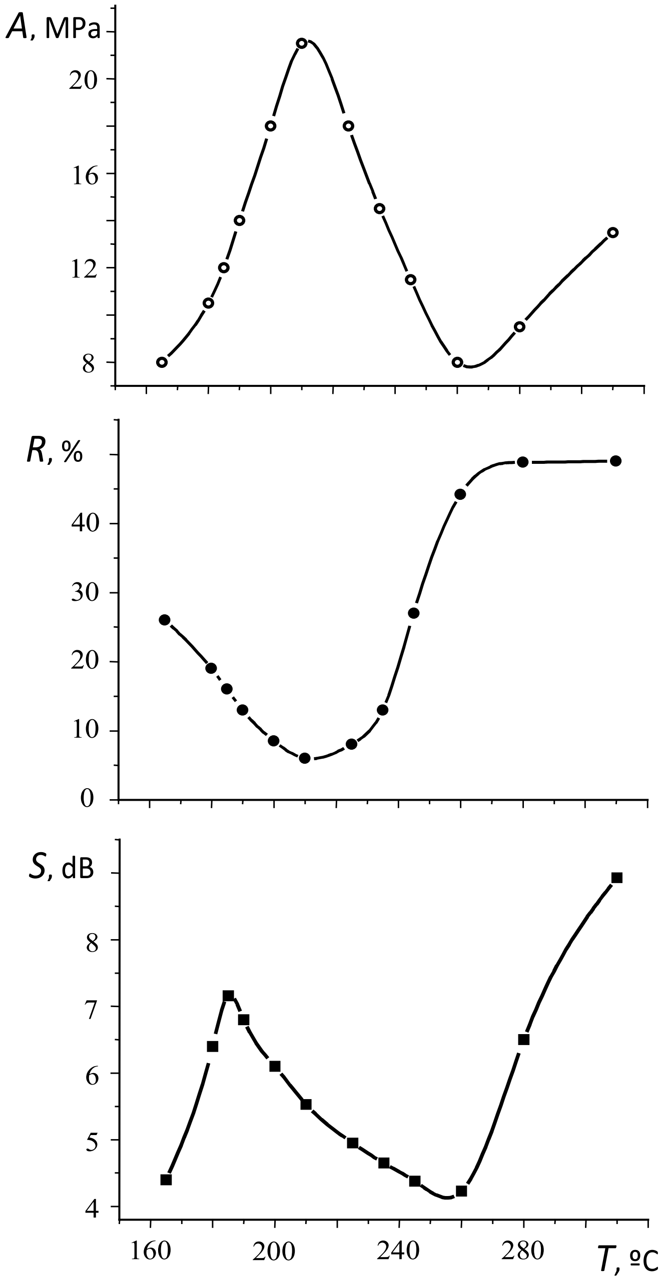

Fig. 7. Adhesion (*A*) of PE to steel, reflectance factor (*R*) and attenuation of EMR energy (*S*) versus forming temperature for RAM samples. Composition of samples: PE + CI (50 mass %), *h* = 3 mm

Proceeding from above-mentioned principles of optimizing EMS by the criterion of EMR energy attenuation, the authors have elaborated sheet radioabsorbers based on PE and dispersed FF. Frequency dependencies of *R* and *S* recorded in the waveguide for the radioabsorbing laminated plastics reinforced by conducting fabrics and these of the polymer composite RAM filled by metallized fibers and/or glass spheres are illustrated in Figs. 8 *a* and *b*, correspondingly.

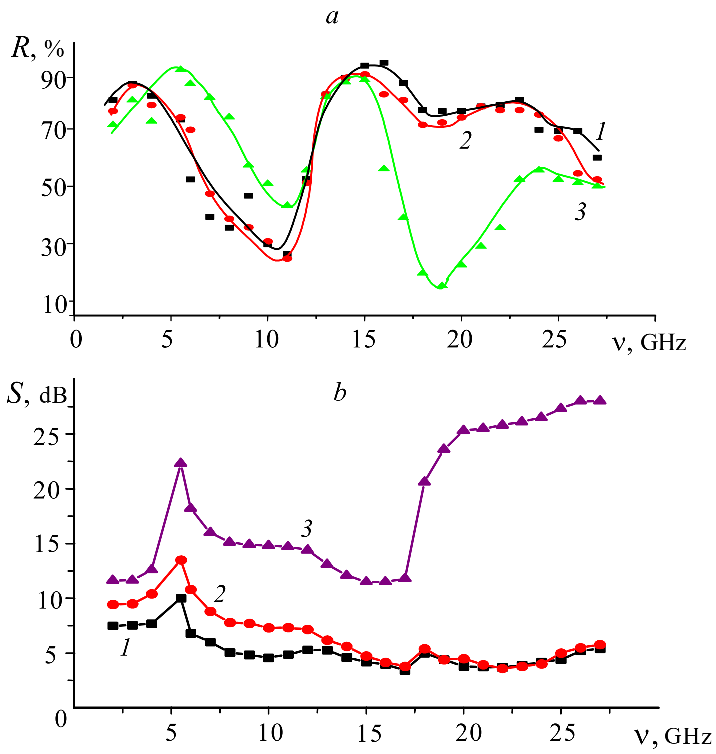

Fig. 8. Frequency dependencies for *a* – reflectance factor (*R*) and *b* – attenuation (*S*) of the energy of normal incident plane EMW (in waveguide) for 3 mm thick RAM samples. Sample composition: *1* – PE + MSF (50 mass %, *d* = 50…200 μm); *2* – PE + MSF (50 mass %, *d* = 50…200 μm) + glass spheres (10 mass %, *d* = 200…500 μm); *3* – PE + MSF (50 mass %, *d* = 50…200 μm) + carbon fabric TR3/2

The filling of the polymer binder by glass spheres as well as reinforcement of the composite RAM by the carbon fabric is seen to improve both R and S. This is attributed to the effect of several factors. Firstly, the increasing total amount of FF results, as a rule, in growing magnetic, Joule's and dielectric losses of the falling on the RAM microwave radiation (at optimized filling degree by the criterion of the minimal EMW reflection). Secondly, parameters R and S improve under an optimal correlation of different mechanisms of the losses and, thirdly, they do improve owing to the optimized conditions of EMR scattering over the structural inhomogeneities of the composite.

4. Conclusions

Proceeding from the analysis of attenuation of the microwave energy by the filled thermoplastics an interaction scheme of EMR with the polymer composite EMS is proposed. A physical model for the EMS has been developed and the criteria for selecting its ingredients have been substantiated. The developed scheme and model evidence that in fact all mechanisms of radiation reflection, absorption and scattering can be realized by the polymer composite screens. A relation is proposed to describe the losses of the EMR energy passing through the screen, which takes into account the concentration gradient of FF in the polymer binder and formation of new phases due to physico-chemical interactions between the polymer and FF during thermal processes of EMS forming. This broadens functional resources of the thermoplastic-based RAM filled by different in nature, size and structure FF. The EMS from described materials are characterized by high manufacturability, small density and elevated specific strength.

5. References

1. Alekseev A.G., Guseva O.M., Semichev V.S. Composite ferromagnetics and electromagnetic safety. – St. Petersburg State University, 1998, 296 p.
2. Ayzikovich B.V., Lapshin V.U., Masalov S.A. et al. Methods for analyzing and calculating the radar characteristics of absorbers of electromagnetic waves. Foreign electronics, 1994, No 4–5, pp. 41–53.
3. Kazantseva N.E., Lazovskaia E.V., Petrov V.S., Ponomarenko A.T. Electrodynamic and thermal properties of ferrite-containing polymer composites. Materials of Internal. Conf. "Polymeric composites", Gomel, 29-30 September 1998, MPRI NASB, pp. 206–209.
4. Alimin B.F., Torgovanov V.A. Methods for calculating of absorbers of electromagnetic waves. Foreign electronics, 1976, No 3, pp. 29–58.
5. Makarevich A.V., Bannyi V.A. Radioabsorbing polymer composite materials in the SHF technique. Materials, technologies, tools, 1999, V. 4, No 3, pp. 24–32.
6. Bannyi V.A., Kovtun V.A. Absorbers of super high frequency energy based on the composite thermoplastics. Emergency situations: education and science, 2015, V. 10, No 2, pp. 14–24.
7. Bannyi V.A., Makarevich A.V., Pinchuk L.S. Influence of dimensional and structural parameters of polymer composite materials on their radiophysical characteristics. Proc. of the National Academy of Sciences of Belarus, 2000, V. 44, No 4, pp. 109–111.
8. Bannyi V.A., Makarevich A.V., Pinchuk L.S. Radioabsorbing composite materials based on thermoplastics: production technology and structural optimization principles. Proc. of 33rd European Microwave Conference (EuMC2003), Munich, Germany, 6-10 October 2003, European Microwave Association, Horizon House Publications, pp. 1123–1126.
9. Kovtun V.A., Mihovski M., Bannyi V.A., Pleskachevsky Yu.M. The complex approach in creation of radioabsorbing and shielding materials based on the polymer composites. Scientific proceedings of STUME, 2017, V. 25, No 1 (216), pp. 97–100.
10. Bannyi V.A. Physico-technological peculiarities of forming of radioabsorbing materials based on composite thermoplastics. Proc. of 16th International Conf. on Microwaves, Radar and Wireless Communications (MIKON-2006), Krakow, Poland, 22-26 May 2006, pp. 1-3.
11. Belyi V.A., Egorenkov N.I., Pleskachevsky Yu.M. Adhesion of polymers to metals. Minsk: Science and equipment, 1971, 288 p.