ЦИВІЛЬНА БЕЗПЕКА
CIVIL SAFETY

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DESIGNING FINISHING MATERIALS WITH A GRADIENT OF ELECTROPHYSICAL PROPERTIES

Abstract. *The article discusses the basics of development and production of materials for shielding electromagnetic fields in a wide range of frequencies. The purpose of these materials is to cover large surface areas. The basic requirements for these types of materials have been established. The main ones are: the front surface must have electrophysical properties (dielectric and magnetic permeability) to ensure the lowest possible reflection coefficient of electromagnetic waves. At the same time, it is mandatory to simultaneously ensure the characteristics of strength, fire resistance, non-toxicity, etc. The content of radio-absorbing particles and effective dielectric (magnetic) permeability in the interlayer of the layered structure in the direction of growth of the substrate should ensure broadband and efficiency of the material. The dispersion dependence should ensure uniform absorption of electromagnetic energy and its passage from the input surface to the substrate in a given frequency range. Based on the maximum and minimum wavelengths of the shielding field, permeability and thickness of individual layers, calculations of the required thickness of the gradient material for a given reflection coefficient are given. Thanks to heat treatment of the surface of the material in the manufacturing process, the possibility of manufacturing monolithic metal-polymer screens with surface layers of low dielectric permeability is shown. The possibility of creating monolithic metal-polymer screens from ferromagnetic finely dispersed substances with an adjustable gradient in the direction from the front surface to the bottom is demonstrated, and a technical solution is given. This material can be used to control the ratio of shielding factors for high-frequency electromagnetic fields, ultra-low-frequency electric and magnetic fields, as well as concomitant shielding from natural magnetic fields.*

Keywords: *electromagnetic fields; screening; shielding coefficients; facing protective building material*

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Introduction

For many years, the main goal in the development of materials for shielding electromagnetic fields and the design of shielding structures was to obtain the maximum shielding coefficients by any physical mechanism. Recently, in connection with the growing awareness of the harmfulness of the hypogeomagnetic field (artificially reduced natural magnetic field), the need for stable functioning of wireless communication devices with a simultaneous decrease in the intensity of man-made fields of other origin, there has been a need to develop protective materials that at an acceptable level satisfy these requirements. But solid metal structures with regular metal structures and most composite materials do not meet the requirements. This is due to high reflection coefficients of all solid metal (crystalline and amorphous) materials, shielding of narrow-band high-frequency fields with lattice and mesh materials, high shielding coefficients of ultra-low-frequency and high-frequency fields with composite metal-containing materials.

To solve the problems of rationalizing the degrees of protection against electric, magnetic and electromagnetic fields, based on theoretical considerations, it is advisable to consider protective materials of the gradient type - multi-layered and heterogeneous continuous with a gradient of electrophysical and magnetic properties in the body of the material.

Analysis of recent research and publications

Sufficient attention is paid to the development and research of protective properties of non-homogeneous materials [1, 2]. But the technologies developed by them relate to the solution of electromagnetic compatibility problems, that is, the reduction of fields of previously known amplitude-frequency characteristics [3] is also intended for electromagnetic compatibility problems in the aviation industry, therefore, along with the fixed requirements for protection in a defined frequency band, in this material, many attention is paid to increasing strength characteristics and reducing weight.

In a thorough survey work [4], it is shown that gradient properties can also be found in materials intended for individual protection and not very suitable for facing surfaces. Research [5] shows that it is possible to obtain a gradient of physical properties in a heterogeneous material.

The task of calculating and predicting the protective properties of materials or preliminary calculation of a possible design based on the required functionality is important [6, 7]. But in the first publication, although it is about the optimization of protection, the optimization problem was not solved either analytically or graphically. In the second, the developed material, especially in terms of moisture content, although it has high functional qualities, is prone to degradation and is not acceptable for lining large areas.

Materials [8] present modern approaches to the design of facing surfaces, the parameters of which can be calculated. And work [9] shows a fundamental possibility to rationalize the degrees of protection against the influence of magnetic and electromagnetic fields of heterogeneous sources, which is the basis for further research.

The purpose of the work is to develop basic algorithms for the design of gradient-type cladding materials and to determine the possibilities of their application for the controlled reduction of electromagnetic field levels.

Presenting main material

Modern facing materials must meet a number of requirements – general and special.

The general requirements for mechanical properties – strength, specific weight, reliability (absence of material degradation in the process operation), reliability of fixing on working surfaces, as well as high fire resistance and minimal release of harmful substances.

The special requirements include high shielding coefficients in a wide frequency range (with the possibility of controlling the absorption coefficients of electromagnetic energy) and the minimum possible reflection coefficients of electromagnetic waves.

Unambiguous provision of all the above requirements in one material at an optimal level is practically impossible, therefore there is a wide range of protective and facing materials that solve local problems of electromagnetic safety. But there is an opportunity to rationalize the ratio of degrees of protection for different critical frequencies or frequency bands of magnetic, electric and electromagnetic fields. It is necessary to achieve a compromise between the desired and technically feasible effect for each individual electromagnetic influence, taking into account other influences, approaches to shielding of which may contradict each other. For example, by reducing the levels of man-made magnetic fields of ultra-low frequencies (industrial and its harmonics), we can, under certain conditions, shield the natural magnetic field, which is harmful to people and is regulated by the relevant standard.

In general, the simplest task is to reduce the levels of electromagnetic fields of very high, ultrahigh and extremely high frequency fields, inherent radiations of communication means and parts of industrial and household equipment. The building or individual rooms can be shielded with metal or composite flat material, taking into account the short length of the electromagnetic wave and minor diffraction phenomena at the edges of the protective structures. But a significant contribution to protection against high-frequency radiation comes from the reflection of electromagnetic waves, which is undesirable due to reflection towards other building premises, the increase of the electromagnetic background due to re-reflection inside buildings and premises.

Avoidance of this effect is possible due to the use of gradient shielding materials (multi-layer and continuous). Despite the fact that the method of reducing reflection coefficients by creating a gap between two surfaces with a thickness of a quarter of the length of the incident wave is well-known, in many cases it is applied incorrectly (the electrophysical and magnetic properties of the upper and lower layers are not taken into account). In addition, this design has narrow-band protection.

The electromagnetic wave reflection coefficient is uniquely determined by the electrical and magnetic properties of the surface. For example, the reflection coefficient of an electromagnetic wave during its normal incidence on the surface:

$$K_r = \frac{1-\sqrt{\varepsilon_m}}{1+\sqrt{\varepsilon_m}}, \qquad (1)$$

where ε_m is the dielectric constant of the surface layer of the material on which the wave falls.

To ensure the broadband of the material, the quarter-wave gap (or gaps) should be filled with one of the many developed radio-absorbing elements based on ferrites, carbon compounds, etc. When developing material for shielding high-frequency fields, it is necessary to proceed from the following principles:

– the front surface must have the minimum dielectric constant possible to meet the specified requirements for the material (strength, non-flammability);
– the content of the radio-absorbing substance in the layer (layers) and the regularity of its change in thickness should ensure a gradual increase in the equivalent (effective) dielectric constant (mainly the imaginary part of the complex dielectric constant) in the direction of the surface of the incident wave – the substrate;
– dispersion dependence should ensure uniform absorption of electromagnetic energy during its passage from the input surface to the substrate and in the opposite direction.

The required thickness of the material can be estimated based on the ratio [10].

$$\left|\ln R_r\right|\left(\lambda_{max} - \lambda_{min}\right) < \sum_i \mu_i d_i , \qquad (2)$$

where R_r – maximum reflection coefficient by power; λ_{max}, λ_{min} – maximum and minimum wavelengths of the frequency band; μ_i – relative magnetic permeability of each i-th layer; d – its thickness. For non-magnetic materials, the full thickness of the material structure is taken instead of the sum in the right-hand side of the expression.

In general, the loss (absorption) of energy of electromagnetic waves in the environment is determined by the complex nature of the values of its dielectric and/or magnetic permeability.

If complex permeability:

$$\varepsilon = \varepsilon' + i\varepsilon'', \ \mu = \mu_i' + i\mu'', \qquad (3)$$

where ε', μ' – gums; ε'', μ'' – imaginary components of the complex permeability, then the loss (absorption) coefficient is defined as:

$$\alpha = \left(\sqrt{\varepsilon\mu}\right)'' . \qquad (4)$$

At the same time, the attenuation of the energy of the wave that has passed through the medium is the distance:

$$e^{\frac{-4\pi\alpha d}{\lambda}} , \qquad (5)$$

where λ – the length of an electromagnetic wave in free space.

But the production of multilayer structures, at least those that require the connection of layers, is associated with a number of technological problems (ensuring long-term adhesion of layers, accurate maintenance of gap sizes, etc.). In addition, it requires the use of materials with the lowest possible values as a front layer and to minimize reflection coefficients. At the same time, a mandatory condition is the presence of a metal substrate in a multilayer structure, which can completely block mobile signals.

The use of composite materials – metal-polymers can solve the problem of simultaneously reducing the levels of electric and magnetic fields of ultra-low frequencies – industrial and its harmonics. But most polymers have significant dielectric constants. For example, latex, which was used as a matrix in work [11], has $\varepsilon \approx 24$, which automatically provides high reflection. At the same time, iron ore dust, which was used as a shielding filler, has $\varepsilon \approx 1{,}5$. Studies show that during heat treatment of metal latex material, metal-containing iron ore particles accumulate in the near-surface layer. That is, it is possible to reduce the reflection coefficient of the material by creating a concentration gradient of filler particles during heating and vulcanization of the surface layer (Fig. 1).

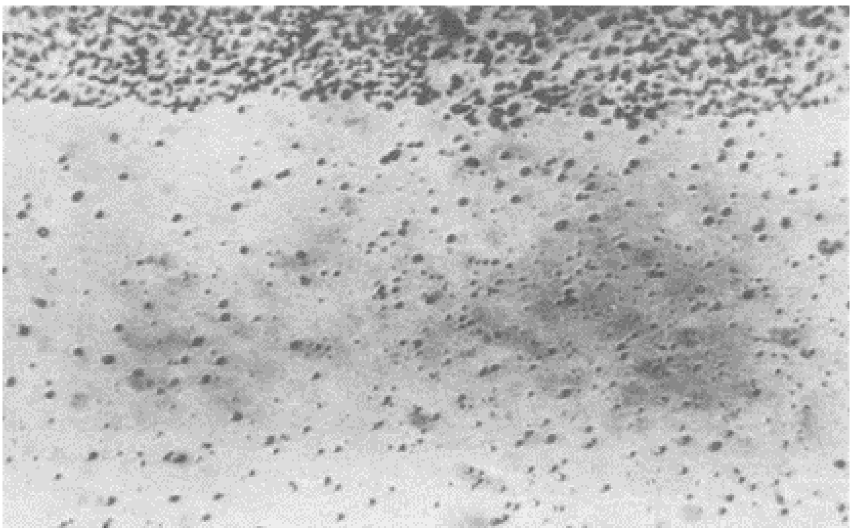

Fig. 1. Cross-section of a heat-treated metal-polymer material sample

As can be seen from the figure, the thin near-surface layer is mostly saturated with iron ore particles, which brings the dielectric constant to the minimum values possible for such compositions.

At the same time, the metal-polymer composite itself has, due to the content of iron and its oxides, high shielding properties in relation to low-frequency magnetic and electric fields.

Experimental data and theoretical considerations indicate that it is possible to obtain a gradient-type protective material from a metal-polymer mixture without applying separately produced layers. For this, it is necessary to create a concentration gradient of the shielding substance in the body throughout the body of the matrixpolymer matrix. This is realized due to the use of iron ore dust of different dispersion and weight of individual particles, which settle at different speeds in the liquid mixture (Fig. 2).

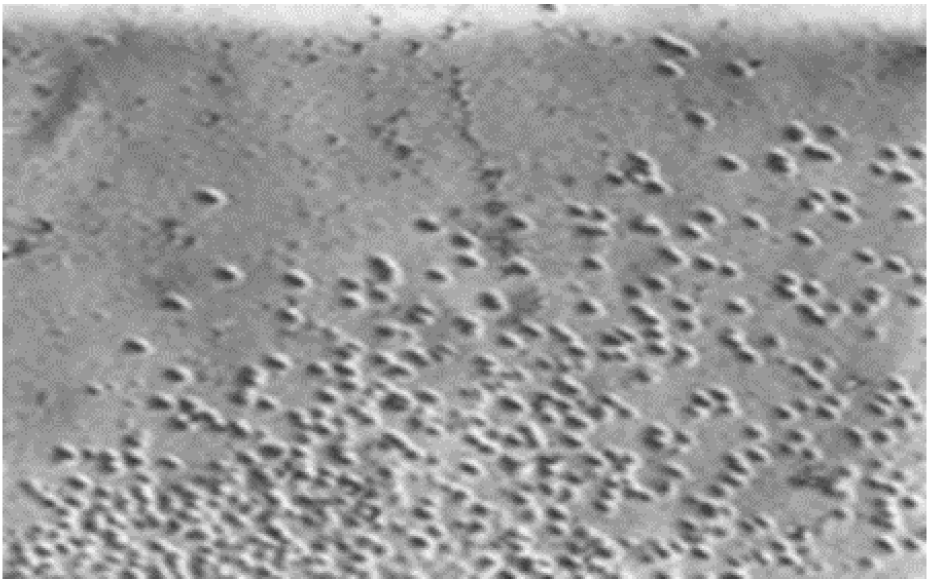

Fig. 2. Concentration gradient of iron ore particles in the polymer matrix

This method can be used in a gradient material without a metal substrate.

The practical implementation of this method is possible due to the processing of the finished initial mixture, which is poured onto a flat surface with a constant inhomogeneous magnetic field, which will create a gradient of shielding particles with compaction in the lower part of the cuvette with the solution, where the magnets are located. But in this case, it is necessary to use a filler with higher magnetic properties, for example, iron ore concentrate, which has a dispersion of 150-200 μm and mixes well with liquid polymer. But simultaneously obtaining the upper layer, saturated with iron ore dust, and the gradual compaction of the distribution of particles in the direction of the lower side of the material is quite difficult, therefore, in each specific case, it is necessary to determine the priority factor of influence on the electromagnetic environment and choose constructive solutions regarding the introduction of shielding.

Conclusions

1. The requirements for modern cladding materials for shielding electromagnetic fields are defined. The main ones are: shielding of electromagnetic fields of frequencies (frequency bands) inherent in most sources of man-made electromagnetic fields, the most critical from the point of view of human safety, mechanical strength, adhesion to the base, fire resistance, non-toxicity.

2. It is shown that shielding of fields of very high, ultrahigh and extremely high frequencies is expedient to be carried out by a gradient multilayer structure, and the principles of its design are provided. The main criteria for ensuring the necessary level of protection, in particular for the front layer of a multi-layer structure, are provided. Estimated prediction of the effectiveness of the protective structure is proposed, based on the electrophysical and magnetic properties of the shielded materials and the frequency band of the electromagnetic field.

3. A method of obtaining a surface layer in a solid material with low dielectric constants is presented. It consists in surface heat treatment of a liquid metal-polymer mixture.

4. A method of obtaining a concentration gradient of metal and metal-containing particles in a composite metal-polymer material is proposed, which allows the production of high-efficiency facing materials in a wide range of frequencies. The advantage of such a material is low weight and cost, monolithicity, which reduces the probability of delamination and degradation under the influence of physical and chemical factors.

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ПРОЄКТУВАННЯ ОЗДОБЛЮВАЛЬНИХ МАТЕРІАЛІВ З ГРАДІЄНТОМ ЕЛЕКТРОФІЗИЧНИХ ВЛАСТИВОСТЕЙ

Анотація. У статті розглянуто основи розробки та виробництва матеріалів для екранування електромагнітних полів у широкому діапазоні частот. Призначення цих матеріалів – покриття великих площ поверхні. Встановлено основні вимоги до даних видів матеріалів. Основні з них: лицьова поверхня повинна мати електрофізичні властивості (діелектричну та магнітну проникність), щоб забезпечити якомога менший коефіцієнт відбиття електромагнітних хвиль. При цьому обов'язковим є одночасно забезпечення характеристик міцності, вогнестійкості, нетоксичності та ін. Вміст радіопоглинаючих частинок і ефективна діелектрична (магнітна) проникність у прошарку шаруватої структури в напрямку росту підкладки повинні забезпечувати широкосмуговість і ефективність матеріалу. Дисперсійна залежність повинна забезпечувати рівномірне поглинання електромагнітної енергії та її проходження від вхідної поверхні до підкладки в заданому діапазоні частот. На підставі максимальних і мінімальних довжин хвиль екрануючого поля, проникності та товщини окремих шарів наводяться розрахунки необхідної товщини градієнтного матеріалу для даного коефіцієнта відбиття. Завдяки термічній обробці поверхні матеріалу в процесі виготовлення показано можливість виготовлення монолітних металополімерних екранів з поверхневими шарами низької діелектричної проникності. Продемонстровано можливість створення монолітних металополімерних екранів із феромагнітних дрібнодисперсних речовин з регульованим градієнтом у напрямку від лицьової поверхні до нижньої та наведено технічне рішення. Цей матеріал можна використовувати для керування співвідношенням коефіцієнтів екранування для високочастотних електромагнітних полів, ультранизькочастотних електричних і магнітних полів, а також супутнього екранування від природних магнітних полів.

Ключові слова: електромагнітні поля; екранування; коефіцієнти екранування; облицювальний захисний будівельний матеріал

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