Досліджено захисні властивості металополімерних електромагнітних екранів. Встановлено, що підвищення дисперсності металовмісних наночастинок у 2–4 рази знижує коефіцієнт відбиття на 0,15–0,20. Визначено кількісну залежність електрофізичних характеристик розробленого матеріалу від вмісту металевої субстанції. Це дозволило здійснити розрахунки коефіцієнтів екранування і внеску до них захисту за рахунок відбиття електромагнітних хвиль. Мікроструктурними дослідженнями підтверджено рівномірність розподілу металевої субстанції у полімерній матриці. Це дозволяє за малих концентрацій розраховувати захисні властивості матеріалу з використанням співвідношень для регулярних структур. Експериментально показано можливість отримання електромагнітного екрана градієнтного типу у одношаровому матеріалі.

Ключові слова: електромагнітний екран, металовмісні наночастинки коефіцієнт екранування, коефіцієнт поглинання, коефіцієнт відбиття, електрофізичні властивості

Исследованы защитные свойства металлополимерных электромагнитных экранов. Установлено, что повышение дисперсности металлосодержащих наночастиц в 2–4 раза снижает коэффициент отражения на 0,15–0,20. Определена количественная зависимость электрофизических характеристик разработанного материала от содержания металлической субстанции. Это позволило осуществить расчеты коэффициентов экранирования и вклада в них защиты за счет отражения электромагнитных волн. Микроструктурными исследованиями подтверждена равномерность распределения металлической субстанции в полимерной матрице. Это позволяет при малых концентрациях рассчитывать защитные свойства материала с использованием соотношений для регулярных структур. Экспериментально показана возможность получения электромагнитного экрана градиентного типа в однослойном материале.

Ключевые слова: электромагнитный экран, металлосодержащие наночастицы, коэффициент экранирования, коэффициент поглощения, коэффициент отражения, электрофизические свойства

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RESEARCH INTO PROTECTIVE PROPERTIES OF ELECTROMAGNETIC SCREENS BASED ON THE METAL-CONTAINING NANOSTRUCTURES

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1. Introduction

Protection from the effect of technogenic electromagnetic fields is one of the important problems of modern times. A feature of research and applied work in this direction is to address two problems. The first one is the protection of people under industrial and household conditions. The second is the protection of electronic equipment against electromagnetic impacts (providing for electromagnetic compatibility of technical means).

The most effective measure to reduce the levels of electromagnetic fields is their shielding by protective surfaces of different composition and designs. This necessitates research and development of materials with satisfactory shielding coefficients of electromagnetic fields with different frequency-amplitude characteristics.

2. Literature review and problem statement

Development of electromagnetic screens and study of their properties is a relevant problem both in Ukraine and all over the world. In this case, a global trend is the work in three areas:

– protection of people from electromagnetic influences under industrial conditions at relatively high levels of electric fields of a wide frequency spectrum;

– protection of people from electromagnetic fields under household conditions considering the impact of internal and external sources of electromagnetic fields and radiation;

– reducing the cost of materials for shielding the electromagnetic fields, which is predetermined by the need to fabricate screens with large areas.

In most cases, creation of protective materials is linked to a single impact, that is, the electromagnetic field of a single or a group of sources is shielded [1]. Under contemporary conditions, this cannot be considered satisfactory because of the variety of sources of electromagnetic fields. Under industrial and household conditions, they possess different amplitudes and a wide frequency spectrum.

Traditional materials for shielding the electromagnetic fields and radiation (copper and aluminum alloys, electrical steels, permalloys and metal grids) do not meet modern needs. Article [2] shows that such materials possess a complex frequency dependence of shielding coefficient. It is unsatisfactory in some of the frequency bands; however, recommendations to improve the means of shielding for a wide frequency range are not given. Study [3] reports that the electromagnetic background in modern premises is quite complex. This is predetermined by the widening of frequency spectrum of electromagnetic fields, dense arrangement of electrical and electronic equipment in the production areas and stricter requirements to protect the staff and electromagnetic compatibility. Nevertheless, this work applies only to the protection of computing equipment users. Under actual conditions, shielding should be employed to electromagnetic fields over a wide frequency range [4]. The proposed technique to design location of the screens makes it possible to normalize the levels of such magnetic fields, but it does not account for the reflection of electromagnetic waves of ultrahigh frequency.

Electromagnetic screens made of amorphous magnetically soft metal alloys have been widely used in recent years [5]. The main obstacle to employing the amorphous metallic materials is their extremely high cost caused by the complexity of their fabrication technology. That is why they are applied only for the manufacture of means of individual protection, or for the purposes of electromagnetic compatibility of technical equipment – shielding separate electronic units from external electromagnetic influences.

At large coefficients of absorption that is caused by high values of magnetic permeability, these materials have significant coefficients of reflection and cannot be produced in accordance with a particular electromagnetic environment. Study [6] reports that control over protective properties, in particular coefficient of reflection, is achieved by a change in the content of granulated metal in a silicate matrix. However, this material can be considered as a model due to low manufacturability and small limits of control over protective properties.

In the silicate metal-containing protective materials, copper balls of quite large dimensions (up to 15 % by weight) are used as a filler, which also significantly increases their cost. In addition, there is a problem of uniform distribution of metal particles in the body of the matrix.

Article [7] proposed and investigated the properties of elastic metal-containing materials. They have much better ranges of control over shielding coefficient, but their ratios of coefficients of reflection and transmission are not always acceptable. In addition, a shortcoming of such materials is the use of metal macro particles as a filler. Flat aluminum petals possess small thickness at large relative size. That is why the processes of manufacturing the material yield different results. The petals of the metal are oriented in the body of a polymer in unpredictable manner, which leads to a certain continuity of the metal plane (the petals are parallel to the plane of material). That is why at low (13–15 % by weight) content of metal, reflection coefficients amount to 0.3–0.6, which is unacceptable under production conditions with a large density of arrangement of technological equipment. These deficiencies are partially eliminated in the elastic electromagnetic screen based on ferrite-aluminum [8]. An analysis revealed that it is very difficult to manufacture and is very expensive. Its development and implementation with regard to the particular electromagnetic environment is not expedient. In this case, reflection coefficients of electromagnetic waves are high. This renders it inapplicable for premises with significant levels of external electromagnetic fields with the presence of internal sources. An analysis of the above studies proved that the improvement of protective properties is associated with the dispersion of metal substance in the body of a non-conducting material (matrix). Detailed research [9] demonstrated that adding metal-containing nanostructures to non-conducting materials enables changing the electrical-physical characteristics of such composite materials, which are essential for protective properties, as well as to control them.

Special attention should be paid to the research and development of composite electromagnetic screens with regular structures [10]. Nevertheless, production of specialized fabrics for shielding is linked to technological problems. Control over protective properties of such materials is very complicated. The same is true for regular structures with conducting linear elements [11]. They possess satisfactory protective properties but are not suitable to cover large areas because of large weight, width and cost.

The analysis performed reveals that dependences of shielding coefficients on size of the particles of a metal filler in the body of a dielectric matrix have been insufficiently investigated. It is necessary to determine the quantitative values of shielding coefficients on the weight content of metal filler in a protective material. Development of such materials is desirable with regard to the use of waste from other industrial processes. A calculation method for the estimation of required parameters of a screen, given the dimensions and regularity of arrangement of metal particles, which would be simple in practical application, is still missing.

3. The aim and objectives of the study

The goal of present study is to develop and examine protective composite materials in order to create electromagnetic screens based on the metal-containing nanostructures with a wide range of control over coefficients of absorption and reflection.

To accomplish the goal, the following tasks have been set:

– to obtain protective surfaces with a filler of metal nanostructures and to determine the prospects of their use for the fabrication of electromagnetic screens;

– to establish dependences of the protective properties of composite screens on the concentration of a finely dispersed metallic substance and size of the particles;

– to establish dependences of the protective properties of composite materials on their electrical-physical properties and to propose a method for calculating the shielding and reflection coefficients of electromagnetic waves, which would prove convenient for practical application;

– to find promising directions of research into improvement of the protective properties of composite electromagnetic screens.

4. Materials and methods for examining protective properties of composite electromagnetic screens

A general trend in the development of the field of wireless communication for various purposes is a gradual increase in the operating frequencies of technical means. That is why we chose the 5 GHz frequency for conducting the tests. The wavelength of such radiation is not fundamentally different from the parameters of the most common sources with working frequencies of 0.9–2.4 GHz. Research at this frequency will make it possible to clarify the prospects of the chosen approach to implement the measures of electromagnetic safety. Determining the protective properties of a shielding material was carried out by the methods of direct measurement of energy flux densities (mW/cm^2), which is predetermined by the acting standards of electromagnetic safety for the electromagnetic fields at frequencies above 300 MHz.

The measurement was carried out using the calibrated energy flux density meter PZ-31. A relative error of measurement did not exceed 1 dB. Electromagnetic wavelength at a frequency of 5 GHz is 0.06 m. Dimensions of the samples for conducting the tests excluded the effect of diffraction phenomena at the edges of the screen (emergence of "half-shadow" distorts the results of measurements).

The source of radiation was at a distance of 1 m from the screen, which matched two mandatory conditions. The first one is for the sample to be in the wave field of the electromagnetic field. The second one implies that dimensions of the screen are much larger than the length of the electromagnetic wave.

The measurements were carried out in three stages. At the first stage, we measured the density of energy flux without using the screen. At the second stage, we measured this parameter when the screen was placed between the source of electromagnetic radiation and the measurement antenna. This allows us to determine the total shielding coefficient of the tested sample. At the third stage, the measuring antenna was located between the source of radiation and the screen. This enabled us to establish a contribution of the reflection of electromagnetic waves to the total shielding coefficient.

In all cases, orientation of the receiving antenna of the measuring device was the same. During measurements, a background of the external electromagnetic measurement of ultrahigh and higher frequencies did not exceed 0.08–1.00 mW/cm^2. The intensity of radiation of the tested source of electromagnetic field was at least two orders of magnitude larger, which minimized an error of measurement due to the external electromagnetic influences.

5. Results of research into composite materials for shielding the electromagnetic fields

A large size of the screen, even at the stage of experimental determining of its properties, is critical in terms of the accuracy of measurements (minimizing the diffraction phenomena at the edges of the product). Uniformity of distribution of the filler is critical for homogeneous protective properties and it reduces the volumes of experimental work. In this case, at the stages of testing, such uniformity should be guaranteed to prevent obtaining false data.

Receiving a composite material with the required concentration of nanoparticles is possible using two methods. The first is the synthesis of particles directly in a polymeric material from appropriate additives (in situ). The second implies the addition to the solution or melt of ready metal-containing finely dispersed particles. The first method was sufficiently developed [12]. However, obtaining the samples with large areas for testing proved to be quite problematic. To receive the examined samples, we used finely dispersed iron oxides Fe_2O_3 and Fe_3O_4 of average size 50–300 nm. This minimizes the effects of reflection, which manifested themselves at application of aluminum powder (petals of thickness 0.25–0.50 μm with average minimum size 20–50 μm).

We chose the epoxy resin with subsequent polymerization using a polyamide hardener as a matrix (model material). The amount of a metal component was determined by weight.

Measurement of the total shielding coefficient and the contribution of the shielding due to reflection to it was conducted on the samples the size 0.75×0.75 m. Penetration of radiation beyond the screen was excluded. We used a high-frequency generator and antenna as the radiation source.

The tests were carried out for samples with the dispersion of a metal-containing component of 50–100 nm and 200–300 nm, and a thickness of 5 mm. Measurement results are shown in Figs 1, 2.

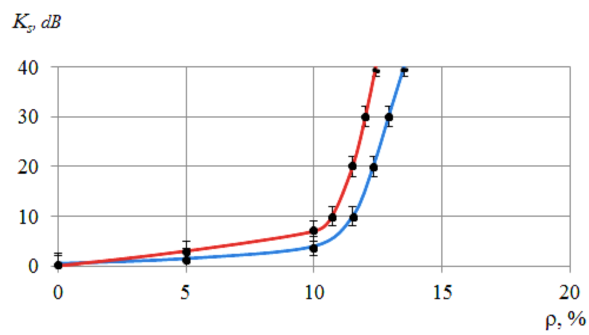


Fig. 1. Dependence of shielding coefficient of a composite material on the size of metal-containing particles and their concentration (by weight):
◆ – 50–100 nm; ■ – 200–300 nm

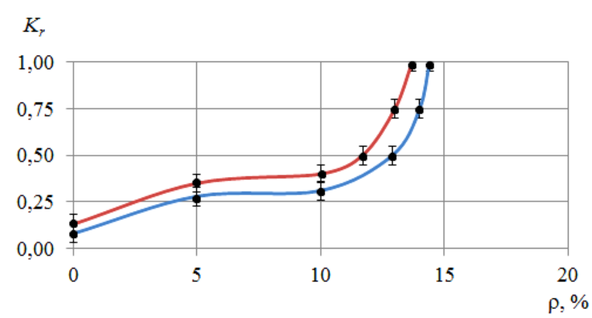


Fig. 2. Dependence of reflection coefficient of a composite material on the size of metal-containing particles and their concentration (by weight):
◆ – 50–100 nm; ■ – 200–300 nm

Earlier studies [6, 9] indicate that the protective properties of materials depend on their electrical-physical properties. We measured electrical conductivity of the received materials. It was conducted using the compensation method by bridge circuit. Results are shown in Fig. 3.

The results show that the growth of protective properties occurs at the border of the electric current flow (concentration of 11–13 % in Fig. 3). In this case, reflection coefficient rises as well; however, the presence of such data allows us to optimize the ratio of coefficients of absorption and reflection, depending on the required levels of protection under actual conditions.

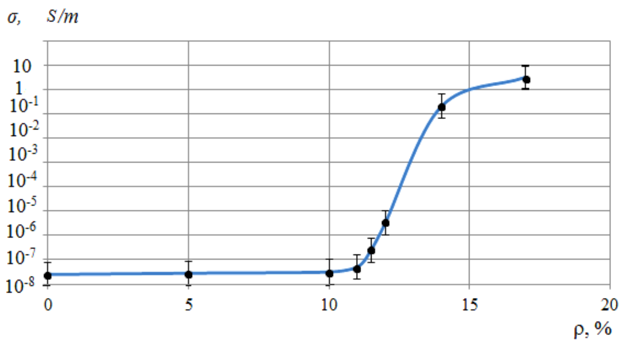


Fig. 3. Dependence of electrical conductivity of a composite material on the concentration of a metal-containing material

The required coefficients can be determined in advance based on the electrical-physical properties of materials.

Thus, the attenuation coefficient of electromagnetic wave K_s (by power) is determined as [6]:

$$K_s = \frac{(n+1)+\chi^z}{4n}\exp\left(\frac{z\chi\omega x}{c}\right). \tag{1}$$

The coefficient of reflection K_r in the case of a normally incident wave is determined as:

$$K_r = \frac{(n-1)^2+\chi^z}{(n+1)^2+\chi^z}, \tag{2}$$

where n is the refractive coefficient of a material; x is the thickness of the sample; ω is the cyclical radiation frequency; χ is the extinction coefficient of a material, which defines the speed of a wave attenuation.

In this case, we can assume that

$$Z = \frac{\sigma_d}{\sigma_m}, \tag{3}$$

where σ_d and σ_m are the conductivities of a dielectric (matrix) and a metal.

Coefficients n and χ are easily determined from the ratio of the real and imaginary parts of the complex dielectric conductivity of a material:

$$n = \sqrt{\frac{\varepsilon_1 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2}}{2}}, \tag{4}$$

$$\chi = \sqrt{\frac{\varepsilon_1 - \sqrt{\varepsilon_1^2 + \varepsilon_2^2}}{2}}, \tag{5}$$

where ε_1 and ε_2 are the real and imaginary parts of the complex dielectric conductivity $\hat{\varepsilon}$:

$$\hat{\varepsilon} = \varepsilon + i\frac{4\pi\sigma}{\omega}. \tag{6}$$

Results of the calculation of reflection coefficient by the above ratios are presented in Table 1.

Table 1

Dependence of reflection coefficient of the electromagnetic screen on the concentration of a metal-containing component

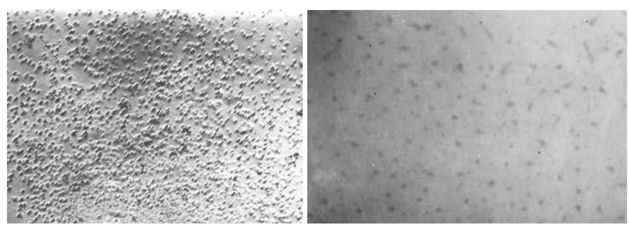
ρ, %	5	10	11	12	13	14
K_r	0.18–0.22	0.2–0.33	0.27–0.35	0.38–0.42	0.48–0.52	0.68–0.76

In the course of calculation, we employed the parameters of starting materials from reference sources. Electrical conductivity of epoxy resin is ~10^{-8}–10^{-7} S/m, ε~14. Electrical conductivity of the mixture of iron and iron oxides is ~10^5–10^6 S/m.

6. Discussion of results of research into composite materials for shielding the electromagnetic fields

An analysis of the results obtained indicates that the differences between experiments and calculations are satisfactory, at least in terms of the requirements for electromagnetic safety. Given the errors of field measurements and a number of assumptions when determining mathematical interrelations (1)–(6), these results can be considered acceptable.

As noted above, a necessary condition of stability of the protective properties of a material is the uniformity of distribution of the particles, which influence this parameter, in the body of the matrix. This was verified using a raster electron microscope (Fig. 4).



a *b*

Fig. 4. Distribution of metal particles in the body of the matrix: *a* — magnification ×800, *b* — magnification ×1100

The images above show that the arrangement of particles in the body of a polymer is dense and uniform (Fig. 4, *a*); in this case, distances between separate particles differ with acceptable spread (Fig. 4, *b*). The result received testifies to the possibility of fabricating a material with the required protective properties without the use of complicated technology for the synthesis of nanostructures in the body of the matrix, which limits the size of the screen.

Theoretical considerations indicate that it is thus possible to obtain a material with the concentration of particles in the body of the material variable by depth. This will make it possible to manufacture a gradient type screen without the use of multiple layers of material, which is always associated with the problems of adhesion between layers and the degradation of materials.

Results of the tests confirm the prospects of the chosen path in the development of electromagnetic screens. However, the examined material can be considered as a model only. Because of the fragility of the matrix, it possesses large thickness, which is not convenient for practical application while specialized obtaining of finely dispersed metal-containing particles is complex and expensive in large quantities.

At the same time, effectiveness of using local means for the protection of people from the radiation of communication means is questionable. A special feature in the formation of electromagnetic background of radiation of ultra-high and higher frequencies inside and outside the premises is its practical isotropy. One should not consider the sources of such radiation as pointed [13]. Under such conditions, electromagnetic screens must meet the following criteria to implement efficient protection:

– the possibility of fabricating a protective surface with a large area;

– manufacturability of material for lining the surfaces with complex configuration;

– acceptable cost of components and manufacturing technology.

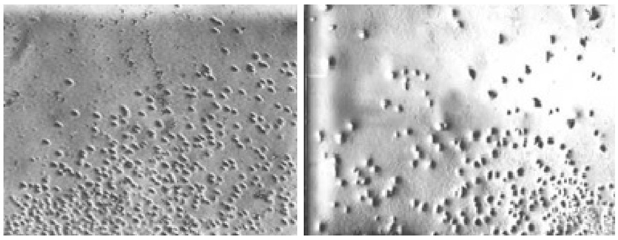
That is, it is necessary to have sufficient amount of metal-containing finely dispersed powder and flexible polymer matrices with low cost.

Data shown in Figs 1–3 indicate a significant reserve of protective properties, based on the actual conditions even in energy-saturated industrial environment. The calculations that are based on the above ratios indicate that increasing the size of metal-containing particles to 2–10 μm will improve reflection coefficient by 18–20 % only, which is not critical for most industrial conditions. Such particles in large quantities are a byproduct of the iron-ore enrichment plants [14].

This dust is deposited on the filtration curtains of aspiration systems. An analysis revealed that the content of Fe in the dust and gas flows, depending on the industrial area, is 43–58 %, that of FeO – 8–15 %. In this case, the last curtain accepts the dust of iron ore particles the size of 2.5–10.0 μm (up to 90 %). The use of such dust includes an environmental component as well because of the constant need for its disposal.

To obtain a protective surface, the iron-ore dust in the required amount was dissolved in an aqueous suspension of polyvinyl acetate with subsequent polymerization at a temperature of 60–70 °C. As a result, we obtained a metal polymer material of thickness from 0.8 mm. Control tests have proved that the dependences of the coefficient of reflection and the coefficient of shielding on the concentration of metal and metal-containing substances differ from those shown in Fig. 1, 2 within the measurement error.

In this case, given the thickness of the material is 1.0–1.2 mm, as a result of different dimensions of metal-containing particles, it is possible to receive their different concentration in the body of the matrix by thickness (Fig. 5).



a *b*

Fig. 5. Gradient of a metal-containing component in the polymer matrix: *a* — magnification ×800; *b* — magnification ×1100

Such design allows for a more effective shielding of electromagnetic radiation of a specific frequency band or a broadband radiation. This is caused by the fact that there occurs the alignment of absorbing structure by depth and the medium of propagation of electromagnetic waves. Thus, for a facial layer, to minimize the reflection, wave resistance of the material:

$$Z = \left(\mu / \varepsilon \right)^{\frac{1}{2}}, \tag{7}$$

where μ, ε are the relative magnetic and dielectric conductivities of the material.

Wave resistance must be maximally close to the resistance of air (377 Ohms). This ratio varies by depth, contributing to the the maximum absorption of electromagnetic energy.

Studies have proven that by employing such a procedure, it is possible to pre-calculate the required parameters and to fabricate an electromagnetic screen with required performance efficiency for any frequency composition of radiation of ultra-high and higher ranges.

As noted above, the protective properties of electromagnetic screen can be determined based on the electrical-physical properties of material (1)–(7). However, the process is labor-consuming and it is more suitable for use at the search stages of research into electromagnetic safety. To ensure safe working conditions, of practical importance is the through attenuation (total shielding coefficient) and contribution to it of the lowering intensity of radiation through the reflection of electromagnetic waves.

An analysis of Fig. 1–3 reveals that at concentration of the metal component exceeding 12–13 %, the developed material can be considered a solid screen with sufficiently pronounced conducting properties, that is, with values of relative magnetic permeability that approach the indicators of ferromagnets.

In a general case, shielding coefficient depends on the orientation of the wave relative to the surface of the screen.

Thus, for a normal incident wave, for the screens with high concentrations of a ferromagnetic component, a shielding coefficient can be determined from ratio (8):

$$K_s = 20\lg\left\{ \mathrm{ch}\,k\delta \left[1 + \frac{1}{2}\left(\frac{Z_q}{Z_m} + \frac{Z_m}{Z_q} \right) \mathrm{th}\,k\delta \right] \right\}, \tag{8}$$

where $k = \sqrt{j\omega\mu\sigma_m}$ is the coefficient of eddy currents; δ is the thickness of the screen; Z_q and Z_m are the wave resistances of the dielectric (air) and metal of the screen, respectively.

If we have a gradient screen, made of layers with different concentrations of a metal component, then Z_q is taken as the resistance of the preceding layer.

In this case, total shielding coefficient K_s will consist of the coefficient of reflection K_r and absorption coefficient K_a:

$$K_r = 20\lg\left[1 + \frac{1}{2}\left(\frac{Z_q}{Z_m} + \frac{Z_m}{Z_q} \right) \mathrm{th}\,k\delta \right], \tag{9}$$

$$K_a = 20\lg \mathrm{ch}\,k\delta. \tag{10}$$

These relations demonstrate that the absorption of electromagnetic energy increases with an increase in the field frequency, thickness, magnetic permeability and conductivity of the material of the screen, while reflection coefficient is determined by a mismatch in the wave characteristics of layers.

Thus, thickness of the screen, which provides for the required shielding coefficient at the border "air – solid screen" can be easily calculated by ratio:

$$\delta = \frac{K_s}{15{,}4\sqrt{\frac{\omega}{2\pi}\mu\sigma_m}}, \quad (11)$$

where ω is the circular frequency of feeding electromagnetic field, μ is the relative magnetic conductivity, σ_m is the conductivity of screen's material.

Fig. 4 shows that the location of metal particles is sufficiently regular, which is why at low concentrations of a metallic filler (less than 12 %), this material can be considered as a metal grid with the defined size of the particles and the gaps between them.

When the electromagnetic wave is incident at a right angle to the surface of the screen, given its linear polarization, vectors of electric and magnetic components of the electromagnetic field are parallel to the plane of the screen. In this case, the shielding coefficient is determined from relation:

$$K_s = 10\lg\frac{4\left(\frac{d}{\lambda}\ln\frac{d}{2\pi r_0}\right)^2}{1+4\left(\frac{d}{\lambda}\ln\frac{d}{2\pi r_0}\right)^2}, \quad (12)$$

where r_0 is the radius of a metal particle, d is the average distance between the particles (a particle step in the orthogonal projection), λ is the length of the incident electromagnetic wave.

The most interesting in terms of practice is the case when the electromagnetic wave is incident at a certain angle to the screen. In this case:

$$K_r = 10\lg\frac{4\left(\frac{d\cos\varphi}{\lambda}\ln\frac{d}{2\pi r_0}\right)^2}{1+4\left(\frac{d\cos\varphi}{\lambda}\ln\frac{d}{2\pi r_0}\right)^2}, \quad (13)$$

$$K_s = 10\lg\frac{(1-\cos\varphi)^2+4\left(\frac{d}{\lambda}\ln\left(\frac{d}{2\pi r_0}\right)\right)}{1+4\left(\frac{d}{\lambda}\ln\left(\frac{d}{2\pi r_0}\right)\right)}, \quad (14)$$

where φ is the angle between the direction of propagation of electromagnetic waves and a normal to the surface of the screen.

The given relations are derived from the fundamental physical laws regarding the scattering of electromagnetic waves by regular metal structures.

For the effective absorption of electromagnetic waves by the regular structures, there should be maintained certain relations between their parameters and wavelengths. The most important of them are $d<0.1\lambda$, $r_0<0.1d$.

7. Conclusions

1. The most promising materials for the protection of people against exposure to electromagnetic fields and ensuring the electromagnetic compatibility of technical means are metal polymer composites with a filler made of nanoscale particles. They provide shielding coefficients to 10 dB at the content of metal substance of 11–12 % and reflection coefficients of 0.27–0.30, which is unattainable for the materials based on macro particles.

2. Protective properties of nanocomposite electromagnetic screens depend not only on the concentration of metal-containing particles, but on their dimensions. Increasing the dispersion of particles by 2–4 times reduces reflection coefficient by 0.15–0.20 at a satisfactory shielding coefficient of 7–8 dB. This provides control over protective properties of materials depending on the frequency-amplitude characteristics of the shielded field and on particular industrial needs.

3. The resulting dependence of conductivity of a metal polymer material on the concentration of a metal component allowed us to calculate the value of the total shielding coefficient and a contribution of reflection coefficient to it, which simplifies the process of designing and fabricating the screens and has an economic component.

4. We examined the uniformity of distribution of finely dispersed particles in the body of a polymer matrix. High regularity of metal-containing structures makes it possible at their low concentrations (up to 10 %) to calculate coefficients of absorption and reflection using the relations of physical optics.

5. We developed a protective material and confirmed by the micro structural research the possibility of obtaining the concentration of metal-containing particles variable by depth (by thickness of the screen). This enables designing electromagnetic screens of the gradient type without the use of multilayered structures.

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Наведено результати досліджень механізму прямого і зворотного мартенситного перетворення в поверхневому шарі шліфований деталі із загартованої сталі. Показано, що при шліфуванні в основному має місце зворотне мартенситне перетворення за схемою мартенсит – перліт –аустеніт. Показана можливість швидкісного відпустки мартенситу до перліту, під дією контактної температури шліфування, який при подальшому підвищенні температури перетворюється в аустеніт, утворюючи припік гарту

Ключові слова: мартенситних перетворення, контактна температура, швидкість на гріву, відпустка мартенситу, швидкість дифузії, температура аустенітизації

Приведены результаты исследований механизма прямого и обратного мартенситного превращения в поверхностном слое шлифуемой детали из закаленной стали. Показано, что при шлифовании в основном имеет место обратное мартенситное превращение по схеме мартенсит – перлит –аустенит. Показана возможность скоростного отпуска мартенсита до перлита, под действием контактной температуры шлифования, который при дальнейшем повышении температуры превращается в аустенит, образуя прижёг закалки

Ключевые слова: мартенситное превращение. контактная температура, скорость нагрева, отпуск мартенсита, скорость диффузии, температура аустенитизации

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MARTENSITE TRANSFORMATIONS IN THE SURFACE LAYER AT GRINDING OF PARTS OF HARDENED STEELS

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1. Introduction

Most often, thermal grinding defects are formed in cemented, improved high-carbon, low and medium-alloyed steels with a martensite or tempered martensite structure [1–3]. When the surface of the part of the hardened steel is rapidly heated by the grinding temperature above the Ac_1 line, the martensitic structure of the surface layer transforms