Розроблено технологію виготовлення текстильного матеріалу з вмістом феромагнітних наночастинок для екранування електромагнітних полів. Показано, що найбільш ефективним методом зчеплення наночастинок з волокнами текстильного матеріалу є нанесення магнітної рідини з наночастинками на матеріал та витримка його у неоднорідному постійному магнітному полі. За умов напруженості магнітного поля 450 А/м та його впливу протягом 12 годин імплантація наночастинок у лляну тканину стає практично незворотною. Досліджено захисні властивості розробленого матеріалу. За просочення магнітною рідиною з витратами 45–50 г/м^2 (вміст феромагнітних частинок – 9 % за вагою) коефіцієнти екранування для 1–3 шарів матеріалу складають: для електричного поля промислової частоти 1,4÷4,8; для магнітного поля – 1,9÷8,1. Після магнітної обробки ці показники складають 2,9÷8,6 та 2,3÷8,9 відповідно. Для видалення з магнітної рідини технологічних компонентів, таких як вакуумне мастило та олеїнова кислота, достатньо застосувати синтетичний миючий засіб, що підтверджено експериментальним шляхом.

Досліджено ефективність отриманого результату у реальних виробничих умовах. Встановлено, що зниження напруженості магнітного поля промислової частоти та її інтергармонік одним шаром просоченого матеріалу без магнітної обробки складає 1,4, з магнітною обробкою – 2. При цьому не відбувається суттєвого зниження рівня природного геомагнітного поля. Проведено моделювання розподілу магнітного поля у тілі людини у разі виготовлення з розробленого матеріалу захисного костюму. За умов гарантованого зниження напруженості магнітного поля у 2 рази у критичних місцях спостерігається підвищення рівня поля у шийному відділі через підвищення у цьому місці магнітного опору. Це необхідно враховувати при проектуванні конфігурації захисного костюму

Ключові слова: електромагнітне поле, наночастинки, текстильний матеріал, коефіцієнт екранування, магнітна обробка

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STUDYING THE SHIELDING OF AN ELECTROMAGNETIC FIELD BY A TEXTILE MATERIAL CONTAINING FERROMAGNETIC NANOSTRUCTURES

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1. Introduction

Current requirements for the occupational safety of personnel operating the sources of electromagnetic fields [1] imply the availability of individual and collective protection means. This is because the electric and magnetic fields of anthropogenic origin are harmful to human health. In the appendix to [1], it is noted, based on the analysis of hygienic data, that the broad-spectrum electromagnetic fields cause both temporary and irreversible health consequences. These are, first of all, the suppression of oxidation-reduction processes in tissues, vasodilation, the increase and decrease in blood pressure, bilateral cataract, electrocardiographic changes, changes in behavior caused by disorders of the nervous system exposed to chronic electromagnetic effects. The maximum permissible values for a magnetic field of the industrial frequency inside the premises are 0.5 μT, and for an electric field   0.5 kV/m. The World Health Organization applies the principle of ALARA (As Low As Reasonably Achievable) to electromagnetic fields. This means that the magnitudes of electromagnetic fields must be minimized if technical capabilities are available.

The most effective means to reduce the levels of electromagnetic fields are electromagnetic screens and special clothing made from shielding materials. In particular, such clothes are obligatory for workers in the energy sector. The main requirements for such materials are reasonable coefficients of shielding an electric field, a magnetic field of ultralow (industrial) frequency and its harmonics, manufacturability, and reasonable cost. In addition, such materials must withstand mechanical and thermal treatment (washing, chemical cleaning, etc.) without significant loss of protective properties. At present, there are no materials that meet all these requirements. It is a relevant task to design an innovative material suitable for the manufacture of personal protective equipment against the effect of electromagnetic fields.

2. Literature review and problem statement

Practically all materials for protection of workers under conditions of the influence of electromagnetic fields have a metal wire woven into the fabric [2]. A fundamental disadvantage of such structures is the decrease in the protective properties of the material during operation because of wire breaks. In addition, the articles made from these materials imply grounding. It also refers to materials with microwires [3]. These shortcomings are not inherent in the materials with a uniform distribution of the shielding substance in the body of a material (matrix) [4]. However, ferrite particles in the matrix are of large size, which makes the material thickness (1 mm or larger) unacceptable for the manufacture of protective clothing. Paper [5] proposes a protective material with a wide frequency range consisting of cellulose that contains moisture. However, this material quickly degrades, that is, it loses moisture under mechanical influences. Study [6] addresses the use of nanocarbon as a screening substance in a polymeric matrix. Such material has acceptable shielding coefficients. However, it cannot be used to make special clothes because of poor thermodynamic characteristics. It is shown in [7] that the efficiency of shielding the industrial-frequency magnetic field and the electromagnetic field of ultra-high frequency increases with a decrease in the dimensions of metallic particles in a composite metal-polymer material. These screens were made using iron microparticles and iron oxides and had a thickness of 1–3 mm. Therefore, it is expected that decreasing shielding particles to the nanosize could reduce the material thickness while maintaining the efficiency of shielding.

Work [8] investigated the possibilities of applying nano-particles based on ferrites as the screening materials. Its advantage is the presence of a mathematical apparatus for calculating the screening efficiency; the work, however, considers the protection from electromagnetic fields of ultra-high and extremely high frequencies. The use of polypropylene as the base makes the material unacceptable for the manufacture of personal protective equipment.

Study [9] addresses the possibilities to apply nano-size carbon fiber for electromagnetic field shielding, but it considers the protection against fields at the frequencies of 8 GHz and above. There are no data on the use of nanocomposites to protect against electrical and magnetic fields of industrial frequency.

The authors of work [10] theoretically substantiated and performed a computational experiment on the use of a magnetic liquid as a magnetic screen. They considered a layer of the magnetic liquid, which is impossible to obtain under actual conditions; however, the results indicate the prospects of its application.

Article [11] modeled the possibility for magnetic nanoparticles to penetrate porous materials under the influence of a magnetic field. However, no experimental data are given about its implementation. That was reported in [12]. Specifically, it was shown that a thin layer of a magnetic-based fluid based on nano iron (up to 0.25 mm) has the industrial-frequency magnetic field shielding coefficients from 2.4 to 3.4 depending on the intensity of the screened field. It was demonstrated that the effective magnetic permeability of a spherical liquid on a surface is 420–1,050, and this indicator is for the magnetic liquid itself is about 100. Given that the coefficient of shielding of a magnetic field increases with an increase in the relative magnetic permeability of a material, it is concluded that the protective properties of the material were due to the density of nanoparticles inside the material. However, the protective material described is a model because the magnetic liquid was applied to the porous paper, which is of no practical significance.

Thus, there are tasks related to using a magnetic liquid as the shielding substance on an actual carrier – textile material, the irreversible dense fixation of the shielding particles in fibers, to investigating the protective properties of a material and determining the possibilities to apply it for making personal protection means against the effect of electromagnetic fields.

3. The aim and objectives of the study

The aim of this study is to identify the protective properties of a textile material containing iron and iron-containing nanoparticles and to determine the possibility to apply it to make individual protective equipment.

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

– to devise a technology for applying and fastening metallic nanoparticles on a textile material;

– to investigate the dependence of the protective properties of a material on a manufacturing technology;

– to substantiate the possibility of making protective clothing from the examined material.

4. Materials and methods to study the protective properties of a shielding material

The chosen base for a material to shield the electromagnetic fields was a standard linen cloth recommended in Ukraine for the production of specialized clothing. Its advantage is that the linen fibers have large porosity, which increases the possibilities to implant metallic nanoparticles into them. The shielding substance is the magnetic liquid made by Ferrohydrodynamic ltd. in the city of Mykolaiv (Ukraine). A magnetic fluid is a settled colloidal solution of solid particles in a liquid medium – vacuum oil and ethyl alcohol. The dispersed phase of the solution consists of particles of ferromagnetic materials (magnetite, ferrites, iron) the size of 3–10 nm. The content of nanoparticles, according to the manufacturer, is 9 % (by weight). To prevent the sticking of the particles, the magnetic liquid is added with a surfactant – oleic acid.

We measured the intensity of the electric field and the induction of the magnetic field of industrial frequency at the calibrated VE-meter, modification "AT-004" and "50 Hz" equipped with the control unit "NTM-Terminal" (Russian Federation) according to the manual. The limit of a permissible relative error of measurements of the mean quadratic values of the electric and magnetic field intensity is 15 %.

We determined changes in the amplitude values of the electric and magnetic field of the low-frequency spectrum at the calibrated spectrum analyzer Spectran NF-5035 (Germany) according to the manual. The maximum measurement error did not exceed 1 %. In all cases, the tested screen was geometrically closed around the measuring antenna. Modeling of the spatial distribution of the magnetic field and the effectiveness of protective clothing made from the developed material was carried out using the COMSOL software suite.

5. Development of the technology for applying and fastening metallic nanoparticles on a textile material

To obtain the textile material for shielding electrical and magnetic fields, it is necessary to implant the nanosized shielding iron particles into its structure.

In the first stage of our study, this was achieved by impregnating a linen fabric with the magnetic liquid based on a 40 % aqueous solution of ethyl alcohol. It is difficult to change the amount of nano iron per unit of fabric area to a fixed value, therefore, in the course of the study, we changed the number of layers of the material that corresponds to the double and triple concentrations of the shielding substance. The magnetic liquid consumption at a single impregnation of the fabric was 45–50 g/m^2. The number of nanoparticles was up to 4.0–4.5 g/m^2.

However, the resulting material, despite using ethyl alcohol as its base, is not suitable for practical use due to the oily structure. The magnetic liquid manufacturing technology implies the addition of a surfactant – fatty oleic acid, which prevents the sticking of nanoparticles.

In the second stage of the study, the main task was to remove fatty oleic acid from the fabric. Two techniques were used to remove the acid, alkaline solution neutralization (a 20 % aqueous solution of NaOH) and washing out by a synthetic detergent; in this case, the phosphate-free agent for fat removal "HG" (made by HG International B. v., Netherlands).

That is why, in the third stage of the study, in order to improve the protective properties of the material, we devised a technology of nanoparticle implantation in the fabric fibers under the influence of a heterogeneous permanent magnetic field. To this end, we used a neodymium magnet with a maximum intensity of the magnetic field of 450 A/m. The material was treated with a magnetic field for 12 hours. The study involved two samples, impregnated with the magnetic liquid, one of which is control. We used magnetic liquid based on VM-3 vacuum oil. This vacuum grease can be removed only by a detergent, but its functional properties are better, compared with an alcohol solution, because of the greater viscosity, which reduces the washout of the liquid from the fabric during treatment. The magnetic-treated and control samples were exposed to the synthetic detergent similarly, until the complete removal of vacuum grease and oleic acid.

6. Investigating the dependence of the protective properties of the material on a manufacturing technology

We determined the coefficients of shielding the electromagnetic fields by textile materials also in three stages.

The first stage implied studying the protective properties of the materials impregnated with a magnetic liquid based on ethyl alcohol.

Given that the electric and magnetic field of industrial frequency is quasi-stationary, our measurements involved the geometrically closed surfaces made from the examined material (dimensions 0.2×0.2×0.2 m), for which a distance from the source of the field is not important. The measuring antenna was placed in a protected zone through a technological hole.

The results of measuring the shielding of electrical and magnetic elements of the industrial-frequency electromagnetic field by the material are given in Table 1.

Table 1

Shielding of the electromagnetic field of industrial frequency by the textile material impregnated with a magnetic liquid with iron-containing nanoparticles

	E, V/m			*B*, μT		
n	E_f	E_s	K_s	B_f	B_s	K_s
1	720	525	1.4	146	76	1.9
2	720	290	2.5	146	29	5.0
3	720	190	3.8	146	18	8.1

Note: n – the number of layers of protective material; E_f – intensity of the electric field of a field source; E_s – intensity of the electric field in the zone protected by the shielding material; K_s – coefficient of shielding (normative dimensionless quantity that shows a decrease in the field intensity, $K_s=E_f/E_s$), B_f – induction of the magnetic field of a source, B_s – magnetic field induction in the zone protected by the shielding material, K_s – shielding coefficient of a magnetic field

Data in Table 1 show that with an increase in the number of layers of the protective material the shielding coefficient of both components of the industrial-frequency electromagnetic field increases sharply, which is due to the increase in the concentration of ferromagnetic nanoparticles. Given that the maximum allowable levels under industrial conditions are seldom exceeded by larger than 2–3 times [12], the result obtained can be considered acceptable.

In the second stage, we studied the protective properties of the materials impregnated with a magnetic liquid and treated with a detergent and an alkaline solution (Table 2).

Table 2

Shielding properties of the textile material treated with an alkaline solution and a synthetic detergent

	E, V/m					*B*, μT				
n	E_f	E_a	K_a	E_w	K_w	B_f	B_a	K_a	B_w	K_w
1	770	592	1.3	476	1.7	190	123	1.5	110	1.7
2	770	355	2.2	325	2.3	190	100	1.9	90	2.1
3	770	230	3.4	215	3.8	190	78	2.4	72	2.6

Note: E_a – electric field intensity in the zone protected by the shielding material treated with an alkaline solution; E_w – electric field intensity in the zone protected by the shielding material treated with a synthetic detergent; K_a, K_w – corresponding shielding coefficients; B_a – magnetic field induction in the zone protected by the shielding material treated with an alkaline solution; B_w – magnetic field induction in the zone protected by a shielding material treated with a synthetic detergent

An analysis of the data given in Table 2 shows that the removal of oleic acid from the material is followed by a decrease in its protective properties (Table 1). In the process of washing out a technological fluid, there is an additional removal of shielding particles from the material. Data in Table 2 demonstrate that the neutralization of acid with an alkaline solution, when compared to the mechanical treatment with a synthetic detergent, does not produce the desired effect.

In the third stage, we investigated the protective properties of the materials impregnated with a magnetic liquid based on a vacuum grease, exposed to a heterogeneous magnetic field, and treated with a detergent (Table 3).

Table 3

Shielding of the electromagnetic field of industrial frequency by the textile material treated with a magnetic liquid in a heterogeneous permanent magnetic field

	E, V/m					*B*, μT				
n	E_f	E_m	K_m	E_w	K_w	B_f	B_m	K_m	B_w	K_w
1	360	125	2.9	320	1.13	490	200	2.3	460	1.06
2	360	80	4.5	240	1.50	490	95	5.2	420	1.17
3	360	42	8.6	185	1.96	490	55	8.9	380	1.30

Note: E_m – electric field intensity in the zone protected by the shielding material after it was exposed to a magnetic field and treated with a synthetic detergent; E_w –electric field intensity in the zone protected by the shielding material treated only with a synthetic detergent; K_m, K_w – corresponding shielding coefficients; B_m – magnetic field induction in the zone protected by the shielding material after it was exposed to a magnetic field and treated with a synthetic detergent; B_w – magnetic field induction in the zone protected by the shielding material treated only with a synthetic detergent

The data collected indicate that the magnetic treatment of the fabric, impregnated with a magnetic liquid, significantly improves its protective properties, and ensures the irreversible implantation of the shielding particles into the fabric fibers. The above results were obtained for the magnetic field from the stabilized laboratory source. To determine the effectiveness of the resulting material under actual conditions, we conducted experiments on shielding the magnetic field of an alternating current electric machine (Fig. 1).

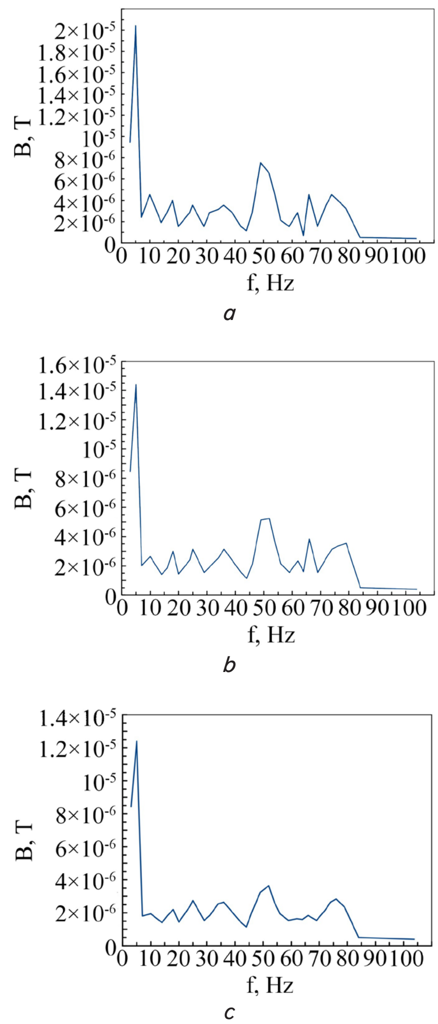

Fig. 1. Shielding of the magnetic field of an alternating-current electric machine by the textile material containing ferromagnetic nanostructures:
a — the output spectrum of the electric machine magnetic field;
b — a spectrum of the magnetic field in the zone protected by a single layer of the textile material treated with a magnetic liquid;
c — a spectrum of the magnetic field in the zone protected by a single layer of the textile material treated with a magnetic liquid in a heterogeneous permanent magnetic field

The specified spectra show that a magnetic field of industrial frequency is reduced by a single layer of the material without magnetic treatment, by 1.4 times; with magnetic treatment, by 2 times. The similar results relate to the inter-harmonics of a magnetic field (canonical and noncanonical), which are always present in the spectra of fields in actual electrical equipment. A peak at about 5 Hz, present in all spectra, is the low-frequency component of a natural geomagnetic field, whose significant decrease is undesirable.

The reported results, taking into consideration the data from laboratory studies and a small thickness of the textile base, can be considered satisfactory, and the designed material is suitable for making the shielding structures.

7. Discussion of results of studying the protective properties of the textile material containing ferromagnetic nanostructures and the possibility of using it for making protective clothing

When analyzing the acquired experimental data, one can notice some discrepancies between the results of measurements given in Table 3 and those shown in Fig. 1. Such differences may be due to a slightly different concentration of nanoparticles in the material and to different amounts of the output substance, which is washed off by a synthetic detergent. As noted above, the consumption of a magnetic liquid was 45–50 g/m^2. At the same time, according to the manufacturer's data, the number of the shielding substance, ferromagnetic nanoparticles, is 9 % (by weight). Therefore, some differences, given such content of the basic substance, are quite possible, at least under laboratory conditions. In addition, it is known that the shielding coefficients of electrical and magnetic fields depend on the amplitudes of these fields in each case. However, following the magnetic treatment, the fields' shielding coefficients remain sufficient for most industrial conditions.

It is necessary to estimate the possibilities of manufacturing protective clothing from the designed material. Experimental determining of the effectiveness of the protective gowns is very difficult given the necessity of remote measurement of the levels of magnetic fields at many points. Therefore, the set task has been solved by a numerical method of finite elements using the Comsol software.

In order to simulate the distribution of a magnetic field in the space behind a gown, the most unfavorable case was chosen: a magnetic field is directed vertically from the top, the protective properties of the material correspond to those given in Table 1. It was believed that the entire human body was covered with the protective material. Simulation results are shown in Fig. 2.

The obtained results suggest that even with the small content of ferromagnetic nanoparticles (up to 5 g/m^2) the warranted shielding coefficient of the magnetic field in the head and chest area is 2, which can easily be improved by using the devised technology.

The result of our simulation has revealed the unpredicted fact of the increased level of the magnetic field in the neck area, which has never been considered in the design of protective clothing. The cause is the passage of the magnetic flux along the surface of the material with a small area at the place of narrowing, which leads to an increase in the magnetic resistance. This predetermines the magnetization of the protective material and the penetration of the field into the inner space. Therefore, in the design and manufacture of protective clothing one should avoid such structural creases and to design a protective helmet together with the gown at the expense of single cut helmet and jacket components.

The devised technology for the magnetic treatment of a material has made it possible to obtain the material with a sufficient number of shielding particles after removing the chemical impurities. In such a form, it is suitable for making protective clothing and could be used for the adjacent industry – ensuring the electromagnetic compatibility of equipment. However, a multi-layer structure is not technological and is impractical. This is explained by the need to ensure compliance of protective clothing with the regulatory thermodynamic and ergonomic requirements, that is, the comfort of clothing. Our study involved the magnetic field of relatively low intensity, therefore, it is advisable, in order to improve the concentration of shielding particles in the fibers of a textile material, to improve the magnetic treatment by increasing the intensity of a permanent magnetic field and by creating zones of its great heterogeneity. This requires that a special installation should be designed with the structure of the poles of the magnet, which could provide for such heterogeneity.

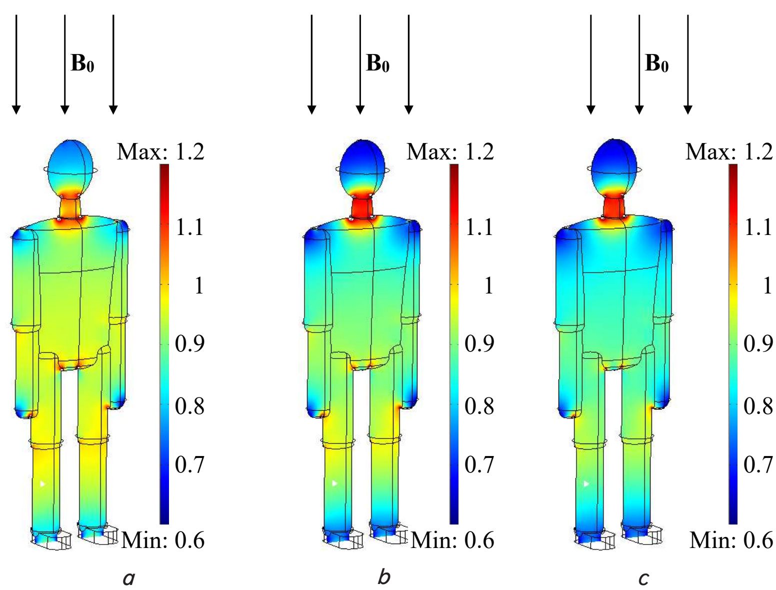

Fig. 2. The distribution of a magnetic field B/B_0 in the human body (in the middle plane) exposed to the longitudinal magnetic field B_0 and in the presence of protective clothing: *a, b, c* – the presence of 1, 2, 3 layers of protective fabric

8. Conclusions

1. It has been established that the most efficient method to ensure the *sticking together* between ferromagnetic nanoparticles and a textile material is to apply a magnetic liquid to the material and to expose it to a heterogeneous permanent magnetic field. Our study has proven that under the influence of a magnetic field with an intensity of 450 A/m for 12 hours the implantation of nano-particles into the fibers of a linen fabric becomes practically irreversible.

2. The study has shown that when impregnating a textile material with a magnetic liquid in the amount of 45–50 g/m^2 (the content of nanoparticles is 9 % by weight) the shielding coefficients for 1–3 layers of the material are: for an electric field of industrial frequency, 1.4÷3.8; for a magnetic field, 1.9÷8.1. Following the magnetic treatment of the material, these indicators are 2.9÷8.6 and 2.3÷8.9, respectively. At the same time, the magnetically-treated material was treated with a synthetic detergent.

3. It has been determined that in order to remove the technological liquids (grease, oleic acid), which are the mandatory ingredients of a magnetic liquid, it would suffice to use synthetic detergents. In this case, the degree of washing out the ferromagnetic particles is acceptable. The use of the ethyl alcohol-based fluid, with the subsequent neutralization of oleic acid by an alkaline solution, turned out to be impractical because of the washout or chemical destruction of the nano-particles by alkali, which was confirmed experimentally.

4. In order to determine the possibility of manufacturing special clothing from the designed material aimed to protect against electrical and magnetic fields, we simulated the magnetic field distribution in the human body using a finite element method and the Comsol software. It was established that, notwithstanding the acceptable, in general, results, the cervical spine of the human body experiences the increased field intensity due to the magnetic flux compression. This should be taken into consideration when designing protective clothing.

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