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Protective shielding fabric materials on the base of ferromagnetic microwire

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Abstract. The article presents the protective and operational characteristics of the developed protective fabric from electromagnetic radiation. The article proposes a technological scheme for the production of tissue that protects against electromagnetic radiation. At the heart of this fabric, it is proposed to use a nanostructured ferromagnetic microwire in a glass shell. It is determined that the protective characteristics of the fabric (screening and reflection coefficients, surface resistance) will depend on the following main factors: chemical composition of the microwire; diameter of the microwire; the number of cores of a microwire in a complex thread; the number of complex threads in the warp and weft systems.

1. Introduction

Some occupations bear the risk of human being exposure to electromagnetic fields with the radio frequency range (RF-EMF). The biological effect of electromagnetic fields (EMF) depends, mostly, on two parameters, namely a power and a frequency of radiation.

Depending on power, the exposure can be thermal or non-thermal.

The conventional value to distinct the exposure types is a power of 10 milliwatts per square centimetre of the exposed surface area. This power level can warm up body tissues by a few tenths of a degree.

Electromagnetic field energy absorbed by the tissues is transformed into heat that can impair thermoregulation and cause possible body temperature rise. Organs and tissues with poor thermoregulation capability (such as brain, eyes, kidney, intestinal tract and testis) are more sensitive to radiation. Overheating of tissues and organs leads to diseases, body temperature rise by 1 °C and higher is unacceptable.

The effect of electromagnetic fields includes not only a heat impact. Being exposed to fields, macromolecules of tissues become polarized and are positioned parallel to the electric field lines. This leads to changes in their properties.

The influence of electromagnetic fields can cause reversible and irreversible changes in the organism, namely: inhibition of reflexes, lowering blood pressure, slowing heartbeats, changes in blood composition tending to increase of WBC count and decrease of RBC count, as well as eye lens opacity. Subjective criteria of adverse effects of electromagnetic fields include undue tiredness, irritability, sleepiness, shortness of breath, reduction in vision and fever.



Absorbed energy depends on radiation frequencies. At a frequency of up to 10^6 Hz, body dimensions are small in relation to the wavelength and the dielectric properties of body tissues are mild. At higher radiation frequencies, especially at UHF, body dimensions and a thickness of certain tissue layers are comparable with wavelengths. Dielectric losses become significant, they vary in dependence on kinds of tissues. VHF waves (30 - 300 MHz) are weaker absorbed in tissues than decimetric waves (300 - 3000 MHz), while radiation of super high frequency band (3-30 GHz) can completely "be trapped" in the living tissue at a depth of a few centimetres. Radiations of the extremely high frequency band (30 - 300 GHz) also have significant effect on the biological organism.

Irradiation can be continuous or intermittent. The total effects of intermittent irradiation are slightly weaker in comparison to the continuous irradiation or equal to it.

2. Theoretical Aspects of the Research

Functional disorders caused by EMF are accumulated in the body, but remain reversible if the exposure to radiation field ceases and working conditions are improved.

An effective way to protect biosystems, including human beings, against EMF radiation, is the use of personal and group protective means on the base of special materials that can shield, reflect and absorb EMF radiation. For human beings, as a rule, this is fabric materials, i.e. protective clothes.

The core of any woven fabric structure that absorbs electromagnetic radiation is a thread to be treated with some kind of textile processing [1]. In view of this, it is reasonable to assume that radiophysical properties of the thread used will play the key role in obtaining the required characteristics of the structure as a whole.

In general, the thread can possess both electrical and magnetic properties. Requirements for the end product related to the operating frequency band of the incident electromagnetic wave (EMW) and the highest possible absorbed power impose, obviously, similar conditions on the feedstock.

It is clear from general physical considerations that uniform and high absorption of electromagnetic energy in a wide frequency band cannot be provided with the help of thread's electrical parameters only.

Indeed, it can be assumed that for each wavelength of the operating spectrum there is an optimal electrical resistance of the thread per unit length, at which the electromagnetic power absorbed by the thread reaches the maximum value. Thus, in case of the perfectly conducting thread (an electrical conductivity $\sigma \rightarrow \infty$), only electromagnetic energy dissipation is observed, the radar cross section (RCS) per unit length is maximum, while absorption is absent. On the other hand, for all-dielectric thread ($\sigma = 0$), the RCS is maximum, but energy absorption is not observed, as well.

If the thread is described with such parameters as backscattering cross section per unit length σ_s , determined by the ratio of reflected and incident powers and absorption cross section per unit length σ_a , determined by the ratio of corresponding powers, then it can be said that σ_s is steadily decreasing with the rise of the thread resistance per unit length from 0 to ∞ , whereas σ_a has a resonant appearance in case of the similar resistance behaviour, and the position of resonance (and presumably resonance magnitude) varies with changes in the length of irradiating electromagnetic wave.

Mathematical proof of the assumptions made can be found in study [2]. Based on the formulas proposed in this study, the absorbed power of the incident electromagnetic wave has been estimated for various electrophysical characteristics of the conductor (thread) for the specified wavelengths. The relations derived in the papers enable to plot the following (Figure 1).

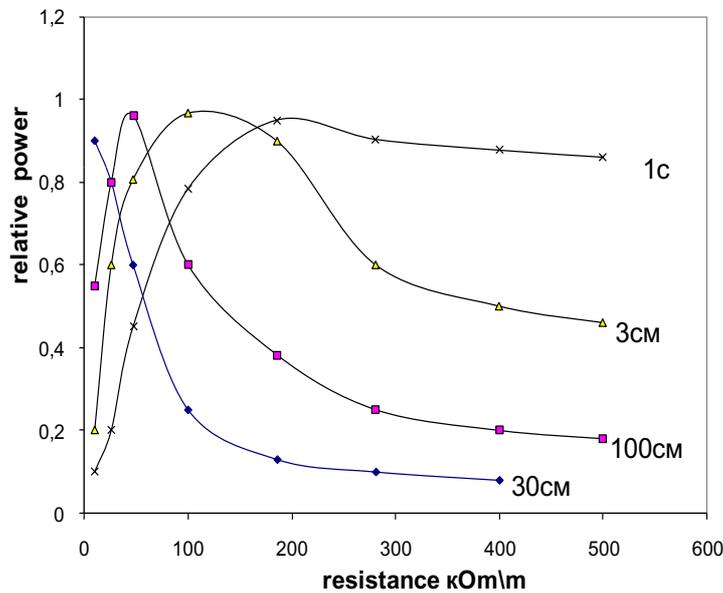


Figure 1. Relative absorbed EMW power as a function of resistance for a microwire with a diameter of 5 μm (skin layer thickness exceeds the microwire diameter).

The desired structure could be manufactured using conductive threads with different resistances corresponding to the optimal power absorption at various wavelengths. At the same time, in the general case, the absorption cross section per unit length of the conductive thread can be described by the well-known formula:

$$\sigma_a = \frac{\pi}{P_0} \quad (1)$$

where P_0 – stands for a power impinging upon the unit area: $P_0 = \frac{E^2}{2Z_0}$,

E and H stand for amplitudes of electrical and magnetic fields in a conductor of r radius,

μ'' – an imaginary part of conductor magnetic permittivity μ ,

$K_0 = \frac{2\pi}{\lambda}$, where λ is a wavelength,

$Z_0 = 120\pi$ – a free-space characteristic impedance.

In this case, the condition for effective absorption of electromagnetic wave energy impinging upon the fabric with conducting threads after considering all physical parameters and relations takes the following form

$$\frac{Z_0}{R \cdot \lambda} \quad (2)$$

From expression (1) it can be seen that the absorption cross section could be increased by using a ferromagnetic thread with high magnetic permittivity, provided however that condition (2) is met. Violation of this condition will lead to the rapid decreasing in the depth of field penetration into the thread and, as a result, to the reduction in the amount of energy absorbed by the thread.

Such ferromagnetic thread can be created on the base of a nanostructured ferromagnetic microwire (NFMW) in glass insulation. Among known ferromagnetic materials where natural ferromagnetic resonance is observed in ultra high frequencies (UHF) ranges with high magnitudes of $|\mu|$ a

nanostructured microwire in glass insulation with a conductive core made of ferromagnetic alloys (NFMW) seems promising (figure 2).

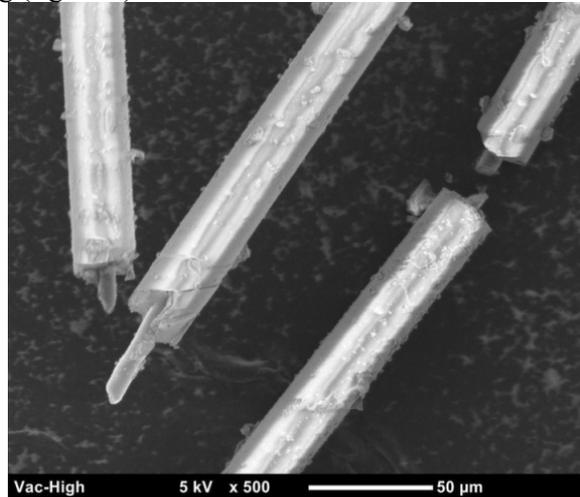


Figure 2. Electron microscopical image of nanostructured ferromagnetic microwire, the scale bar length in the image is 20 and 10 μm .

The microwire manufacturing technology have certain peculiarities, namely, different thermal expansion coefficients of the core glass insulation and the conductive core itself, as well as the nonzero magnetostriction constant of the conductive core alloy. These features cause the phenomenon of natural ferromagnetic resonance (NFMW) and changes in the material magnetic permittivity in the UHF range. Physically, the NFMW is produced by the high (almost to saturation) intrinsic magnetization of the conductor due to high magnetoelastic stresses in the core.

As shown in [3], the frequency of natural ferromagnetic resonance in such microwires can fall in the UHF range. Evaluation of the maximum UHF magnetic permittivity of a microwire with iron-based alloy core gave the result higher than 200. Thus, the microwire with the ferromagnetic nanostructured glass-insulated core is an exclusive material that combines the following properties:

- occurrence of magnetic losses in the UHF range;
- ability to change NFMW magnitude and frequency and adjust the microwire resistance per unit length using simple techniques;
- ability to produce continuous, up to several kilometres, microwire sections with predefined characteristics;
- chemical stability of insulation;
- advantageous weight and dimensional characteristics (one kilometre of the microwire weighs less than one gram.).

The properties of a ferromagnetic microwire, namely, the position of the natural ferromagnetic resonance (NFMW), the peak value (i.e. the values of μ' and μ''), and the width of the resonance curve can be adjusted by changing the conductive core alloy composition and the parameters of the NFMW manufacturing process modes.

The first ferromagnetic thread parameter to be selected must be its electric current resistance per unit length. It seems advisable (when using threads of the same diameter and same electrical conductivity to manufacture radar absorbing structures) to choose thin NFMW with a resistance per unit length of about 100-200 kOhm/m and with NFMW lying in the relatively long wave region. This allows the alignment of power absorbed by the wire in a wide range of wave lengths.

With that said, for each wavelength, there is an optimal electrical resistance per unit length of the conductor, which ensures maximum absorption of the wave energy dissipated by the conductor.

The radar cross section of a conductor with finite electrical conductivity decreases with increasing the wavelength rises. Using NFMW with a high conductor resistance against direct current as a base and with the NFMR lying in the wavelength range of 30-10 cm, it is possible to create the textile shielding structure of protective material for work clothes if the magnetic permittivity of the NFMW in the NFMR region does not exceed the value $\frac{\lambda R}{Z_0}$.

The technological scheme for the production of tissue that protects against electromagnetic radiation can be performed in two ways. In the first embodiment, the microwire is connected to the carrier yarn by jointly wrapping the microwire and the carrier yarn with a fastening thread.

In the second embodiment, the core thread, which determines the physico-mechanical properties of the complex thread, is entwined with a microwire. The result is a complex thread for the production of tissue with a microwire. In the first embodiment, the permissible deformation of the complex filament is determined by the properties of the microwire, i.e. very limited. In the second, the properties of the core thread and the pitch. In [4, 5], the influence of the properties of the upholstery component on the strength of the complex filament is considered.

The production process scheme for manufacturing fabrics that protect against electromagnetic radiation is as follows. The microwire and the warp yarn are coupled together by jointly wrapping them with a fastening thread [6]. The result obtained is a multifilament yarn for producing the fabric with microwire. Protective characteristics of the fabric (shielding and reflection coefficients, surface resistance) depend on the following basic factors:

- microwire chemical composition;
- a microwire diameter;
- a number of microwire cores in the multifilament yarn;
- a number of multifilament yarns in the warp and weft systems;
- upholstery step.

The variation range of these factors is restricted by both process and economic aspects.

So, for example, a certain chemical composition provides good shielding performance, but has a low plasticity and tensile strength, which leads to rupture during weaving. Moreover, it may be too expensive.

A larger diameter microwire increases a shielding factor of the fabric and a microwire strength, but significantly reduces the microwire casting productivity and increases its cost.

The additional microwire cores in the multifilament yarn also increases the shielding performance of the fabric, but increases its cost and complicates the multifilament yarn manufacturing process. A large number of multifilament yarns in the warp and weft fabric systems increases the protective characteristics, but complicates the weaving process and makes the fabric more expensive.

3. Conclusions

The above mentioned aspects define the shielding factor value within the ranges of their changes. Various combinations of them in the production process allow creating multifilament yarns and fabric patterns to obtain an effective in terms of protection, inexpensive and advanced fabric with predefined properties. The calculation shows that if the surface resistance of the protective material with a nanostructured ferromagnetic microwire does not exceed 30 Ohms, the shielding factor of this material will be at least 25 dB that provides the significant decrease (by a factor of 300) in the power of incident electromagnetic wave.

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