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Effectiveness of Shielding Electromagnetic Radiation, and Assumptions for Designing the Multi-layer Structures of Textile Shielding Materials

Abstract
In many cases, to obtain the required extent of protection against electromagnetic radiation (EMR) emitted by operating electrical and electronic devices, it is not enough to use only shielding materials that non-transmit the radiation as a results of its reflection, but it is indispensable to use shields (materials) possessing the capability to reflect and absorb EMR at the same time. Depending on their practical use, such materials should be characterised by a high EMR absorption coefficient, even twice as high as their reflection coefficient within as wide a frequency band as possible. This paper presents assumptions for designing multi-layer textile-polymeric materials, the dominating feature of which that increases the shielding effectiveness consists in absorbing EMR as a result of so-called multiple internal reflection. Methods for testing the coefficients of reflection and transmission as well as the preliminary assessment of the test results concerning the EMR shielding materials are also presented.

Key words: *electromagnetic radiation, attenuation, reflection, internal reflections, shielding effectiveness, multi-layer textile materials.*

Introduction

Fast progress in knowledge and technology has brought about a huge increase in the use of various types of electrical and electronic equipment that are a source of electromagnetic radiation (EMR), which, depending on the needs, can be regarded either as a desirable or undesirable phenomenon.

Thus, the problem of protection against electromagnetic radiation has a very important technical aspect concerning a reduction in the level of reciprocal interference of electronic instruments, i.e. on this basis: " do not interfere and do not be interfered". Furthermore, an even more important element of protection against EMR is the social aspect: the health protection of persons present in the vicinity of equipment emitting EMR with an appropriate power and frequency, and exposed to its prolonged effects.

This has intensified research aimed at the development of effective protective barrier materials designed for various practical uses. Depending on the type of electrical equipment and conditions of its use as well as the user's expectations, there are many structural solutions concerning EMR shielding materials.

Generally speaking, effective protection against EMR can be provided by its reflection or absorption, and in the best case by reflection and absorption at the same time.

The simplest is protection by the *reflection* of incident EMR. Such materials with a high reflection coefficient are mass-produced and used both at home and abroad. They include sheets or wire nets as well as thin metallic foils or metal-plated films and flat textiles such as woven, knitted or non-woven fabrics containing very thin mono- or two-layer coats of metal such as Ag, Cu or Ni deposited on their surfaces. Such coats are prepared by various methods, e.g. by chemical methods through vacuum evaporation; but the most recent and primary technique is plasma treatment [13, 28, 40 - 44, 47, 48]. Textiles finished in this way have great advantages, such as a generally low surface weight, high elasticity and shaping capability, high mechanical stability, ease of storage and transport, as well as relatively low costs [6 - 8, 10 - 11, 15]. A wide range of such metal-coated shielding textile materials, showing very high reflection coefficients up to 100 dB, is manufactured by many companies and commercially available [40 - 48]. Materials of this type mostly have no capability to absorb EMR, which in numerous cases, for example in shields of electronic equipment operating in rooms with a permanent presence of persons or in masking shields is of vital importance.

The problem of constructing shielding materials that effectively absorb EMR is incomparably more difficult as the level of barrier properties obtained depends, to a large extent, not only on the structure and thickness of the shielding material but also on the range of EMR frequency. Commercially available materials with EMR absorption as the dominating component constitute, as a rule, spatially developed complex structures, which are mostly exclusive non-textile materials, generally, of considerable thickness, stiffness with a large surface weight, which radically limits the range of their applications, e.g. excluding their suitability for making portable shields [1, 3, 5, 14, 16 - 27, 41, 42, 48].

In the present study, being the result of four research units, the authors have attempted to develop basic principles of the manufacturing technology of effective multi-layer EMR shields using the techniques of thin-layer coating on various textile substrates. Such shielding materials should be suitable for making new types of light, relatively thin, elastic textile or textile-polymeric protective shields as well as special protective clothing for workers exposed to effects of EMR in various branches of the economy, especially in the defence sector. Hence, the solutions proposed by us will be of importance for protection against EMR within the frequency range of 1 – 18 GHz. These are very high and ultra high frequencies. Assuming that the velocity of electromagnetic wave propagation in a vacuum amounts to $2.998 \cdot 10^8$ m/s, the frequency range considered corresponds to a range of waves with a length λ from about 30 cm to approx. 1.5 cm. Such a range of wavelengths allows one to confine the issue under discussion to a so-called far field , where the distance from the EMR source is higher than $\lambda/2\pi$, or is about 1/6 of the wavelength, which takes place in all the cases under consideration. In the far field, electric and magnetic fields are conjugated to form a so-called flat wave; in which case the field properties depend mainly on the properties of the medium in which the propagation takes place. The ratio of the electric field intensity E to the magnetic field intensity H is equal to the wave impedance. In the far field, the relationship E/H is equal to the characteristic impedance of the medium, being a constant value, e.g. in air or a vacuum it amounts to 377 Ω.

As assumed, the textile shields designed are to be thin and show as high a value of absorption coefficient of incident EMR as possible, with simultaneous minimisation of reflection and transmission coefficients.

Additionally, it is also predicted to impart other specified performance properties to such materials, e.g. water-tightness.

The test results of the effectiveness of EMR shielding by the multi-layer textile shielding materials designed will be the subject of our subsequent paper.

Effectiveness of electromagnetic shielding

In the literature one can find various definitions of the shielding notion. One of them describes electromagnetic shielding as a structural-technical process consisting in enclosing a space with an appropriate material to reduce the levels of electromagnetic fields on the opposite side of the shield in relation to the location of the field source [39].

A parameter that characterises any shield is the effectiveness of shielding. The same relationships is valid in relation to the conjugated field (far field) or electric component (near field) and is expressed by the following equation [2]:

$$S = 20 \log(E_1/E_2) \text{ in dB} \tag{1}$$

where: E_1, E_2 - intensities of electric field before and beyond the shield, respectively.

Taking into account the phenomena occurring at the boundary of two media, the absorption properties inside the shield and the effect of internal reflection, the relationship determining the total effectiveness of shielding can be given in a logarithmic form:

$$S = K_{ref} + K_{abs} + K_{correction} \quad \text{(all values in dB)} \tag{2}$$

or in a linear form:

$$S = k_{ref} \cdot k_{abs} \cdot k_{correction} \tag{3}$$

where:

K_{ref}, k_{ref} - coefficient characterising the effect of reflection at the boundary of two media;

K_{abs}, k_{abs} - coefficient characterising the internal absorption of the shield (or other material);

$K_{correction}$, $k_{correction}$ - coefficient characterising the multiple reflection inside the shield.

The particular coefficients of equation (3) can be calculated from the approximate relationships given below [1, 2, 36 - 38]:

$$k_{ref} \approx \frac{377\sigma\delta}{4\sqrt{2}} \tag{4}$$

$$k_{abs} \approx e^{\frac{d}{\delta}} \tag{5}$$

$$k_{correction} \approx \frac{2d}{\delta} \tag{6}$$

$$\delta \approx (2n-1)\frac{\lambda_0}{4\sqrt{\varepsilon_w \mu_w}} \tag{7}$$

where:

σ - electrical conductivity of the shield material;

δ - depth of electromagnetic field penetration in the shield, at which its power drops by 50%;

d - shield thickness;

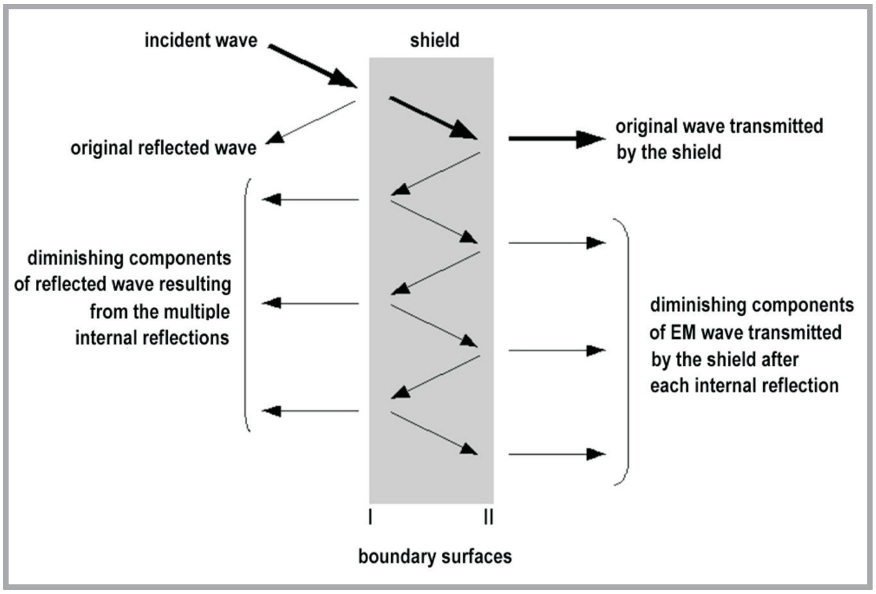

***Figure 1.** Approximate scheme of multiple internal reflection in a thin shield [1].*

n - depends on the value of the loss tangent of the material for ε and μ;
ε_w - relative permittivity of the shield material;
ε_o - permittivity of the air;
μ_w - relative magnetic permeability of the shield material;
λ - wavelength of EMR in the air.

From a review of scientific and technical literature on shielding effectiveness, it follows that most test reports determine the total EMR shielding effectiveness without diversification into three components: the reflection coefficient, transmission coefficient and absorption coefficient [1 - 3, 5, 9]. Most papers in this field concern the effective shielding of EMR on the basis of the 100% contribution of the coefficient of reflection, which is characteristic of various types of wire gauzes, metal foils and metal-coated surfaces [1, 2, 5, 12]. In the case of applications such as medicine or means of defence, it is indispensable to know the values of particular coefficients characterising the effectiveness of EMR shielding. Of particular importance here is the so-called insertion loss ($k_{abs} + k_{correctioni}$) component, which brings about EMR wave scattering on the basis of absorption and internal reflections. In radiolocation the shields with a dominating contribution of the insertion loss component minimise the EMR incident wave component, consequently making it impossible to effectively localise, for example, military objects.

From the assumptions of this study, it follows that the textile shields designed should show high elasticity, a low surface weight and thickness as well as a dominant value for the insertion loss coefficient. In thin shields, the shielding mechanism can be explained by means of the phenomenon of multiple EM wave reflection.

Figure 1 schematically shows the phenomenon of multiple EMR reflection in the shield. If the shield is thin, the wave reflected from the second boundary surface is again reflected from the first boundary surface and returns to the second boundary surface to be reflected. When the wave reaches the second boundary surface for the second time, it has a negligibly low amplitude as it has already passed, for example, three times through the shield thickness [1].

The effectiveness of shielding as a result of internal reflections can be considerably increased by using various multi-layer systems.

Principles of designing multi-layer textile-polymeric structures of EMR shielding systems

From the analysis of relationships (4 - 7) describing the shielding effectiveness, it follows that [1, 2]:
- the smallest depth of EM field penetration into the shield material can be obtained with high values of ε_w, μ_w and loss tangents. The smaller the penetration depth, with the assumed shield thickness, the higher the absorption coefficient is;
- to design a shield with a very low thickness, one should use a material with very high ε_w, μ_w and loss tangents, which will increase the shield impedance and, consequently, the reflection coefficient; by decreasing the material thickness, we also reduce the value of the coefficient characterising the multiple reflection inside the shield;
- the greater the difference of wave impedance in the „contacting" media is (materials) the greater the reflection.,.

In designing and selecting multi-layer textile-polymeric materials for the construction of shields, masking elements or special protective clothing, including camouflage clothes, a significant element is knowledge of the following properties of these materials within the required band of frequency:
- Reflection coefficient – the reflection of a electromagnetic wave from the media boundary resulting from the misfit of the wave impedance of the media. One should also take into account the portion of incident waves that results from the internal reflections in the material (shield).
- Absorption coefficient – the absorption of EMR wave energy by the material (including the phenomenon of internal reflections).
- Transmission coefficient – EMR penetration into the medium behind a barrier (shield or clothes etc.).

This analysis indicates the potentially great suitability of multi-layer textile-polymeric systems, with an appropriately diversified ε_w and μ_w of succeeding component layers, for the production of light, thin, elastic and formable shielding

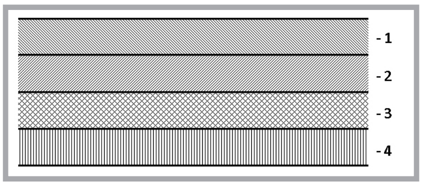

Figure 2. *Example of a four-layer textile-polymeric shielding system; 1 to 3 - layers with a dominating absorption coefficient, 4 - layer with a dominating reflection coefficient.*

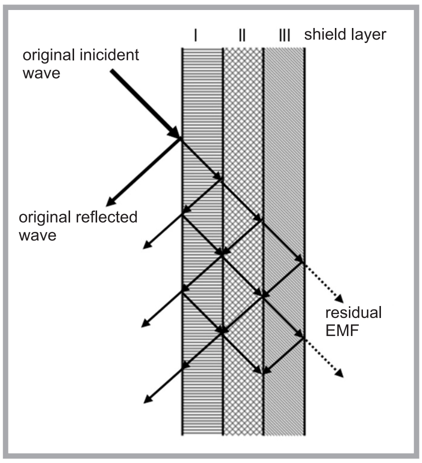

Figure 3. *Scheme of multiple internal reflections in a multi-layer shield.*

materials, which are at the same time capable of effectively shielding against and absorbing EMR. Hence, in the production of materials for component layers, there should be electro-conductive and ferromagnetic substances, with appropriately high permittivity and permeability values, durably incorporated into a polymeric coat with non-conductive properties, e.g. polyurethane or polyacrylate and also intrinsically conductive polymers (IPC), e.g. polyaniline, formed on the surface of textile substrate,.

Such coats can be applied on textile substrates in mono- or multiple thin-layer coating processes using appropriately prepared pastes, mostly in the form of aqueous dispersions [4]. From these considerations it follows that the characteristics of composite materials specified could be obtained by appropriate selection of the type and concentration of fillers in such coats, their thickness and number of layers, as well as by appropriately designing the structure and properties of textile substrates for such coats. Suitable selection of successive component layers in multi-layer shielding materials/systems is also vital to attain the characteristics specified.
Based on the relationships presented in

previous chapter, concerning the shielding effectiveness and conclusions resulting from the analysis of these relationships, basic assumptions were developed for designing the structure of multi-layer textile-polymeric shielding materials/systems, which should be characterised by simultaneous, mutually supplementary EMR absorbing and reflecting effects.

To sum up, the basic principle of designing multi-layer textile-polymeric shields (systems), based on the assumptions mentioned above, consists in their being composed from several, mostly 3 – 7, thin component layers with diversified values of relative permittivity ε_W and magnetic permeability μ_W (see ***Figures 2*** and ***3***). When designing an ideally reflectionless shield, its impedance must be equal to the impedance of the medium with which it will be in contact. In an extreme case, it implies the equality of the permittivity and magnetic permeability of the material and medium. Practical fulfillment of this condition is difficult, at least for the reason that the magnetic permeability changes as a function of the frequency, while the permittivity remains independent of it. A solution consists in designing a heterogeneous material with a variable value of permittivity.

Based on the analysis of the test results for EMR reflection and absorption using various types of coating materials with different properties, it can be concluded that such an optimised, light, elastic and simultaneously effective shielding material can consist of multi-layer textile-polymeric shielding systems. Such systems will be prepared by bonding coating component materials as individual layers, characterised, as mentioned above, by appropriately diversified permittivity and magnetic permeability. It should be added that the component materials can also have multi-layer structures, e.g. a two- or three-layer polymeric coat on a textile substrate.

This assumption constitutes a base for the whole conception of designing multi-layer systems with controllable EMR shielding properties.

Figure 3 shows a scheme of the phenomenon of multiple internal reflections in a multi-layer shield. The incident EMR on the first boundary surface is partially reflected from this surface. A part of the EMR passes into the inside of the shield, where it undergoes a series of multiple internal reflections, while the unattenuated part of the EMR that has passed through the second boundary surface undergoes a similar series of multiple internal reflections in the second layer of the shield. To the third shield layer passes only a negligible portion of the incident wave, which, similarl to before, undergoes considerable attenuation according to the same mechanism. In consequence, only a residual part of the EMR passes into the protected space (transmission).

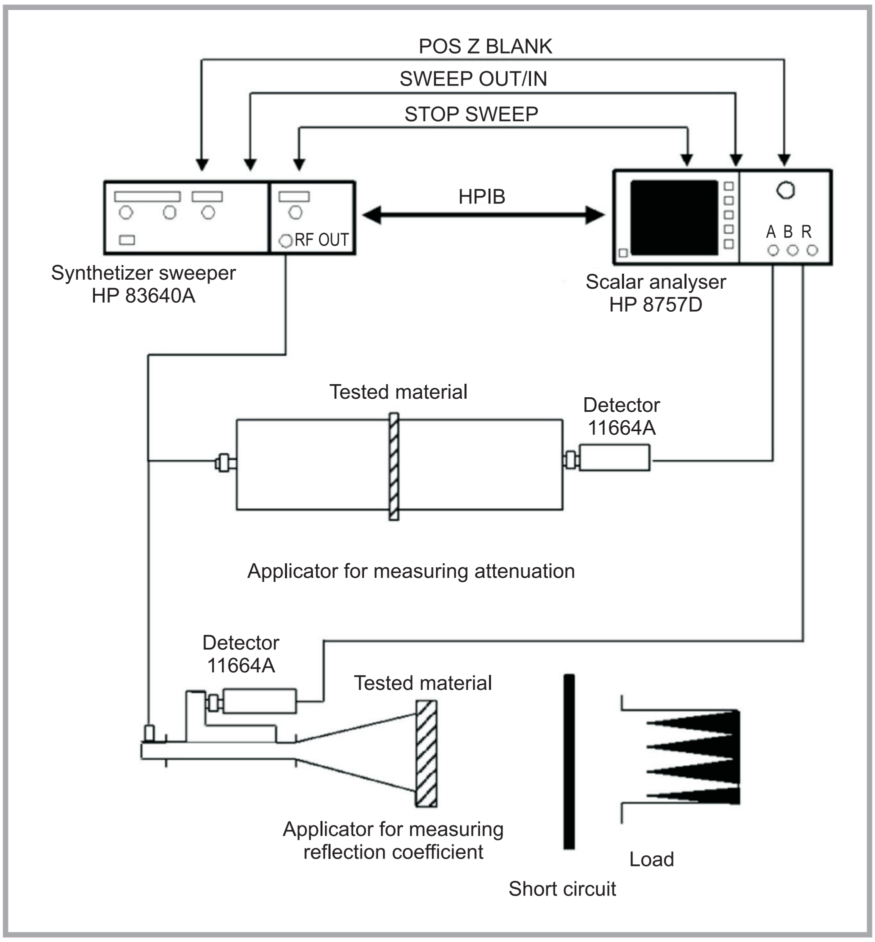

Figure 4. *Simplified block diagram of the stand for measuring the coefficients of transmission and reflection*

Finally, the method of designing presented creates opportunities to adapt the expected shielding properties of various versions of the multi-layer systems designed to the requirements resulting from specific practical applications of such materials.

In the present study, various types of textile substrates (carriers) were used, including polyester woven fabrics, silver-coated polyamide fibers, textiles metallised by plasma treatment, steel fibres, and plastic foils metallised with Al and Cu/Al. Auxiliary substances used included various types of particles such as nano- and micro-carbon blacks, submicro- and micro-powders of Al, Cu, Ni, submicro- and micro-powders of ferromagnetic substances as well as various types of coating pastes containing non-crosslinked acrylic (PAC) or urethane (PUR) polymer in the form of aqueous dispersion, and coating paste based on polyaniline (PANI), among others.

Methods of measuring EMR attenuation

The EMR attenuation of the textile-polymeric coating materials developed, including those designed for the component layers as well as multi-layer shielding systems, was measured by a method using a wave-guide applicator with the possibility of independent determination of the reflection coefficient and transmission in dB units. The measurements were carried out at the accredited (by the Polish Accreditation Centre) Research Laboratory of Radiolocation, Commanding Systems, Radiolocation Fighting and Microwave Technique of the Military Institute of Technical Armament in Zielonka near Warsaw. A simplified scheme of the measuring stands is illustrated in ***Figure 4***. The tests were performed according to the accredited test procedure LR.PB.18: "Measurement of frequency characteristics of reflection and transmission coefficients" within the following ranges of frequency:

- 0.8 GHz ÷ 2.4 GHz (transmission coefficient only);
- 2.4 GHz ÷ 4.8 GHz;
- 8.0 GHz ÷ 13.0 GHz;
- 13.0 GHz ÷ 18.0 GHz.

(the gap in the frequency range from 4.8 GHz to 8.0 GHz is due to instrumental reasons)

The choice of the above measuring ranges is justified by the fact that a high number of industrial and laboratory devices (medical, scientific or radiolocation instruments) operate within the range of frequency presented. On the other hand, the choice of a measurement method based on the wave-guide applicator is justified by the possibility of measuring two basic characteristic properties of the screen: transmission coefficient T in dB and reflection coefficient Γ in dB. The coefficient of absorption is calculated as a complement to 100% in the linear measure, after taking into account the coefficients of transmission and reflection measured [29 - 35].

The transmission coefficient (T [dB]) is defined as a ratio of the power measured behind the tested sample to the incident power on its surface:

$$T = 10\lg \frac{P_2}{P_1} \text{, in dB} \qquad (8)$$

where:
P_1 – incident power on the test sample;
P_2 – measured power behind the test sample.

As P_2 is always lower than P_1, the coefficient of transmission assumes negative values.

To illustrate the transmission coefficient on the linear (percentage) scale, it is necessary to adopt a univocal level of reference. Such a level of reference, treated as 100% transmission, is a situation in which there is not any test sample in the applicator for the attenuation to be measured, which is in accordance with the assumption $P_2 = P_1$, which corresponds to level 0 dB.

The reflection coefficient (Γ in dB) is defined as a ratio of the power of the signal reflected from the test sample to the incident power on its surface:

$$\Gamma = 10\lg \frac{P_0}{P_1} \text{, in dB} \qquad (9)$$

where:
P_1 – incident power on the test sample;
P_0 – power reflected from the test sample.

As in the case of the transmission coefficient, the values of reflection coefficient calculated are negative. In the graphic representation of this coefficient in the linear scale, it was also necessary to adopt a level of reference. Such a level, treated as 100% reflection, is a situation in which the wave-guide applicator is short-circuit a material that maximally reflects the radiation, e.g. a metal plate, which is in accordance with the assumption $P_0 = P_1$, which corresponds to level 0 dB. For inspection purposes it is also possible to obtain another level of reference with a value of 0% reflection. In measurment terms, it corresponds to the situation in which the test sample is replaced with an element capable of maximally absorbing the radiation, as a result of which the reflection phenomenon practically does not occur [1, 2].

Based on the assumptions presented, systematic studies have been undertaken concerning the shielding properties of materials, including in particular specially designed textile and textile-polymeric materials as well as their multi-layer systems.

The results of the preliminary tests prove that by appropriately selecting the coat-forming polymer and nano- and micro-particle fillers added to coating pastes, as well as the structure and raw material composition of the textile substrate, it is possible to obtain multi-layer materials showing various properties of permittivity ε and magnetic permeability μ.

It has been also found that the use of textile substrates (carriers) containing an addition of metal fibers – steel fibers or silver-coated fibers in a "unordered" form makes it possible to considerably increase the attenuation of EMR in the coating materials obtained. Better results of attenuation were obtained with the use of a conductive polymer, such as polyaniline. The increase in attenuation is considerably higher when using carriers with spatial structures.

Detailed test results will be presented in our next paper, which will published in Fibres & Textiles in Eastern Europe.

Conclusions

- The combination of coating materials of different permittivity and magnetic permeability into multi-layer systems creates potential opportunities to design a structure for light textile-polymeric, multi-layer systems characterised by the expected properties of EMR shielding with a considerable contribution from the insertion loss component.
- Experimental confirmation of the solidity of the presented method for designing multi-layer textile-polymeric systems with expected properties of the simultaneous adsorption and reflection of incident EMR with the considerable contribution of the insertion loss, being the subject of the next report, can create a basis for the production of various shielding materials designed for light protective shields as well as protective clothing for special applications, effectively protecting against electromagnetic radiation.

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