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Textile materials for electromagnetic field shielding made with the use of nano- and micro-technology

Research Article

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Abstract: Studies have been carried out aimed at the development of structures and technology for making special multi-layer textile-polymeric systems of shielding electromagnetic field (EMF). The use of textiles as EMF shielding materials is commonly known, however the EMF attenuation obtained practically exclusively results from the reflection of EMF, while the materials used for this purpose as a rule, show poor EMF absorption abilities. The basic assumption for a new solution is the exploitation of the multiple internal reflection of incident EMF either in textile-polymeric coating materials containing fine-particle electromagnetic materials or in special textile structures. This paper presents the results of investigating the EMF shielding effectiveness of several selected and developed textile-polymeric materials in respect of both their practical applications (protective clothing elements, technical materials, masking elements, etc.) and the structure and content of components with various EMF reflection and absorption properties. The measurement method for independent determination of reflection and transmission coefficients with a wavequide applicator was used. The results obtained with the 2.5 GHz to 18 GHz frequency range show a low value of transmission coefficient (min. -35 dB) and accepted reflection attenuation from about -4 dB to -15 dB for higher frequencies.

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1. Introduction

A huge increase in the number of electrical and electronic devices and appliances being in everyday use that are a potential source of electromagnetic energy has become an increased problem in the last decade. It can be especially observed in the area of wireless communication systems

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which require a certain level of electromagnetic emission for proper work. However, from the point of view of other electrical devices this type of electromagnetic energy is the electromagnetic interference (EMI) that may affect the performance of other equipment by creating undesirable responses or even operational failure. One of the simplest methods to eliminate the EMI is shielding. Shielding was and still is a very popular method of maintaining the electromagnetic compatibility and is based upon the separation of two or more electromagnetic environments [1]. Shields can be used in one of two ways: to isolate equipment from outside sources of EMF or to prevent electromagnetic emission radiated by internal devices. Historically, the oldest and most frequently used were shields and shield's constructions made as metal boxes or enclosures. They were mainly composed of different types of sheet metal and presented the features that would be rather unwanted in today's world. Among those one can distinguish two main categories: technological and electromagnetic properties. In the area of undesired technological properties one can state that metal shields are heavy, inflexible, undergo the thermal expansion and are relatively difficult to shape and model. The use of EMF reflection as the main element in shielding is also unfavourable and can be the cause of disturbances in the operation of other electronic equipment as well as a bigger hazard to operators. To overcome the above unwanted properties of metal shields, researches all over the world try to find different types of materials to work as better shields. One of the proposals concerns textile based shielding materials that are lightweight, flexible and less expensive in comparison with metal ones. In general, textile products that can be found in everyday garment are transparent to electromagnetic radiation due to their electrical insulating properties [2, 3]. That is why, in such a form, they cannot act as electromagnetic shields at all. To impart shielding properties to textiles, these should be subjected to a special treatment. It can be divided in two main groups: surface treatments of textiles and special types of additives incorporated into textiles. The first group includes thin mono- or two-layer coats of metal such as Ag, Cu or Ni deposited on textile surfaces [4–6]. Such coats are prepared by various methods, e.g. by chemical methods through vacuum evaporation, but nowadays the most recent and primary technique involves plasma treatment. The other group includes different types of conductive or electromagnetic materials in the form of wire nets, metallic foils, metal-plated films and electro-conductive fibres, which are inserted into fabrics during the process of weaving or knitting. This group also includes textile-polymeric coating materials, in which the polymeric coat of a textile substrate contains fine-particle electromagnetic materials, such as nano- or mostly micro-particles of metals, ferromagnetic or other substances with a high value of electrical permittivity. The main aim of the research presented in the paper is to develop structures and technology of special, layerd textile-polymeric systems, with a low EMF transmission coefficient, maintaining a high absorption coefficient. The aim stated this way is quite complex and interdisciplinary, and taking into account our own experiences, can be divided into several smaller objectives which require different teams of specialists and include:

1 — Developments concerning the composition and procedures of coating paste preparation and deposition as well as making textile-polymeric coating materials (paste preparation and deposition team). With reference to this area investigated fields include the following:

  a — Selection of fine-particle materials with electromagnetic properties as fillers of polymeric coats capable of EMF reflection or absorption (nano-, submicro- or micro-particles of ferromagnetic substances, metals or special materials).

  b — The development of methods for the preparation of stable aqueous dispersions or organic solutions of properly selected fine-particle materials with a high, possibly mono-particle dispersion being also stable in coating pastes based on film-forming mostly urethane or acrylate pre-polymers as well as cross-linked polymeric coats on textile substrates.

  c — The development of optimized compositions and rheological characteristics of coating pastes and most beneficial coating conditions with the use of direct and reversible multi-layer coating techniques for the preparation of coats with a specified thickness, strength and a high interlayer adhesion to textile substrates. Such pastes were deposited on the textile substrate of properly designed structures and subjected to drying and thermal cross-linking to form soft and elastic films. It should be mentioned that the modification of various types of textiles with the use of coating techniques to deposit polymer layers on their surfaces belongs to the intensively developed worldwide research fields searching new types of products, especially multifunctional ones for practical applications [7].

2 — The development of textile structures with conductive properties (knitting and weaving team),

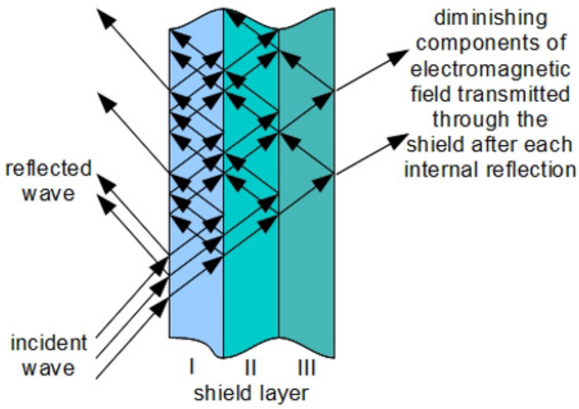

Figure 1. Scheme of multiple reflections in a multi-layer shielding system.

3 — The development of multi-layer complex systems composed of component layers made of textile structures and textile-polymeric coating materials (electromagnetic compatibility team).

2. Multi-layer shielding materials

EMF shielding effectiveness can be significantly increased using various types of multi-layer systems. The basis of designing multi-layer textile-polymeric shields consists of composing them from several, mostly 3 to 6 thin component layers with different values of relative electrical permittivity and magnetic permeability. The assumption for the design of a multilayer textile system is that it is sensitive to the direction of the incoming wave. As our experiences show the layers which are closest to the electromagnetic field source should demonstrate the absorption properties. As the distance from the EMF source increases the layers should present more reflection properties. The last layer is designed to be the most reflecting of all. The shielding effectiveness using multilayer systems can be explained through the phenomenon of internal reflections. Figure 1 shows a scheme of the phenomenon of multiple internal reflections in a multi-layer shield. The incident EMF is partly reflected from the first boundary surface. Its remaining portion passes inside a shield where it undergoes a series of multiple internal reflections. The unsuppressed portion of EMF that has passed through the second boundary surface undergoes a similar series of internal reflections in the second layer of the shield. Only a negligible part of the incident wave passes to the third layer where it is considerably suppressed according to the same mechanism. Consequently, the space under protection receives exclusively the residual EMF.

The following materials were used in the study to compose layers of different properties from the EMF shielding point of view:

— special knitted structures containing metal or metal-coated fibres - the basis for reflecting layers preparation;

— electro-conductive or ferromagnetic nano- or micro-particles, such as carbon black, graphite, aluminum (Al) - the fillers for absorption layers preparation;

— various types of coating pastes based on non-cross-linked acrylic (PAC) or urethane (PUR) polymers in the form of aqueous dispersions or solutions in organic solvents as well as conductive polymers as polyaniline (PANI) [8, 9] - the polymers for absorption layers preparation.

2.1. Textile structures

As was stated in the previous section, during the preparation phase of the textile multi-layer shielding system one layer should demonstrate the most reflecting properties of all. Based upon our previous experiences the best reflecting properties show knitted and woven fabrics with different types of electroconducting threads [10–12]. Their transmission coefficient is lower than −35 dB and reflection losses very close to 0 dB, which indicates very good shielding effectiveness using EMF reflection mechanism. As a result the following fabrics were chosen as textile structures of celected textile-polymeric coating materials - specially designed knitted fabric of polyester multifilament yarn (plain stitch) containing 47% of conductive yarn X-Static 100D/34F (silver-coated filament yarn) and 11% of PET/Inox 11% of PET/Inox, 20tex × 2, 80% PES, 20% Inox (polyester staple fiber yarn containing steel fibers) were used as textile substrates of selected textile-polymeric coating materials.

2.2. Electromagnetic fine-particle materials

The following fine-particle materials (powders) were used to fill the polymeric shielding coats:

* Metals:

  — aluminum powder with an average particle size of 0.9 μm, (Al-01,Euromet, Trzebinia, Poland)

* Carbon-based materials:

  — graphite powder – average particle size: 45 μm, (Graphite 390, Stachem, Lublin, Poland)

— carbon black – average particle size: 336 nm (a granulated product with a modified particle surface) (Vulcan XC 72, Cabot Corp., Boston MA, USA).

2.3. Polymeric materials

The selection of film-forming polymers for making coats filled with fine-particle nano-, submicro- or micro-powders of metals, ferromagnetic or other inorganic materials was made according to the practical application assumed of shielding coat materials, including first of all light, portable, folding and durable to atmospheric conditions protecting shields against EMF or masking covers as well as special protective clothing for workers exposed to high-frequency electromagnetic fields [10].

2.3.1. Non-conductive polymers

Two types of polymers were selected for making shielding coats on textile substrates:

* Aqueous dispersions of non-cross-linked acrylic film-forming polymers - DICRYLAN AC (CIBA A.G., Switzerland), for making coats by direct coating,

* Non-cross-linked film-forming urethane polymers in the form of solutions in organic solvent - UCECOAT AB 7311 and UCECOAT TD 9627 (CYTEC AG, Belgium) for the preparation of coats by the reversible coating method.

2.3.2. Internally conductive polymers

Electro-conductive coats were prepared with the use of thickened paste based on polyaniline (about 6% of solid) containing non-cross-linked acrylic polymers, to be used for direct coating (the preparation took place at the Academy of Technique and Arts, Bielsko-Biała).

2.4. Making polymeric coats on textile substrates and the combination of coat components into multi-layer complex systems

The deposition of coats on textile substrates and combination of textile-polymeric components into multi-layer shielding systems were carried out by means of a pilot coating-drying-setting line from Mathis (Switzerland). It made it possible to deposit coats by both the direct and reversible techniques as well as to combine the component fabrics or textile-polymeric coating materials [11]. Polymeric coats on textile substrates were prepared by the technique of direct coating with the use of an air blade or a roll-supported blade with an adjustable slot size. i.e. the thickness of the paste layer deposited. The coating assembly was coupled with a laminating unit, IR drying field and an air dryer with a helical guidance of fabric; drying temperature: 60 – 90°C; cross-linking temperature: 150 – 170°C, depending on the characteristic of the polymer used.

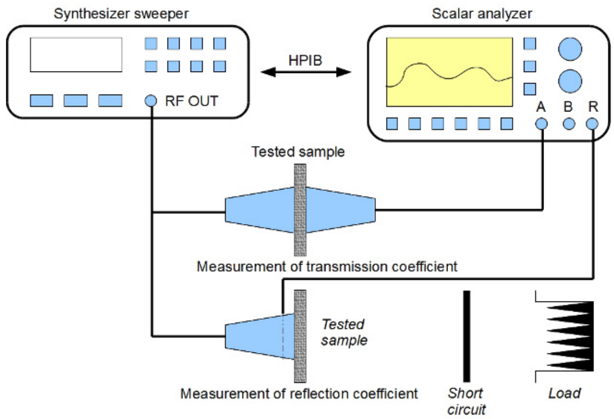

Figure 2. Block diagram of a measurement stand for the determination of EMF transmission and reflection.

3. Shielding effectiveness of textile-polymeric shielding materials (measurement method)

The EMF attenuation capability of the textile-polymeric coating materials developed, both those designed for component layer and the multi-layer shielding systems, was measured by the method with a waveguide applicator for independent determinations of reflection and transmission coefficients in dB [11–13]. The measurements were performed at the Laboratory of Radiolocation Research, Commanding Systems, Radioelectronic Fighting and Microwave Technique of the Military Institute of Technical Armament, Zielonka near Warsaw. This Laboratory has been accredited by the Polish Center of Accreditation. A simplified scheme of the measurement stand is shown in Figure 2.

Measurements were carried out according to the accredited test procedure LR.PB.18: "Measurement of the frequency characteristics of reflection and transmission coefficients":

— 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 selection of the above measurement ranges is justified by the fact that the big number of industrial and laboratory equipment, especially radiolocation devices, operate within these frequency ranges. The choice of the measurement method based on a wave-guide applicator is justified by the possibility to measure two basic properties of a shield: transmission coefficient T [dB] and reflection coefficient R [dB]. Absorption coefficient is calculated as complement to 100% in a linear scale, taking into account both these coefficient measured. Transmission coefficient (T [dB]) is defined as a ratio of the power measured behind test sample to the incident power on its surface:

$$T = 10\log\frac{P_2}{P_1} \tag{1}$$

where:

P_1 — incident power on test sample,

P_2 — power measured behind test sample.

Due to the fact that the power measured behind the sample tested (P_2) is always lower than the incident power (P_1), transmission coefficient assumes negative values. To illustrate the coefficient of transmission on a linear scale (percentage), it is indispensable to assume an explicit level of reference. Such a level of reference, treated as 100% transmission, is a situation where no test sample is present in the measuring applicator. Then, according to the accepted assumptions $P_2 = P_1$, which corresponds to a level of 0 dB. Reflection coefficient (R [dB]) is defined as a ratio of the power of signal reflected from the test sample to the incident power on its surface:

$$R = 10\log\frac{P_0}{P_1} \tag{2}$$

where:

P_1 — incident power on test sample,

P_0 — power reflected from test sample.

As in the case of the transmission coefficient, the calculated reflection coefficient assumes negative values. Based on the assumptions presented, we undertook systematic examinations of the shielding properties of the specially designed textile and textile-polymeric materials as well as their multi-layer systems.

4. Test results of thin- and thick-coat multi-layer materials

The results of preliminary tests prove that though a proper selection of a coat-forming polymer and nano- and micro-fillers added to the coating paste as well as the structure and composition of textile substrate one can obtain multi-layer materials that are characterized by required EMF shielding properties. Four examples of multi-layer materials used in this study were prepared in the following arrangements:

Sample 1 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 15% of submicro-particle Al,

Sample 2 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 20% of submicro-particle Vulcan carbon black,

Sample 3 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 20% of micro-particle graphite,

Sample 4 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 15% of submicro-particle Al and two-layer polyaniline coat.

All four samples of textile shielding multilayer systems are based upon the same textile structures - knitted fabric containing a steel yarn - which creates the reflecting layer. The samples differ in the components and the number of absorption layers. This kind of construction of the sample set (four samples) allows comparisions of shielding properties taking into account the absorption properties mainly.

Figure 3 shows the characteristics of transmission coefficient determined according to equation (1) and expresses in dB. All the samples tested show very good shielding properties: above −35 dB. Samples 1, 2 and 3 are characterized by a similar course of transmission coefficient, especially for frequencies ranging from 8GHz to 18 GHz. The best shielding properties are shown by sample 4, which is due to the more developed shield construction, i.e. a higher number of component layers with specified suppression characteristics.

Figure 4 shows the characteristics of reflection coefficient determined according equation (2) and expressed in dB. The highest (about zero dB) value of this coefficient is observed in the case of sample 3, which proves that this system is mainly characterized by EMF reflection capabilities. Samples 1 and 2 show lower values of reflection coefficient by several dB compared to sample 3, especially within the frequency range of 8 GHz to 18 GHz. The most reflectionless character is shown by sample 4, which is undoubtedly due its two-layer polyaniline coat. It is rather difficult to compare the results of shielding effectiveness properties for the materials obtained during our research with similar works in the field because of at least one of two reasons:

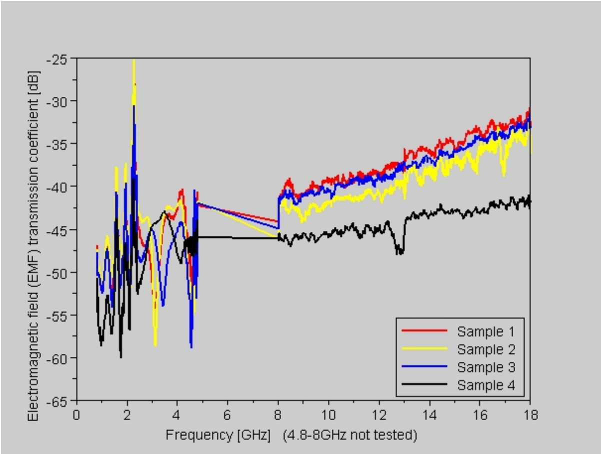

Figure 3. Characteristics of the electromagnetic field (EMF) transmission coefficient of textile-polymeric shields.

Sample 1 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 15% of submicro-particle Al,

Sample 2 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 20% of submicro-particle Vulcan carbon black,

Sample 3 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 20% of micro-particle graphite,

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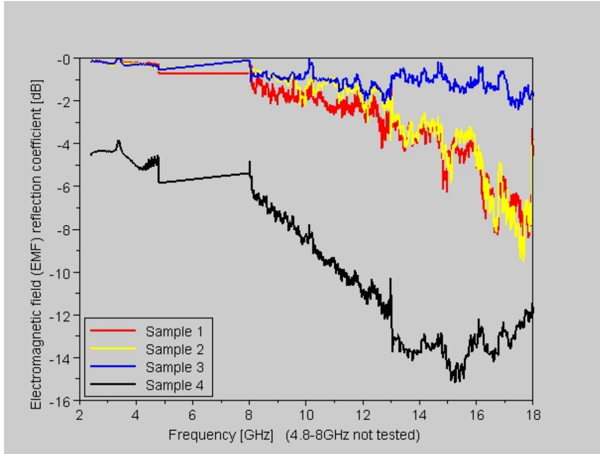

Figure 4. Characteristics of electromagnetic field (EMF) reflection coefficient of textile-polymeric shields.

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Sample 3 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 20% of micro-particle graphite,

Sample 4 — Knitted fabric containing a steel yarn with a polyurethane coat doped with 15% of submicro-particle Al and two-layer polyaniline coat.

— most of the literature reports show that textile composite materials or other types of textile based shields demonstrate mainly the EMF reflecting properties (for instance silver nitrate-plated or other plasma treated materials).

— textile based shields with dominant EMF absorbing properties are made for special, mainly military purposes (eg. masking purposes) and the results of this works are not published to the open area.

5. Conclusions

To sum up the results of our work it can be stated that the authors were able to develop structures and technology of special layered textile-polymeric systems with a low EMF transmission and high absorption coefficients. Particular conclusions can be summarized in the following points:

1. The textile-polymeric systems of appropriate structures and properly selected characteristics of their component layers can constitute a new generation of effective shields against electromagnetic radiation, with a high shielding effectiveness resulting, first of all, from the high contribution of absorption coefficient.

2. The absorption of EMF mainly depends on the number of layer and thickness of polymeric coats containing additions of conductive nano- or submicro-particles.

3. The textile-polymeric multi-layer shields containing nano- or submicro-additives fulfill the shielding effectiveness requirements.

4. Very good results of EMF shielding, connected with a considerable decrease in both transmission and reflection coefficients, have been obtained using coating materials containing an internally conductive polymer such as polyaniline.

Acknowledgments

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