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Textile Multi-layer Systems for Protection against Electromagnetic Radiation

Abstract
This paper presents the results of studies carried out at the Textile Research Institute in Łódź, aimed at developing multi-layer, flat or spatial textile-polymeric materials, designed for shielding electromagnetic radiation (EMR), showing a possible high absorption coefficient, a so-called insertion loss of ≥ 40%. These materials were designed by the method presented in our previous paper, which consists in bonding/laminating component coating materials with diversified permittivity and magnetic permeability into multi-layer systems. Multi-layer shielding materials designed and made according to such assumptions are characterised by a predominant EMR absorption capability, considerably higher than their EMR reflection capability; they also show a low surface density, elasticity and ease of storage and transport. The positive test results of shielding effectiveness obtained, within a wide range of frequency (0.8 – 18 GHz), for the newly developed shielding materials offers real prospects for their practical use in various fields of the economy.

Key words: *shielding, electromagnetic radiation, coat-forming polymers, conductive particles, ferromagnetic substances, thin-layer coating, coating paste, paste rheology, coating materials, multi-layer shielding systems.*

Aim of study

The aim of the studies was to develop new types of multi-layer textiles or textile-polymeric materials designed for protection against electromagnetic radiation (EMR), which are relatively light, with low thickness and surface density, elastic, formable, and modified with electro-conductive as well as ferromagnetic substances, showing simultaneous EMR reflecting and absorbing effects. In the development of component layer materials as well as the final multi-layer shielding systems, the authors used the designing procedure described in their previous paper [1], which also describes test methods for the determination of EMR shielding effectiveness, including reflection, absorption and transmission coefficients. An important advantage of the multi-layer shielding systems is the possibility of imparting other performance properties to them, such as watertightness, for example.

Considering the original concept of the present studies, it was of great importance to make the individual component layers of the shielding systems using the techniques of direct or reversible thin-layer coating [1 - 3] with pastes of non-conductive polymers [2, 4 - 6] and also interstitialy conductive polymers (ICP) [8 - 24], including those filled with nano- and micro-metric particles of conductive and ferromagnetic substances [4 - 8], deposited on textile carriers with flat or specially developed spatial structures [25 - 30]. Textile carries were made from various textile fibres including blends with metal or metallised fibres, creating conductive grids in the structures of such carriers [29 - 34, 40].

The basic assumption of the studies undertaken was to design such coating materials for the component layers and the textile carrier structures, including electro-conductive or EMR reflecting additives, which would make it possible to attenuate EMR by simultaneous absorption and reflection of this radiation. The final laminar products would have layers of different character, e.g. a top layer that absorbs EMR and an internal (bottom) layer that reflects residual incident radiation. Such a complementary way of using both types of shielding effects makes it possible to optimise the protective effect required, with a reduction in material consumption at the same time [1].

It should be noted that the protective materials obtained by means of the textile coating methods should be characterised by a low surface density, soft handle, elasticity and a very stable shielding effect under conditions of use, care and maintenance [2, 27]. This creates the possibility of using such materials not only for shields of various types, including radiolocation shields, but also for special types of protective clothing [37 - 38].

The main practical effect expected should include the development of a fundamental basis for the technological process of making effective multi-layer EMR shields for various textile carriers by means of the thin-layer coating techniques. Such materials should be suitable for making both protective shields and special types of protective clothing for workers exposed to the effects of EMR in various fields of the national economy, including the defence sector.

Experimental

Materials

- polyester - poly(ethylene terephthalate) - woven fabric, made from multifilament yarns, with a surface density of 110 g/m^2;
- non-crosslinked acrylic (PAC) or urethane (PUR) polymer in the form of aqueous dispersion from CIBA Speciality Chemicals Ltd., Switzerland
- coating paste based on polyaniline (PANI) – ATH, Bielsko-Biała; Poland
- nano- and micro-carbon black (various manufacturers);
- submicro- and micro-powders of Al, Cu, Ni (various manufacturers);
- submicro- and micro-powders of ferromagnetic substances and semi-conductors (various manufacturers);
- stainless steel fibres (various manufacturers);
- silver-coated polyamide fibres (various manufacturers);
- plastic foils metallised with Al and Cu/Al (various manufacturers);
- textiles metallised by plasma treatment using Flectron Cu and Cu/Ni from Laird Technologies, USA (commercially available products with shielding properties, purchased for comparison purposes).

Apparatus

- Multi-function equipment for the preparation of coating pastes and coating woven fabrics by the direct or reversible methods of Mathis (Switzerland).
- A 6206 of ELTEX GmbH Teraometer (Germany) for measuring surface resistance.
- Apparatus for measuring EMR attenuation of shielding materials by the tunnel method with the possibility of determining the reflection and transmission in dB and coefficients of reflection and transmission as well as the interposed attenuation in % within the frequency range of 0.8 GHz to 18 GHz. – Military Institute of Technical Armament, Zielonka, near Warsaw, Poland.

Preparation of the model EMR shielding systems

The objective of the study was to assess the possibilities of using, light multi-layer textile-polymeric systems for EMR shielding, in which individual layers would be capable of reflecting and/or absorbing EMR within a wide range of frequency. Considering the character of these materials, they should be of a low thickness, relatively light and elastic, thus easy to transport and store, as well as resistant to atmospheric conditions. Such materials could be used, depending on their structure, as shields as well as for making protective clothing.

In accordance with the adapted assumptions of the studies, their main subject is textile coating materials, prepared by the direct thin-layer techniques, repeated with the use of blades with a smooth edge: so-called air blades and blades supported by a roller. This procedure made it possible to control the thickness and surface density of the pastes deposited and, consequently, the coats themselves. Blades with a profile edge were also used to produce coats with characteristic grooving and thereby a spatial effect of the coats. However, the latter were characterised by considerably higher surface densities than those with a smooth surface [2, 30, 40]. The polyacrylate or polyurethane coats were filled with various electro-conductive or ferromagnetic substances in the form of both nano- and micro-sized particles as well as with conductive fibres [40]. The fillers included carbon black, metal powders and/or ferromagnetic substances and materials showing very high relative permittivity ε and magnetic permeability μ, as e.g. barium titanate. The conductive fibres included mainly steel fibres and silver-plated fibres [40]. As a rule, the multi-layer coating technique was used, including at least two and a maximum of four layers filled with various fine-particle anti-electromagnetic powders [40]. A nano- or micro-powder with electro-conductive or ferromagnetic properties was added to the polymeric coating pastes in experimentally established quantities, being as high as possible, but allowing the preparation of homogeneous dispersions in an aqueous medium or organic solvent, depending on the paste characteristics and coating technique. The condition was to obtain and maintain homogeneous dispersion of such materials in the coating paste, and then in the polymeric matrix, as well as to maintain the rheological properties of pastes required by the coating techniques used to ensure their suitability of use and the mechanical properties of the coats produced [20, 39]. In practice, this stood for the addition of powder in quantities

Table 1.

Sample No.	Multi-layer system	Surface density of the system/ number of layers	Frequency, GHz	Shielding effectiveness, dB	Components of shielding effectiveness, %		
					transmission	reflection	insertion loss
1.	PET knitted fabric (3D) with steel fibres + PUR coat with Graphite 390	314/ 3	0.8 - 2.4 2.4 - 4.8 8 - 13 13 - 18	-22 -17 -15 -11	0.65 1.94 3.40 7.71	- 80.56 45.42 31.95	- 17.50 51.17 60.33
2.	PUR coat with Al + Knitted fabric with steel fibres and silver plated fibres + PET woven fabric with PANI coat (2x)	220/ 6	0.8 - 2.4 2.4 - 4.8 8 - 13 13 - 18	-40 -40 -40 -40	0.00 0.01 0.01 0.01	- 70.29 35.43 8.57	- 29.70 64.56 91.43
3.	PAC coat + Layer of steel fibres + PAC coat + PET woven fabric with PANI coat (2x)	194/ 7	0.8 - 2.4 2.4 - 4.8 8 - 13 13 - 18	-21 -25 -22 -20	0.74 0.32 0.71 1.06	- 81.38 41.58 27.16	- 18.30 57.71 71.77
4.	Knitted fabric with steel fibres and silver plated fibres + PET woven fabric with PANI coat (2×)	282/ 5	0.8 - 2,4 2.4 - 4.8 8 - 13 13 - 18	-40 -37 -35 -32	0.01 0.02 0.03 0.06	- 93.41 70.60 54.49	- 6.57 29.37 45.46
5.	PET woven fabric (3D) with steel fibres and PUR coat with Al (2x) + Knitted fabric with steel fibres and silver plated fibres	277/ 4	0.8 - 2.4 2.4 - 4.8 8 - 13 13 - 18	-50 -55 -50 -50	0.00 0.00 0.00 0.00	- 64.74 61.75 50.83	- 35.28 38.25 49.17

of 10 to 30% by wt. (depending on the type and filler particle size) in relation to the dry weight of the coat, which, in most cases, was a value considerably below the percolation threshold and did not allow one to obtain the electro-conductivity of coats expected. It was attempted to lower the threshold and to obtain a coat with better conductivity by the addition of various amounts of selected auxiliary agents with antistatic properties, based on non-crosslinked, coat-forming acrylate or urethane polymers in the form of aqueous dispersion, to the prepared pastes. Coats were also prepared with the use of electro-conductive polymers such as polyaniline [18, 40], either without anti-electromagnetic fillers or with such an additive (submicro-powder of Al) [40]. Woven and knitted fabrics were used as textile carriers, which were made from various fibres, mainly poly(ethylene terephthalate), with various structures, both flat and spatial e.g. spacer knitted fabric, type 3D [40].

Several special textile fabrics with both flat and spatial structures containing specified additions of conductive fibres or steel filaments were also developed [40]. The interest in stainless steel filaments resulted from their capabilities to both reflect and absorb electromagnetic waves [30, 31, 40]. Conductive fibres or metallised yarns, mainly silver plated, were also used [30, 33, 34, 40]. There was also the development of flat and spatial (spacer knitted fabrics, type 3D) fabrics, chemically metallised in two layers with copper and silver [40]. These fabrics were used both individually and as carriers of polymeric coats filled with metal powders, ferromagnetic substances or carbon black as well as coats of conductive polymers such as polyaniline.

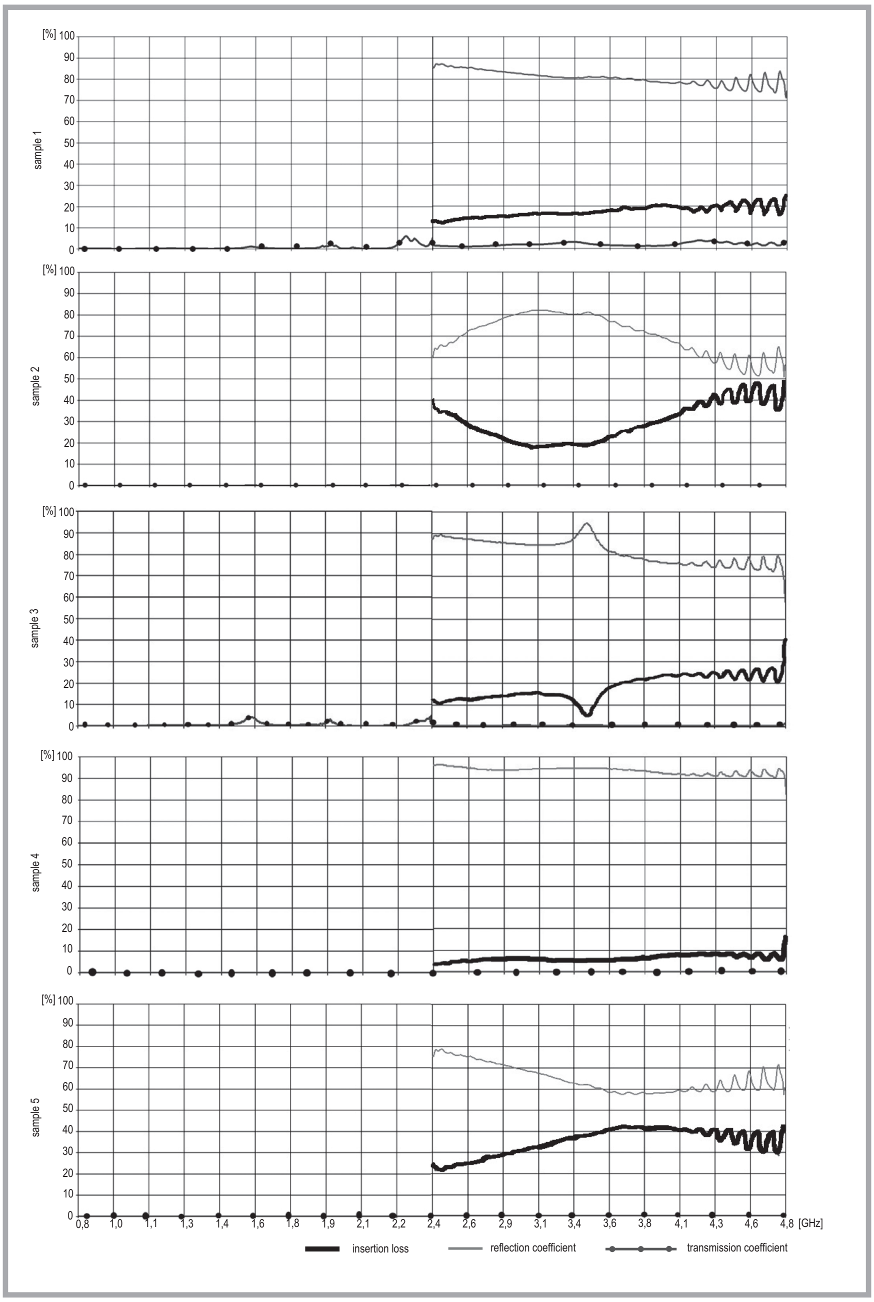

__Figure 1.a.__ Test results of the shielding effectiveness of selected model multi-layer systems within a frequency range of 0.8 – 4.8 GHz.

In total over 100 various component coating materials and textile carriers were designed and made. Based on the analysis of test results concerning the attenuation of the component materials developed, both the textile coating fabrics and textiles with flat and spatial structures, modified with additives of metal or metallised fibres, over 20 various multi-layers systems were designed and made (2 - 7 layers) using various compositions of the component EMR shielding materials with substantial coefficients of EMR reflection and absorption. The main assumption was to obtain shielding materials showing a shielding effectiveness at a level of ≥10 dB, with the components of this effectiveness: transmission, absorption and reflection coefficients being at levels of ≤ 40%, ≥ 40% and about 20%, respectively.

For practical applications requiring complete EMR ”impermeability” with simultaneous EMR absorption, systems containing a fully reflecting material in the lower (bottom) layer were used, e.g. foils or metallised woven or knitted fabrics (41 - 43) prepared by vacuum evaporation or plasma treatment, as well as chemically metallised textiles with a spatial structure [40].

The structures of five exemplifying textile-polymeric shielding systems, meeting the above assumptions, are given in ***Table 1***.

Test results for the shielding properties of the model systems, and discussion

All five samples listed in ***Table 1*** were check in the Military Institute of Technical Armament, Research Laboratory of Commanding Systems, Radio-Electronic Fighting and Microwave Technique, Zielonka, Poland within the frequency ranges of 0.8 - 4.8 GHz and 8 - 18 GHz. The results are presented in ***Figure 1*** as

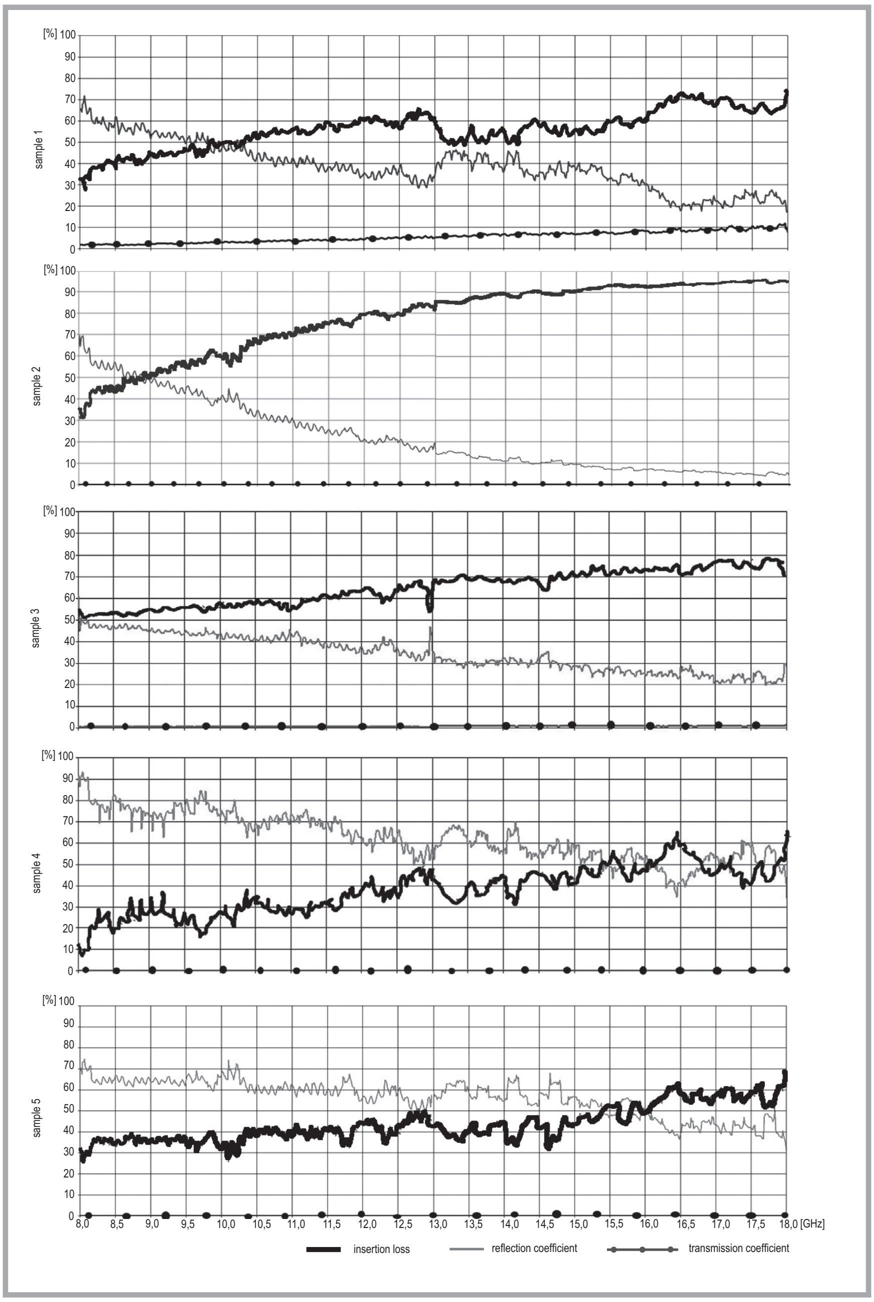

Figure 1.b. *Test results of the shielding effectiveness of selected model multi-layer systems within a frequency range of 8 – 18 GHz.*

the dependences of insertion loss, reflection coefficient, transmission coefficient on the frequency. The average valious of the components of shielding effectiveness (transmission, reflection, insertion loss) for frequency subranges are presented in ***Table 1***. The results presented above showed acceptable attenuation of EMR. The EMR shielding effectiveness of these materials obtained, including their simultaneous capabilities to reflect and absorb EMR, creates wide range of possibilities for developing specific system structures for specified practical uses.

Considering the high number of component coating materials developed, designed for the formation of multi-layer systems, the presentation of detailed test results of their EMR shielding properties would exceed the article volume limit considerably.

The coating textile materials developed and their shielding characteristics were used for the creation of an appropriate database as a basis for rationally designing multi-layer textile-polymeric systems with expected EMR shielding capabilities for various practical applications.

Based on the analysis of the test results obtained, one can also establish several relationships, formulate comments and draw some more general conclusions:

- The idea of inventing ’textile” shielding materials is very impressive and has initiated numerous research studies over the years. This results from the potential advantages of using textile fabrics in to shield EMR as compared with the metal or composite shields commonly used. On the other hand, the finishing of textiles by coating techniques to deposit suitable polymers on their surface is currently one of the most intensively developed areas of fabric modification, which extends the possibilities and areas of their use considerably. It should be also mentioned that the use of direct or reversible thin-layer coating makes it possible not only to deposit suitable anti-electromagnetic substances dispersed in a coat, but also to form multi-layer coats, at the same time allowing each layer to contain an additive with a specific capability to reflect or absorb EMR. Due to the low thickness and high elasticity of such polymeric coats, they do not stiffen textile fabrics to an extent that would adversely affect the comfort of use, e.g. when used in protective or camouflage clothing. Moreover, the structure of the coats makes them resistant to atmospheric conditions, including rain. Their shielding effectiveness is stable in repeated laundering.
- The use of the technique of direct or reversible coating makes it possible to deposit substances on the textile carrier that reflect or absorb EMR, which on the one hand allows one to obtain an effective and uniform shielding effect across the whole fabric surface, but on the other hand it does not deteriorate the ”textile” features of these carriers, e.g. their low weight, elasticity, mechanical strength nor their high and stable EMR shielding effect in use.
- The technique of thin-layer coating used makes it also possible to incorporate other types of functional additives into the polymeric coats formed on textile carriers, and consequently to impart other properties, e.g. bacteriostatic properties, to the coats obtained. It is also possible to apply so-called camouflage dyeing or prints to the textile carriers. These carriers can have different technical characteristics obtained by the appropriate designing of their structures and

selection of fibres as well as special finishing or modification of the fabric surface. All these operations and treatments can considerably increase the multi-functionality of the coated composite materials and extend the areas of their possible use.

- The basic mechanism of EMR shielding consists in reflecting. Therefore, a shield should have movable charge carriers (electrons or holes) that react with an electromagnetic field, and as a result the shield shows electric conduction. This way of shielding is characteristic of metals possessing free electrons. Another mechanism responsible for shielding is absorption. In this case, shields should contain electric and/or magnetic dipoles to react with the electromagnetic field. Electric dipoles can be formed in substances showing a high dielectric constant. In turn, magnetic dipoles are formed in ferromagnetic substances with a high magnetic permeability [2]. It has been found that silver or aluminium particles of sub-micron size, e.g. about 600 nm, due to their high conductance, are a very effective anti-electromagnetic filler and provide good properties of EMR reflection when incorporated into coats.
- Another shielding mechanism is multiple reflection, which refers to the EMR reflection on various surfaces or phases inside the shield. This mechanism requires a large specific surface or interfacial surface. An example of a large specific surface may be a porous or foamed material or a composite containing a filler with a large specific surface. As shown by test results for the attenuation of the systems under discussion, such a shield can be composed of a multi-layer system of textile and coating materials containing active anti-electromagnetic particles.
- In cases where a complete „opacity" of the shield and a high capability to absorb EMR are required, good results can be obtained with the use of light laminar systems, in which the top layer consists of a multi-layer coat of a conductive polymer (e.g. PANI) on a textile carrier or a woven or knitted fabric – preferably with a spatial structure – containing a suitable content of steel fibres, while the internal layer is a metallised flat textile fabric or a polymer foil laminated with the other side of the carrier [41 - 43].

Conclusions

- The use of doping coating pastes based on non-cross-linked acrylate or urethane polymers (in the form of aqueous dispersion) with nano- or micro-particles of fillers such as metals, carbon black, graphite or ferromagnetic substances, in amounts of 10-30% in relation to the dry weight, turned out to be ineffective in terms of EMR shielding. Such coats (coated woven fabrics) also showed very low capabilities to conduct electricity. This seems to be due to the lack of a percolation threshold under these conditions.
- As follows from the data given in ***Table 1*** and illustrated in ***Figure 1***, the model multi-layer shielding materials developed fulfils the basic assumptions for shielding effectiveness and its components within frequency ranges of 0.8 - 4.8 GHz (***Figure 1.a***) and 8 - 18 GHz (***Figure 1.b***). Hence, these model systems can constitute the basis for the development of shielding materials fulfilling specified requirements of protection against EMR, resulting from their specific practical applications.
- The studies performed resulted in a new range of model textile multi-layer shielding materials developed with the use of component textile and textile-polymeric materials, showing acceptable attenuation of EMR. The EMR shielding effectiveness of these materials obtained, including their simultaneous capabilities to reflect and absorb EMR, creates wide range of possibilities for developing specific system structures for specified practical uses.

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