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Simulations and tests of the effectiveness of electromagnetic field shielding by shields made of recycled materials

***Abstract**. The article presents the results of the simulation of the shielding effectiveness of composites with a single-layer and double-layer structure. The layer parameters are based on the actual properties of the waste materials such as scale and nanocrystalline tapes. The use of waste materials indicates the pro-ecological nature of such a solution, as it allows to reduce the consumption of raw materials and energy as well as real savings in obtaining material.*

***Streszczenie.** W artykule przedstawiono wyniki symulacji skuteczności ekranowania kompozytów o strukturze jednowarstwowej i dwuwarstwowej. Parametry warstw bazują na rzeczywistych właściwościach materiałów odpadowych, takich jak zendra i taśmy nanokrystaliczne. Wykorzystanie materiałów odpadowych wskazuje na proekologiczny charakter takiego rozwiązania, gdyż pozwala na zmniejszenie zużycia surowców i energii oraz realne oszczędności w pozyskiwaniu materiału **(Symulacje i badania efektywności ekranowania pola elektromagnetycznego przez osłony wykonane z materiałów recyklingowych)**.*

Keywords: **:** metal powder, metal waste, shields of electromagnetic field, electromagnetic field
Słowa kluczowe: proszki metali, odpady metalowe, ekrany pola elektromagnetycznego, pole elektromagnetyczne

Introduction

Many electronic devices, electrical switchgears and control cabinets contain components that are sensitive to interferences derived an external high frequency electromagnetic field. Additionally, such devices may emit a field that disturbs operation of other close electronic circuits and measurement systems [1]. It is connected with incl. the fact that more and more sources of electromagnetic radiation in the millimeter wave range appear in the human environment.

The article presents the results of the simulation of the shielding effectiveness of composites with a single-layer and double-layer structure. The layer parameters are based on the actual properties of the waste materials such as iron scale and nanocrystalline tapes. The usage of waste materials is a very important assumption in the construction of these composites due to the pro-ecological nature of such a solution. In addition to environment protection, it allows to reduce the consumption of raw materials and energy and real savings in obtaining material.

In order to limit the undesirable influence of electromagnetic radiation, various types of materials can be used, from classic metal shutters (aluminum, copper etc.), through laminates containing conductive reinforcement (metal or graphite), structures sprayed with conductive layers, alloys with very high magnetic permeability (e.g. mu-metal), composites based on electrically conductive polymers, as well as honeycomb structures (e.g. MaxAir™) [2-7]. The materials used for the construction of shielding plates (EMI) must have good parameters of electrical conductivity and magnetic permeability. The natural and basic choice in this case are the shutters made of metals. However, they have some limitations, such as high weight and the necessity of antioxidant protection.

Taking into account the aspects of environment protection and the variety of applications, it was decided to use waste materials to build EMI screens. In industrial processes and in the construction of different components, waste with appropriate parameters is generated, e.g. snips from nanocrystalline and amorphous tapes and iron oxides - iron scale. Examples of the used materials are shown in Figure 1. In combination with thermoplastic polymers (e.g. high density polyethylene - HDPE), they can be used to produce rigid casings and roller shutters. An additional advantage of the proposed solution is the possibility of obtaining of any shape.

As shown in [8, 9], various waste materials have the potential to be used as electromagnetic shields. The influence of the thickness of the entire barrier and individual layers on the shielding effectiveness of waves with frequencies used in data transmission in LTE and 5G technology was investigated.

Fig. 1. Example of recycling materials: nanocrystalline tape, iron scale.

Theoretical basis of shielding effectiveness

According to the IEEE standard [10], the shielding effectiveness of the electric and magnetic field is defined as the ratio (expressed in decibels) between the absolute value of the electric field E_1 (or magnetic field H_1) at a point in the unscreened space, and the absolute value of the electric field E_2 (or magnetic field H_2) in the same point in space with the screen and it is expressed by dependence (1):

$$SE = 20\log_{10}\frac{|E_1|}{|E_2|}\,[\mathrm{dB}] \tag{1}$$

The total *SE* (shielding effectiveness) level depends on three mechanisms: reflections – reflections losses *R* (dB), absorption – absorption losses *A* (dB) and multiple reflections *M* (dB) inside the material:

$$SE(\mathrm{dB}) = R(dB) + A(dB) + M(dB) \tag{2}$$

The electromagnetic shielding mechanism can be illustrated as in Figure 2.

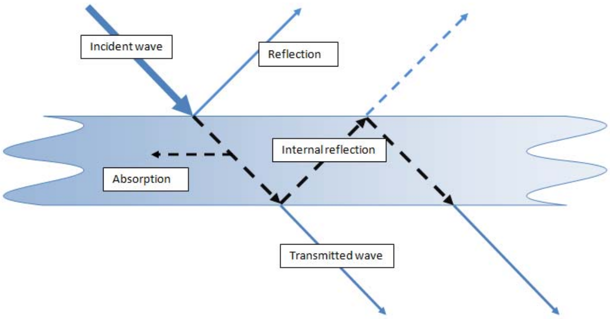


Fig. 2. Schematic diagram of electromagnetic shielding

In the literature on that theme, proposals for different variants of models describing the phenomena of shielding can be found [11-15]. According to [16], for the frequencies of a single layer and high-frequency fields, equation (2) takes the form (3):

(3)

$$SE(\mathrm{dB}) = 8.66\frac{d}{\delta} + 20\log(1 + \frac{Z_0 \sigma d}{2})$$

In the far field region, the free space self-impedance is expressed by the ratio between the amplitude of the incident electric field and the amplitude of the incident magnetic field, and is a constant equal to 377 Ω:

(4)

$$Z_0 = \frac{|E|}{|H|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \cong 377\ \Omega$$

Th respective *SE* components are:

- absorption:

(5)

$$A(\mathrm{dB}) = 8.66\frac{d}{\delta}$$

- reflection:

(6)

$$R(\mathrm{dB}) = 20\log\left(1 + \frac{Z_0\sqrt{\frac{\sigma}{f\mu}}}{10}\right)$$

- multiple internal reflectance:

(7)

$$M(\mathrm{dB}) = 20\log\left(\frac{1 + \frac{Z_0 \sigma d}{2}}{1 + \frac{Z_0\sqrt{\frac{\sigma}{f\mu}}}{10}}\right)$$

Conductor skin effect, called as penetration depth or magnetic diffusion depth and denoted as *δ*, can be calculated from the relationship (8):

(8)

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}}$$

In the described case, individual layers of the composite were analysed. Additionally, in view of the homogeneity of real composites, a simplification, that they form a material of the type *solid*, was adopted.

Simulations

On the basis of the actual parameters of the materials presented in Table 1, the analysis of the shielding effectiveness was carried out, divided into the following components: absorption damping (*A*), damping of reflection (*R*) and multiple reflections (*M*). The frequencies of the electromagnetic wave correspond to the range of bands used for LTE and 5G communication

Table 1. Selected properties of the used materials

Material	Nanocrystalline tapes [13]	Iron scale [14]	HDPE
Density (g/cm^3)	7.2	2.9	0.94-0.96
Saturation induction (T)	1.25	0.1	-
Max magnetic permeability	350000	10	-
Resistivity (Ωcm)	1.3x10^{-5}	1x10^{-3}	1.6x10^{16}

First, the dependence of *SE* on the relative permeability was checked in the range of μ_r from 1 to 350 000 (Fig. 3). This corresponds to the value from HDPE to nanocrystalline tape.

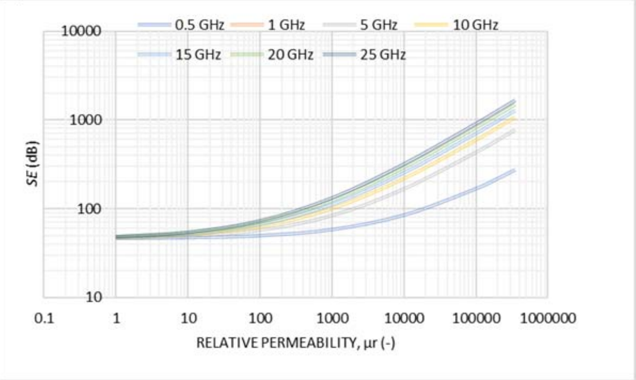


Fig. 3. Dependence of shielding effectiveness (*SE*) on magnetic permeability μ_r

The change in μ_r value begins to significantly affect the total level of *SE* only after the value of 100 is exceeded. This value corresponds to the relative permeability of carbon steel [17]. The shutter thickness *d* was 1 mm. As μ_r increases, the absorption losses and the level of internal reflections increase. On the other hand, the level of reflection losses is reduced. It should be noted that the internal reflection loss *M* (dB) is minus at low μ_r and reduces overall shielding effectiveness. This indicates that weaker shielding is obtained due to many reflections that are not absorbed well enough, as a result of which the EM wave extends beyond the shutter area.

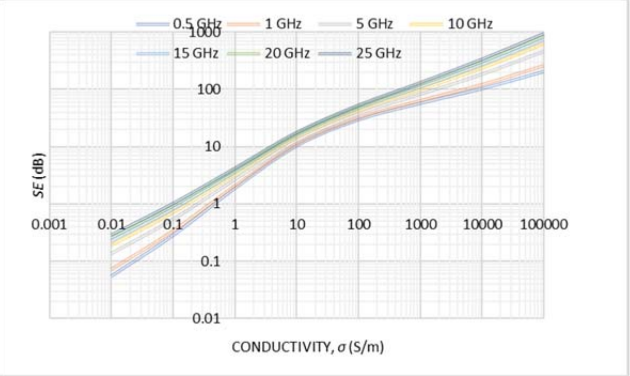


Fig. 4. Dependence of shielding effectiveness (*SE*) on conductivity *σ*

In the next step, the influence of the change in conductivity σ (Fig. 4) on the SE level was checked. As in the previous case, the membrane thickness *d* was 1 mm. The μ_r value was set to 1000.

In this case, the change in the electrical conductivity of the material significantly affects the *SE* level. An increase in *σ* value causes an increase in *SE*. An important difference to note is the change in the *R* (dB) correlation to *σ*. An increase in conductivity leads to an increase in *R* (dB). So contrary to the growth of μ_r. This means that with greater electrical conductivity of a material, more electromagnetic radiation is reflected from its surface

Then, the influence of the coating thickness on the overall SE level was checked (Fig. 5). The μ_r and *σ* values were set to 1000 and 1000 S/m, respectively

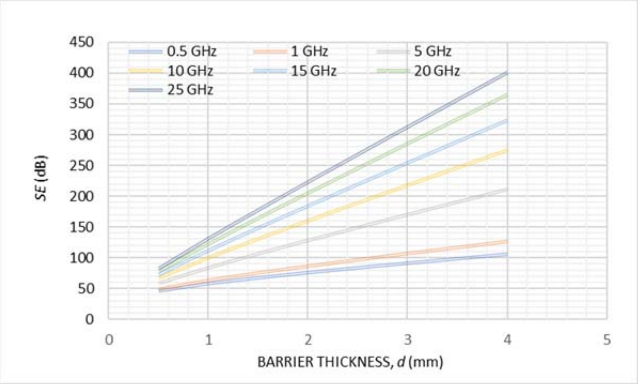
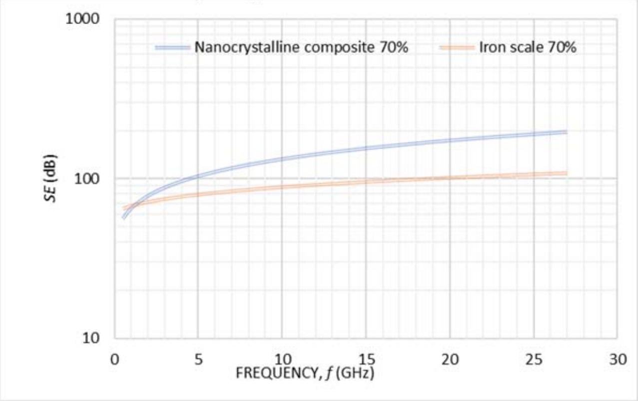
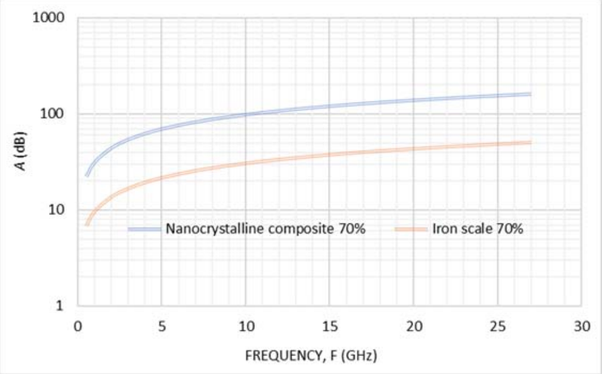
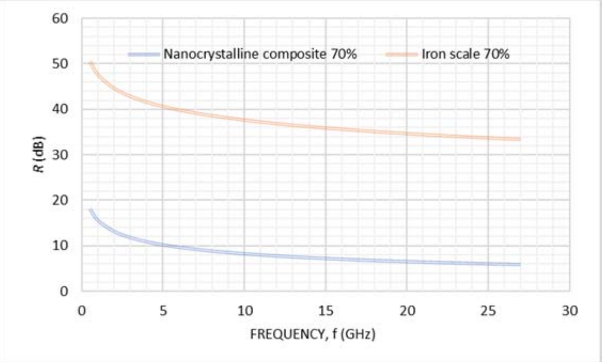


Fig. 5. Dependence of shielding effectiveness (*SE*) on shutter thickness

The shutter thickness has a greater effect on the overall *SE* shielding level as the frequency of the electromagnetic wave increases. This is mainly due to the higher absorption losses *A* (dB). In this case, it should be noted that *d* value does not affect the level of reflection loss *R* (dB) at a constant wave frequency.







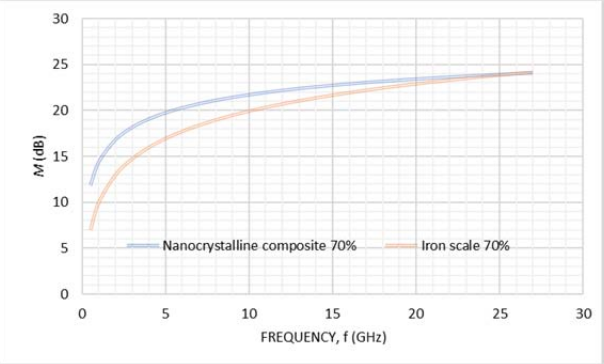


Fig. 6. Dependence of shielding effectiveness (*SE*), absorption losses (*A*), reflection losses (*R*) and multiple internal reflectance (*M*) on frequency *f*

On the basis of the conducted partial simulations, the shielding effectiveness was modelled for two composites (Fig. 6), made appropriately of powdered nanocrystalline (NK) tape and iron scale, with parameters μ_r and *σ* at the level of 70% of their catalogue values.

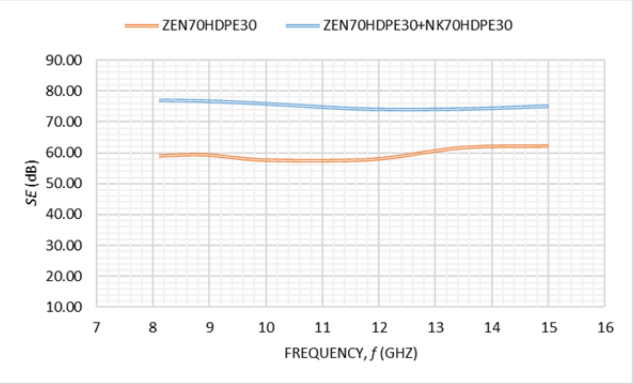


Fig. 7. Shielding effectiveness (*SE*) measurement for a two-layer composite

In the last stage of the research, a composite samples, consisting of two layers: iron scale (70% by weight) and HDPE (30% by weight) and powdered nanocrystalline tape (70% by weight) and HDPE (30% by weight), were prepared. The iron scale-HDPE composite layer was 2 mm thick, while the NK-HDPE layer was 0.5 mm thick. Such an arrangement was necessary due to the inability to obtain a stable and tough sample from nanocrystalline flakes with a thickness of 0.5 mm. For comparison, Fig. 6 shows the measurement results for a single-layer sample - 70% iron scale and a two-layer sample 70% iron scale + 70% NK.

The obtained SE values - approx. 60 dB (for $\mathrm{Zen_{60}HDPE_{30}}$) and approx. 75 dB (for $\mathrm{Zen_{70}HDPE_{30}{+}NK_{70}HDPE_{30}}$) from the actual measurements diverge slightly from the values resulting from the simulation (Fig. 7) and are at a satisfactory level. The obtained shape of the shielding level curve depending on the wave frequency was similar to the shape obtained in the simulation. Measurements were made using HP 70340A signal generator, a slotted waveguide, a detector (B473) and a multimeter. The voltage signal was measured on the detector with and without sample in the aperture. An example of a sample is shown in Fig. 8.

Fig. 8. Samples of single and double-layer composites.

Conclusions

The article presents simplified formulas describing the shielding effectiveness mechanism, taking into account the following components: absorption losses, reflection losses and internal multiple reflectance losses. The conducted simulations allowed to estimate the parameters that must be characterised by the developed composites in order to be able to effectively shield the EM field in the LTE and 5G frequency ranges (0.8 - 27 GHz). The two-layer composite consisting of a mixture of iron scale and nanocrystalline powder with construction polymer achieved a satisfactory level of 75 dB of screening effectiveness. Due to easy availability and low price, iron scale was used as the base material. In combination with HDPE, a durable composite suitable for the construction of covers and casings was obtained. The addition of a composite layer based on nanocrystalline powder, which is a waste in the production of electric cores, significantly increased the shielding effectiveness. Due to the different parameters of the individual layers, it is possible to obtain the desired properties of the final composite. According to the simulations results, the iron scale composite is characterised by a greater ability to reflect EM wave than the nanocrystalline composite. In turn, the nanocrystalline composite absorbs radiation much better. This arrangement allows to take advantage of the positive features of both materials.

The conducted research confirmed the suitability of the usage of iron scale for the construction of cheap shielding materials. This is important both from the point of view of environment protection (waste utilization) and the protection of people and devices (against undesired electromagnetic disturbances).

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