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The application of composites based on recycled materials for electromagnetic field shielding

Streszczenie. *W artykule przedstawiono możliwości wykorzystania kompozytów polimerowo-metalowych jako ekranów elektromagnetycznych. Do budowy kompozytów wykorzystano materiały z recyklingu, takie jak zendra i taśmy nanokrystaliczne. W toku prac prowadzono badania nad skutecznością ekranowania pól elektromagnetycznych w zakresie od 40 Hz do 15 GHz. Wykazano, że skuteczność ekranowania jest konkurencyjna w stosunku do innych materiałów kompozytowych na bazie wypełniaczy niemetalicznych i porównywalna z kompozytami warstwowymi zawierającymi m.in. aluminium..*

Abstract*. This paper presents the possibilities of using polymer-metal composites as electromagnetic shields. Recycled materials such as iron scale and nanocrystalline tapes were used to build the composites. In the course of the work, research was carried out into the effectiveness of shielding electromagnetic fields in the range from 40 Hz to 15 GHz. The shielding effectiveness was shown to be competitive to that of other composite materials based on non-metallic fillers and comparable to that of layered composites containing e.g. aluminum. (**Zastosowanie kompozytów na bazie materiałów pochodzących z recyklingu do ekranowania pola elektromagnetycznego**).*

Słowa kluczowe: kompozyty, materiały odpadowe, skuteczność ekranowania, zgorzelina żelazna, ekranowanie elektromagnetyczne.
Keywords: composites, waste materials, shielding effectiveness,, iron scale, electromagnetic shielding.

Introduction

The optimal use of raw materials is one of the objectives of a sustainable economy. In our research, we focused on the use of waste materials, e.g. iron scale and nanocrystalline strips, generated in various production processes, for the construction of electromagnetic shielding. The great freedom of shaping electrotechnical composites makes it possible to give them the desired features, useful in limiting the negative influence of electromagnetic radiation on electronic systems, e.g. disturbing their operation and communication. Such materials are highly desirable in medical, aerospace and military applications, as well as in everyday human environments. As the number of sources and signal strength increases, the problems caused by the resulting interference increase. This is particularly undesirable in industrial processes, IIoT systems and control and measurement systems [1, 2].

The effectiveness of shielding depends on many factors and varies with frequency, geometrical structure of the screen, type of shielded field, direction of incidence and polarization. A wave which falls on the screen surface is partially reflected and partially absorbed by it. There are therefore two effects called reflection losses and absorption losses. In addition to reflection and absorption, an incident wave passing through a material may be reflected many times within the material, further increasing the absorption. The total shielding effectiveness of a material is equal to the sum of these losses (1) [3]:

(1) $$SE(dB) = R(dB) + A(dB) + M(dB)$$

where *R* (dB), *A* (dB), *M* (dB) represent respectively reflection loss, absorption attenuation, additional multiple reflection effects.

The factor which characterizes the effectiveness of shielding objects and electrical systems from the influence of magnetic fields is the shield's attenuation, also called shielding effectiveness, given in decibels and defined by the formula (2) [4]:

(2) $$SE = 20\log_{10}\frac{|E_1|}{|E_2|}\ [\mathrm{dB}]$$

Where the shielding effectiveness for electric and magnetic fields is defined as the ratio between the absolute value of electric field E_1 (or magnetic field H_1) at a point in space without shielding and the absolute value of electric field E_2 (or magnetic field H_2) at the same point in space with shielding.

Various materials with different properties can be used for protection against unwanted electromagnetic radiation. For example, shields made of metals such as Fe-Si, Al, Ag, Au, Cu are characterized by very high electrical conductivity. As a result, they reflect EM radiation very well [5] However, it is not a prerequisite that the material conducts well throughout its volume, which opens up the possibility of using composites [6, 7]. On the other hand, materials with high magnetic permeability, such as mu-metal (μ_{max} = 250 000), Vacoperm 100 (μ_{max} = 350 000,) Permenorm (μ_{max} = 30 000), Vitrovac (μ_{max} = 100 000) supermalloy and nanocrystalline and amorphous alloys favor the absorption of radiation [8, 9].

The publication presents the results of an experimental study of polymer matrix composites with fillers in the form of iron scale and nanocrystalline flakes. The aim of developing the composite structure was to provide shielding of both magnetic and electric fields. The shielding effectiveness of the waves in the frequency range of 40-600 Hz, 200 - 2750 MHz and 7 - 15 GHz was investigated.

Materials and methods

For the purpose of this task, metal and polymer waste materials were obtained from companies cooperating with the university. Examples are shown in Fig. 1.

Fig. 1. Examples of base materials: a) nanocrystalline tapes, b) flake of iron scale.

The collected materials were examined for chemical composition and structure: shape and size of grains. Based on the obtained materials and the information on the processing parameters of the polymeric binders, more than 50 samples with different qualitative and quantitative compositions were prepared. The aim was to study the stability of the composites and their mechanical strength. Some of the samples crumbled or delaminated due to improper selection of component ratios or moulding pressure [10, 11]. Finally, specimens of the composition $NK_{20}ZN_{50}HDPE_{30}$ (NK- nanocrystalline flakes, ZN-iron scale, HDPE- high-density polyethylene) of dimensions 100x100x4 mm, were prepared for further testing. Additionally, some of them were covered with a 1 mm ceramic layer to increase fire resistance (Fig.2).

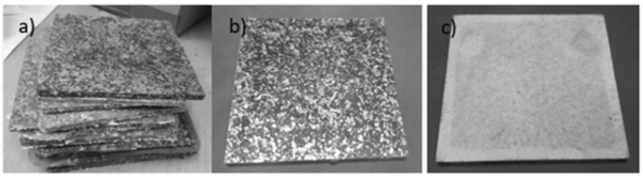

Fig. 2. Examples of specimens: a, b) plates of $NK_{20}ZN_{50}HDPE_{30}$, c) the ceramic coated sample.

Individual samples were subjected to a preliminary measurement of shielding effectiveness in the low and high frequency range. In the first stage, the electromagnetic field shielding ability was tested for the frequency *f* = 40 - 600 Hz. For this purpose, a coil wound on a ferromagnetic core was used as the field source, an ASR-2100 programmable power supply unit, a BGM 101 magnetic field meter and an earthed chamber with an aperture for placing the samples (Fig. 3a-b). The measurement was performed with the same distance between the Hall sensor and coil placed between them, the polycarbonate plate and the samples under test. The measurements showed a weakening of the magnetic field by min. 50%.

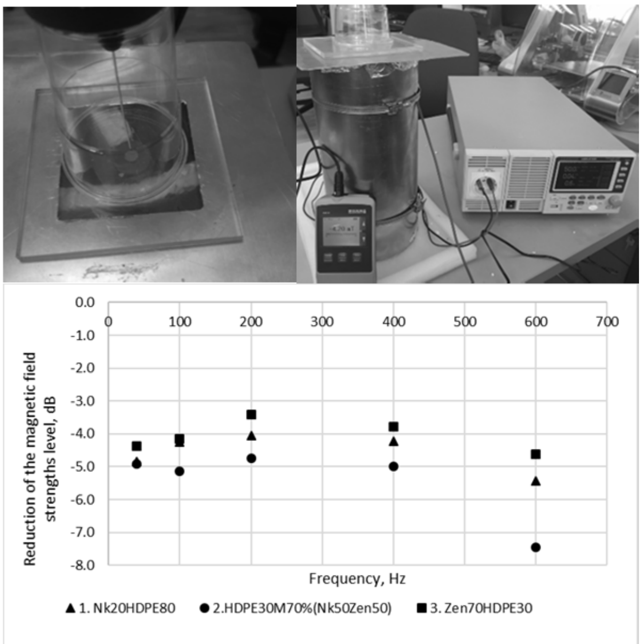

Fig.3. Shielding of composites for frequencies <1 kHz, a) view of the transmitting coil, b) view of the measuring station, c) shielding level in the frequency range 40-600 Hz for three examples.

In the next step, a preliminary verification of the shielding capability at higher frequencies, above 1 GHz, was performed. A waveguide system with a slot in which the test sample was placed was used (Fig. 4). Preliminary measurements showed very good shielding effectiveness, up to 50 dB.

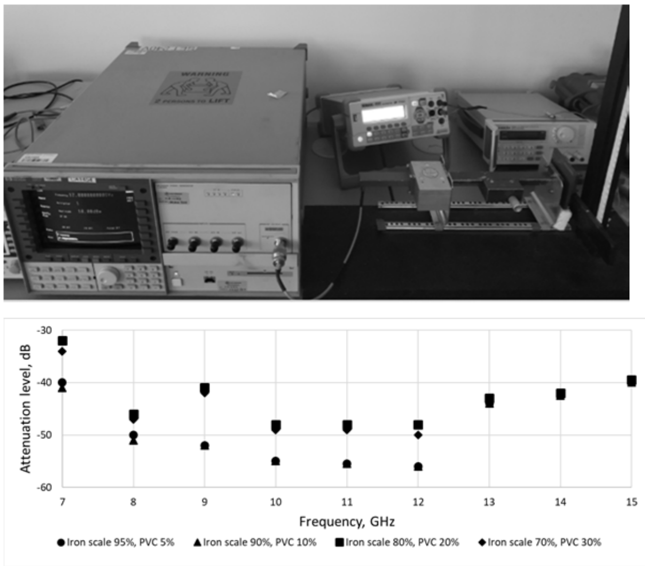

Fig. 4. Test stand for shielding effectiveness: generator, waveguide, multimeter. B) Level of attenuation of EM wave for f = 7-15 GHz of composites

Measurements

In order to test the developed composite materials under near real conditions, two test chambers were made of them. Measurements were made based on IEEE guidelines [12]. The first chamber, measuring 0.3x0.3x0.3 m (Fig. 5), was built on a frame of PE profiles and polycarbonate sheets, to which the composite plates were glued with a paste made of ABS dissolved in acetone and sifted ABS and sifted scrap iron powders. A transmitting system - ADF4351 frequency generator was inserted into the chamber prepared in this way. The whole thing was closed in the GTEM1000 chamber.

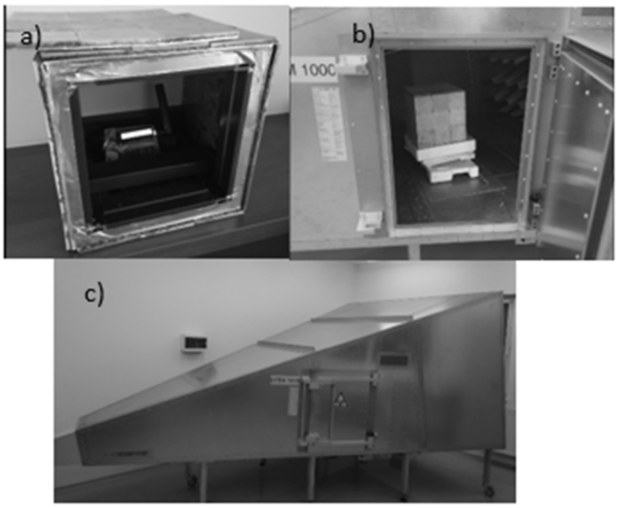

Fig. 5. Test stand: a) small test chamber made of composite plates, b) the chamber placed in GTEM1000 chamber, c) GTEM1000 chamber.

The second chamber made was larger and had dimensions of 1x1x1 m (Fig.6.). It was made of steel profiles and copper sheets. One of the chamber walls was covered with prepared tiles, which were glued to the polycarbonate sheet as in the case of the small chamber. The chamber was closed and earthed for the duration of the measurements. Due to the large size of the second chamber it was possible to place inside it the whole test bench with 3-phase transformer or coils with arbitrary power supply.

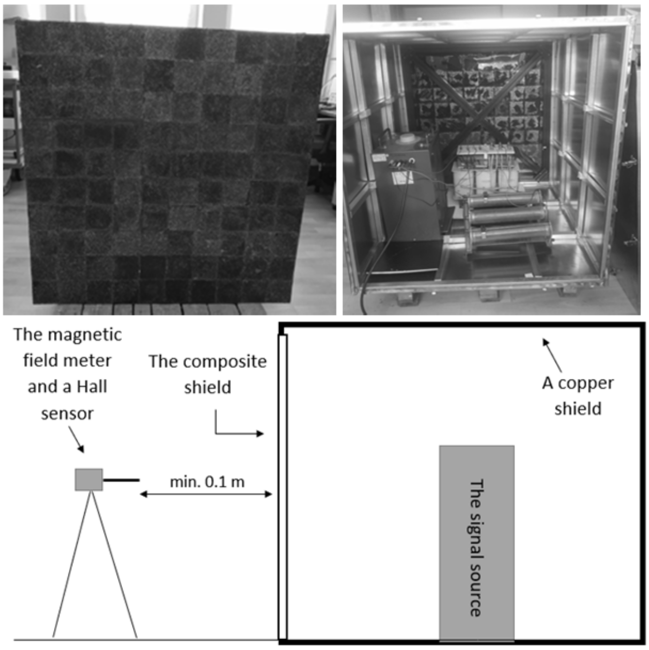

Fig. 6. The large test chamber: (a) composite screen view, (b) interior view, (c) diagram of the stand for measuring the magnetic field induction f = 50 Hz at a distance of 0.1 m from the chamber wall with and without a composite screen.

In this case, a shielding efficiency of about 9 dB was obtained for the 50 Hz field. The result should be considered satisfactory, due to the fact that in the near field, both reflection and absorption losses for low frequency magnetic fields are small. Therefore, the use of copper or steel as shielding materials for magnetic fields at 50 Hz is practically ineffective [8]. The measurement results are shown in Fig. 7.

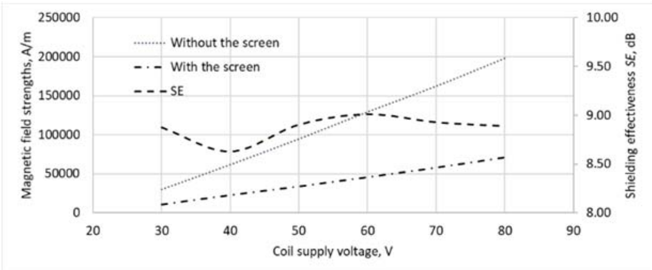

Fig. 7. 50 Hz field shielding effectiveness.

Measurements in the frequency range 0.2 - 2.75 GHz showed an increase in shielding effectiveness with decreasing wavelength. The figure 8 shows the difference between the signal level recorded with the small chamber open and that obtained when the chamber is closed. The values are expressed as an absolute level relative to 1 μV.

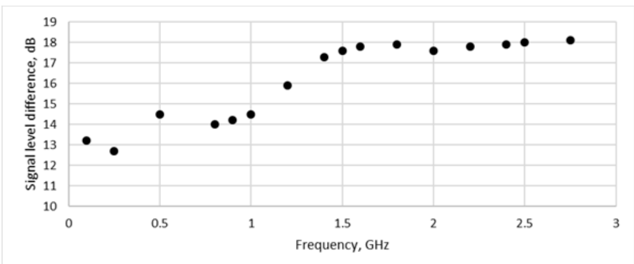

Fig. 8. The result of shielding effectiveness measurements in the range 0.2 - 2.75 GHz.

Conclusions

In this study, the effectiveness of electromagnetic field shielding in the range from 40 Hz to 15 GHz was tested. It was confirmed that the assumed milestones were met and more than 50% of the signal was shielded. The developed composites made it possible to obtain shielding effectiveness from 9 dB for low frequencies (< 1000 Hz), through approx. 18 dB for frequencies around 2 GHz, up to *SE* level of approx. 50 dB for frequencies above 10 GHz.

The values obtained were compared with results obtained by other researchers. Shielding of gigahertz frequencies at the level of 50 dB is a result often better than in the case of other composite materials based on non-metallic fillers and comparable to layered composites containing, for example, aluminum (Tab. 1.). A good example is a textile composite with a vacuum-applied aluminum layer, which achieved a screening efficiency of 42 dB [13]. And also a sandwich composite made of natural fiber mats and ultra-thin aluminum sheet bonded with epoxy resin [14]. The SE values of this composite, depending on the number of aluminum sheet layers, ranged from 30 to 53 dB.

Table 1. EMI shielding properties of different composite materials based reported in the literature.

Materials	Frequency range	*SE* (dB)	Ref.
Natural fiber and aluminum sheet hybrid composites	8–12 GHz	< 54	[14]
Carbon fiber-Fe_3O_40 (3.5 mm) + EVA	8.2–12.4 GHz	34.1	[15]
Composites with Fe_3O_4 nano particles of 1.0 wt.% and carbon fibers	8–12 GHz	≥20	[16]
NCS/Fe (1.2 mm)	8–12 GHz	< 30	[17]
PVDF/Fe_3O_4-8%CNT (1.1 mm)	18-26.5 GHz	<23	[18]
Shielding fabric (80% nylon, 20% silver, specific weight: 45 g/m².)	8–12 GHz	< 60	[19]
MCL61 - EMI foil (Composition: polyester, Co, Fe, Mo, Nb, Si, B. Material thickness: 0.1 mm)	8–12 GHz	< 90	[20]
$NK_{20}ZN_{50}HDPE_{30}$ (4 mm) Present work	<15 GHz	<52	-

The results of the research conducted in this study confirmed the suitability of composites developed on the basis of metal recycled materials for the construction of electromagnetic field shields. HDPE is also a commonly used polymer that can be obtained in the form of recyclate. The properties of these materials mean that in situations where barrier thickness is not crucial, satisfactory shielding effects can be achieved at low cost. The presented solution is an alternative to screens and enclosures made of plastics covered with paint or conductive layers such as aluminium. The use of recycled (and recyclable) materials is much less harmful to the environment than the paints and sprays used to paint plastics, which contain very harmful solvents.

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