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A Review over Electromagnetic Shielding Effectiveness of Composite Materials †

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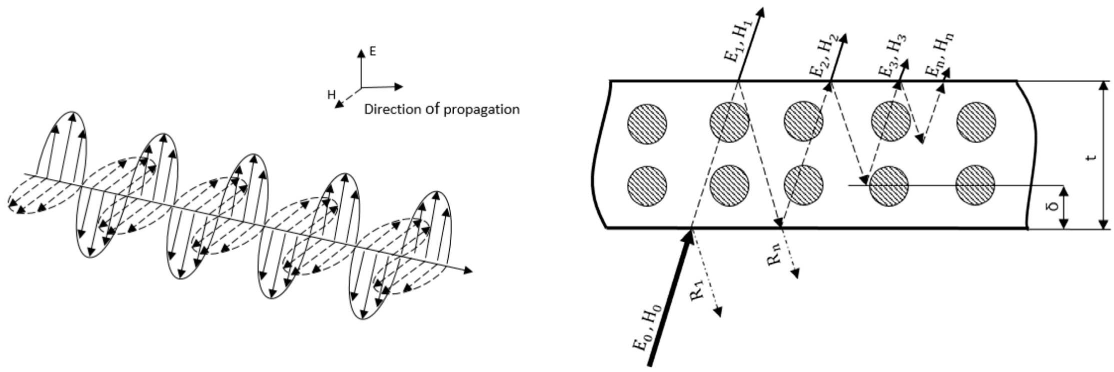
Abstract: The aim of this paper is to review and compare the response to the electromagnetic radiation of different structural or non-structural composites on absorption, reflections and re-reflection grades. The area of interest has been reduced to the carbon allotropy and conducting non-magnetic/magnetic fillers (inclusions, metallic powders, granular ferrites) in dielectric hosts characterized by existing mixing rules. The results could be grouped in distinctive ranges, *SE* ≤ 10 dB corresponding to a poor shielding, 10–30 dB describing an acceptable effectiveness and *SE* ≥ 30 dB exceeding the acceptable range for industrial and commercial applications of 20 dB.

Keywords: composites; carbon; shielding; electromagnetic; interference; frequency

1. Introduction

In the space around us, the presence of electromagnetic waves is observed as a matter of course phenomenon. The light itself is theoretically an unlimited electromagnetic radiation which could be detected by human eye, defining the visible spectrum, or could be invisible for human eye as ultra-violet (UV) or infra-red spectrums. Beside the aforementioned source, there are a lot of artificial sources of electromagnetic waves created by different electric or electronic equipment travelling under different polarization forms illustrated by Figure 1a. The electromagnetic interferences (EMI) thus are unavoidable.



(**a**) (**b**)

Figure 1. (**a**)The electromagnetic wave field propagation through space, vertical polarization; (**b**) the mechanism of shielding effectiveness through a given composite section.

The possibility of combining two or more materials with different electrical and mechanical properties in order to obtain an enhanced material with a high grade of homogeneity, aligns with actual trends of economical and environment global strategies. The materials resulted in aforementioned process are known as composites, having a well-defined structure characterized by two phases: one continuous, depicted as host or matrix medium and one discontinuous, described by reinforced elements or fillers. The aerospace industry was coupled many years with composite materials due to lightweight and particular structural efficiency, nowadays being widely spread in different industry fields from automotive to medical equipment. Generally, the composites are structured by association of two different material types; based on the atomic structure and chemical composition, materials are classified in three major classes: metals, ceramics and polymers (compounds resulted by hydrocarbons refining) [1].

Confining the composite classification to the domain of electromagnetic shielding effectiveness (SE) has delineated two major properties which the material should possess, high electric conductivity σ and low specific weight g. In Table 1 are presented values of conductivity for different kind of materials. Some materials are characterized by a high electric conductivity given intrinsically by its structure: magnetic metals, ferrites, carbon compounds or conducting polymers. For example, the electric conductivity of carbon structures, regardless of type, could be controlled by carbonization temperatures; high temperatures corresponding to top graphitization degree, therefore, to an enhanced σ value. A large interest in carbon and in its allotropic nature is observed since almost half of scientific articles written in the last decade on electromagnetic interference shielding topics contained "carbon" as a keyword [2].

Table 1. Electric conductivity for different classes of materials [3].

Material	Conductivity [σ]		Relative
	[S/m]	[S/cm]	
Cu	5.81×10^7	5.81×10^5	1
Al	3.48×10^7	3.48×10^5	6.01×10^{-1}
S/S	1.16×10^6	1.16×10^4	2×10^{-2}
S/S in polymer	5×10^2	5	8.62×10^{-6}
GRFP	1.16×10^4	1.16×10^2	2×10^{-4}
40%CF	1	1×10^2	1.72×10^{-8}
20%Ni coated	9.09×10^2	9.09	1.57×10^{-5}

One particular form of carbon emerged in this review article it is represented by the carbon fibers under various forms: continuous fibers (CF), long fibers (LF) and short fibers (SF) embedded usually in polymer matrices being grouped in a well-defined category CFRP (carbon fibers reinforced polymers matrix) or ACM (advanced composite materials).

2. The Fundamentals of Shielding Effectiveness (EMC/EMI)

The shielding effectiveness mechanism SE is described in the relation (1) as a sum of three particular losses: wave reflection losses R, wave absorption losses A and wave re-reflection losses B caused by the molecular structure of the material.

When an initial transmitted electromagnetic wave, as shown in Figure 1b characterized by an electric field intensity E_0 and a magnetic field intensity H_0, meets the shielding material surface a certain grade of reflection occurs, followed closely by material absorption and an attenuation of wave intensity caused by n wave internal re-reflections. Mathematically, the shielding effectiveness is given by relation (2) as a logarithmic ration between the plane field intensity of radiated wave P_0 and plane field intensity of transmitted wave P_n. Similarly, the reflection, absorption and multiple reflections are described logarithmically by formulas given in relations (3)–(5).

$$SE = A + R + B[\text{dB}] \quad (1)$$

$$SE = 20\log\left(\frac{E_0}{E_n}\right) = 20\log\left(\frac{H_0}{H_n}\right) = 10\log\left(\frac{P_0}{P_n}\right)[\text{dB}] \quad (2)$$

$$R = -10\log\left(\frac{\sigma_{ac}}{16\omega\varepsilon_0\mu_r}\right)[\text{dB}] \quad (3)$$

$$A = -20\left(\frac{t}{\delta}\right)\log_{10} e[\text{dB}] \quad (4)$$

$$B = 20\log_{10}\left(1 - e^{-2t/\delta}\right)[\text{dB}] \quad (5)$$

Shielding effectiveness SE depends on a series of constants and variables, such as complex permittivity ε_r and permeability μ_r, material type, material thickness t, dielectric properties σ_{ac}, frequency ω, free space permittivity ε_0, skin depth δ. The skin depth δ is defined as being the material thickness where the electromagnetic field intensity is reduced with approximate 37% (examples given ∂_{Cu} = 2.09 µm, ∂_{Ni} = 0.47 µm, at a frequency of 1 GHz).

When high grades of wave reflection are permitted a suitable solution for shielding it is represented by metals, but in general many applications require a high grade of absorption through material, the reflected waves compromising the normal functionality of electronic and electric equipment. Therefore, ways are sought of converting the radiated or conducted wave energy in thermal energy, very often as heat.

3. Composites Used in Shielding Application

Radiated electromagnetic emissions have been measured around an electric vehicle in real drive conditions. These measurements were accomplished between the 30 MHz and 1 GHz frequency spectrum and revealed the highest interference between 30 MHz and 54 MHz when the peak detector was placed at the right and left of the vehicle being at a constant speed. Full scans of the vehicle at a constant speed were performed showing that the peak electric field are 5 dB higher than those measured at the right and left of the vehicle. The measurement techniques proved that the electromagnetic radiations varied significantly during a driving cycle [4].

The 2/2 twill weave carbon fabric with different specific weights was used to form composite laminates. Both dry carbon fibers and laminates were subjected to a frequency spectrum of 30 MHz to 1.5 GHz to measure the electromagnetic shielding effectiveness parameter in a coaxial device according to ASTM D4935 standard. In the case of a 1 mm thick composite laminate (four layers) with 2/2 twill weave carbon fabric, the shielding effectiveness parameter varied between 63.7 dB to 82.3 dB in the domain from 30 MHz to 450 MHz frequency. For a 3 mm thick laminate with eight layers of 2/2 twill weave carbon fabric, the SE shows variations between 70.9 dB to 88.2 dB in the range of 30 MHz to 401.28 MHz spectrum. The dry carbon fabric increases its shielding properties due to the lack of the resin as well as increasing the contact between fibers. On the other hand, the fiberglass allows the electromagnetic radiation to act without any compulsion. Sandwich PVC foam core specimens with one layer of carbon fabric and one layer of fiberglass on both sides as skins present shielding effectiveness values up to 122 dB measured within the 30 MHz to 500 MHz frequency range [5].

Carbon nanotubes paste was prepared and then printed on this plastic film. Measurements of the shielding effectiveness were accomplished in the frequency domain from 15 MHz to 1 GHz with a signal generator according to ASTM D4935. All carbon-based films presented an electromagnetic shielding effectiveness between 12 dB and 28 dB in the frequency range from 30 Hz to 50 Hz; this parameter drops significantly between 3 dB and 6 dB for a frequency domain from 50 Hz to 100 Hz, remaining almost constant until 1000 Hz frequency [6].

In many situations when an enclosure is needed to protect an equipment against EMI, the design of composite material and of the structure are developed virtually using various wave tool simulation as EZ-FDTD (finite difference time-domain process tool) developed by EMC Laboratory of MS&T and IBM, or CST Microwave studio. Koledintseva et al. studied, using a genetic algorithm optimization GA, the performance of Teflon carbon fiber filled composite shielding enclosures in a single layer/multilayer in terms of SE, in the microwave band 100 MHz–10 GHz. The Maxwell–Garnett rule has been used to determine the material effective electromagnetic parameters at given frequency ranges and the afferent carbon fiber properties (aspect ratio, percolation threshold, volume fraction, alignment). Using FDTD simulation at frequencies between 10^{-1}–10^{1} GHz the SE of a composite single layer box is situated at 10–50 dB, while the same box with composite multilayers the peak of SE reaches 90 dB. In the same study it was proven that composites materials have superior properties compared with metals when enclosures contains various geometrical apertures [7].

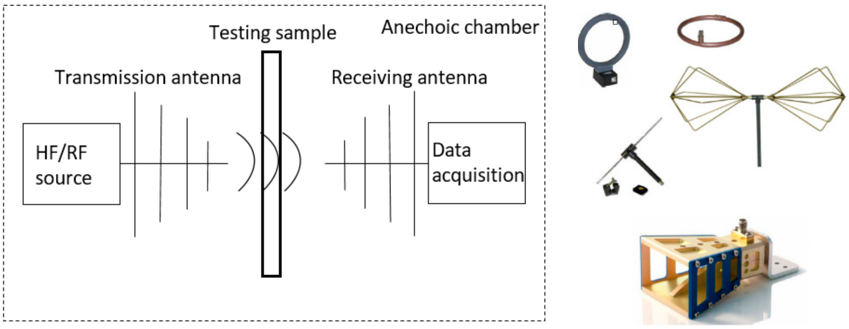
In the automotive industry, various technical solutions have been developed in order to suppress EMI. There is a wide range of conductive elastomers in molded or extruded shapes reinforced with conductive fillers, such as carbon C, passivized aluminum IA, silver plate aluminum Ag/Al, Nickel-coated carbon Ni/C evidenced a shielding effectiveness up to 120 dB at 10 GHz. Thermoformed polycarbonate foils have been coated with conductive metals molded in different shapes, as covers or caps, shown an effectiveness of 60–80 dB in frequency spectrum 30 MHz up to 2 GHz [8].

Neruda et al. tested two types of textile plain weave woven fabrics composite; the first was waved with silver-coated yarns and the second with a mix between non-conductive PES (polyamide) yarns (60%) and silver-coated yarns (40%) characterized by a high electrically conductivity σ = 244 S/m, noticing a reduction of electromagnetic field intensity with 25–50 dB in a frequency range of 0.03–1.5 GHz. Testing was based on ASTM 4935-10, using the coaxial transmission line method [9].

The attenuation of electromagnetic field, the power of the absorbed wave field and the shielding effectiveness were determined for composites materials reinforced with carbon black (TN150 and TN300), graphite (GR150/GR300), ferrites (FT150) and micro particles of iron (FE300) in the frequency spectrum of 10MHz up to 1 GHz, with thicknesses of material varying in the range of 2.3–3 mm. An enclosed plain waved TEM (Transverse Electro-Magnetic) cell with a high grade of isolation from exterior perturbations was used, the electromagnetic field being separated in two components, electric and magnetic as plain waves. Values of shielding effectiveness were observed from 0.5 to 2.13 dB, emerging on the variation plot the highest values at the end of frequency range, near 1 GHz. Among all types of tested materials GR300, 2.6 mm thickness possesses superior shielding properties which puts the graphite on the top of the list with materials with high electromagnetic absorption properties [10]. The same testing technology of TEM cell according to ASTM D4935 has been applied on a composite material with a conductive coating developed by Freudenberg Sealing Technologies GmbH & Co. KG reaching a top sealing of 115 dB at 10 MHz [11].

Petru Ogrutan et al. using the wave guide-based method shown in Figure 2a,b, which presents similarities with MIL-STD-285 and EN 50147 standard specifications, measured the shielding effectiveness for different composites materials and validated the wave power attenuation using a Pspice model simulation. Cardboard sheets, glass fabric phenolic sheets, 3 mm and 5 mm sheets of synthetic graphite and FE300 (Butadiene styrene rubber matrix reinforced with ferrites) with 3 mm thickness were appropriate for testing. The results shown at 10 GHz describe an electromagnetic power attenuation of 1 dB in case of cardboard sheet, 2 dB for glass fabric phenolic screen and 6 dB when FE300 was used [12].

Erhan Sancak et al. investigated the electromagnetic shielding effectiveness of polyamide (PA6) membranes filled with AgNP (Silver nanoparticles, 20 nm, spherical shape on metal basis) at different concentrations (0 wt%, 1 wt%, 2 wt%). The polymer membranes have been obtained combining electro spun nanofibers (sizes from 174 nm up to 238 nm) using the electrospinning technique. The ASTM D4935-10 coaxial transmission line method was used in the frequency domain of 15 MHz–3 GHz.



(**a**) (**b**)

Figure 2. (**a**) Shielding effectiveness wave guide-based method schematic test set-up; (**b**) types of antennas, constructive solutions.

The results show a constant attenuation of 2.5 dB on the entire frequency domain when specimens contained 2 wt% AgNp, approximately 1 dB in the case of 1 wt% and no attenuation in the pure PA6 samples. The shielding effectiveness performance is influenced directly by material electric conductivity. The polyamide, as pure material, exhibits a non-conducting behavior, while the percentages of AgNP have enhanced the material electric conductivity, hence have increased the shielding effectiveness [13].

A wide range of studies have been conducted on the evaluation of electromagnetic compatibility and radiated emissions in the case of high voltage electric vehicles in various operating ways. Anca-Alexandra Săpunaru et al. measured the electromagnetic radiation values for an electric vehicle in charging mode, driving mode and ready-to-drive mode in a frequency spectrum of 30 MHz–1 GHz.

It was found that in driving mode, at 40 km/h, the level of radiated emissions, peaks level exceeded 45 dBμV/m, the quasi-peak detector limit for an antenna at 3 m distance being 42 dBμV/m [14].

A separate category of composites encompassing textiles were tested to fields suppression; considering IEEE STD-299 (using two horn antennas and a shielded structure with an opened window) instrumental set-up various structures containing natural fibers (wool and cotton), polymeric fibers (as nylon and polyester) and conductive fibers (Cu, SS, C) were checked for shielding effectiveness in a frequency domain of 1 GHz to 18 GHz. The samples tested were split based on used conductive fibers in two categories: textiles with copper and stainless-steel wires and textiles which were woven with carbon fibers, in percentages of 4.5–7.5%. It has been remarked that samples knitted with stainless steel threads exhibit an SE of 54.7 dB at 2.7 GHz, while Cu fibers reinforced textiles have reached 20.18 dB at 2.4 GHz. The efficiency of carbon fibers in technical textiles have been issued on a narrow band frequency (13 GHz–18 GHz) ranging between 2–8 dB. Therefore, the study conclusion is confining the shielding efficiency of the carbon yarns in the technical textile in specific frequency domain of 16–18 GHz [15].

Long and short carbon fibers LCF/SCF (7 μm, L/D = 300; 100) were mixed into a cellulose blend in percentages of 5%, 10%, 15%, 20% and dried freeze. Obtained samples were supposed to have electromagnetic radiation in a frequency spectrum of 30 to 1500 MHz, with top values of SE being noted of 25 dB (30–200 MHz) when the material contained SFC and 60 dB (400–700 MHz) when the filler was LCFs [16]. Hao-Kai Peng et al. measured the suppression grade of a sandwich composite formed by a rigid polyurethane (PUR) foam covered by a nylon nonwoven fabric with aluminum foil. The samples were geometrically defined as having a diameter of 80 mm and a thickness of 20 mm. By applying ASTM D4935 test setup, the sandwich composite material reached 45 dB in the range of 600 MHz up to 2.5 GHz. Samples made by pure PUR barely reached 10 dB which is reasonable, given the fact that PUR is naturally an insulator [17]. By applying in situ polymerization method, Nina Joseph et al. developed flexible films of materials based on nanofibers of polyaniline and graphite on nylon and cotton fabric supports. The waves absorption rate given by the 1 mm thin composite sheet had reached 83–89 dB in the 8.2–18 GHz frequency interval [18]. Co-doped barium hexaferrites $BaFe_{11}CoO_{19}$, 3 mm thickness, toroid shape samples were obtained by using ceramic sintering powder processing technique. Using ASTM D 4935 standard setup in the frequency range of 2–18 GHz, an approximatively flat curve of SE was observed, 34 dB attenuation in 4–18 GHz spectrum. The obtained measurements were compared with theoretical calculations made based on each material constituent properties using Nicholson–Ross–Weir (NRW) rule. The complex permittivity was measured in same frequency domain showing values of 5–6 for ε'_r and 0–1 for ε''_r.The two plots describe a high grade of similarity, the calculated SE showing a constant tier of 35 dB in the 4–16 GHz domain [19].

Muhammad H. Zahari et al. manufactured composite structures samples based on in-situ polymerization of aniline mixed with barium ferrite $BaFe_{12}O_{19}$ and multi-wall carbon nanotubes MWCNT in different percentages (0 wt%, 5 wt%, 10 wt%, 15 wt%, 20 wt% and 25 wt%). The reflection and absorption wave losses were determined in the frequency range of 8–12 GHz. The measurements shown reflections losses of 1–5 dB in the aforementioned frequency domain while the absorption losses reached a top of 35 dB at 12 GHz. The real ε'_r and imaginary ε''_r parts of complex permittivity were determined, plots marking values of 22.5–17.3 for energy storage and 15.3–10.8 for dielectric losses. Among all the samples tested, 20 wt% MWCNT registered the best shielding efficiency [20].

A relatively new material which can fulfil the requirements of shielding mechanism in the Ku-band is represented by graphene, as an allotrope form of carbon. On sheets of reduced graphene oxide were applied nano particles of barium ferrites $BaFe_{12}O_{19}$ (20–30 μm) in 3 mm thickness samples. It was observed that in the frequency range of 12.4–18 GHz the nanocomposite behaved an SE of 32 dB [21].

Ranvijai Ram et al. proposed as composite material for shielding application polyvinylidene fluoride matrix (PVDF) doped with MWCNT and SCF (short carbon fibers) in certain weight percentages (0.5 wt%, 1 wt%, 2 wt%, 5 wt%). The results were compared in the frequency range of 8–12.5 GHz. The direct influence of the filler in the EMI SE properties was observed, MWCNT presenting enhanced results compared with SCF. A SE at 5 wt% of 35 dB was established at 12.5 GHz while SCF 5 wt% reached approximatively 20 dB at the same peak frequency [22].

4. Conclusions

The increasing number of engineering applications which are using electric and electronic systems led to the creation of new material requirements regarding the electromagnetic interferences. In Table 2 are reviewed some proposed composites materials which were developed to counteract the effect of interference in functioning. It was proved that the allotropy of carbon suits mostly when the balance between electrical and mechanical performances is sought. The weight percentage included in the matrix plays a crucial role in the shielding effectiveness, the more the better, but always considering also the mechanical and thermal properties.

Table 2. Composites materials shielding effectiveness overview (*ns, not specified).

	Matrix	Filler	Sample Thickness [mm]	Frequency [GHz]	Shielding Effectiveness [dB]	Ref.
1	Polymer	CNT	*ns	0.15–1	3–28	[6]
2	Teflon	CF	3/9	0.1–10	10–50	[7]
3	PC	Metallic inclusion	*ns	0.03–2	60–80	[8]
4	Elastomer	C/IA/Ag/Al	*ns	10	120	[8]
5	Textile	Ag/PES	*ns	0.03–1.5	25–50	[9]
6	*ns	TN150/300/GR150/GR300/FT150/FT300	2.3–3	0.01–1	0.5–2.13	[11]
7	GR/Glass/Cardboard	*ns	3/5	10	1–6	[12]
8	PA6	AgNP	*ns	0.15–3	1–2	[13]
9	PET/Cotton/Wool	Cu/SS/C	*ns	1–18	20.18–54.7	[15]
10	Cellulose	LCF/SCF	*ns	0.03–1.5	25–60	[16]
11	Nylon/Al	PUR	20	0.6–2.5	45	[17]
12	Nylon/Cotton	PANI/GR NT	1	8.2–18	83–89	[18]
13	$BaFe_{12}O_{19}$	Co	3	4–16	35	[19]
14	PANI	$BaFe_{12}O_{19}$/MWCNT	*ns	8–12	35	[20]
15	RGO	$BaFe_{12}O_{19}$	3	12.4–18	32	[21]
16	PVDF	MWCNT/SCF	5	8–12.5	35–20	[22]

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