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Viewpoint Paper

Multifunctional architectured materials for electromagnetic absorption

P. Bollen,[a,b,c,d] N. Quiévy,[c] I. Huynen,[a,b] C. Bailly,[a,c,d] C. Detrembleur,[e] J.M. Thomassin[e] and T. Pardoen[a,d,*]

[a]*Research Center in Architectured and Composite Materials, ARCOMAT, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[b]*Information and Communications Technologies, Electronics and Applied Mathematics (ICTEAM), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[c]*Institute of Condensed Matter and Nanosciences (IMCN), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[d]*Institute of Mechanics, Materials and Civil Engineering (iMMC), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[e]*Center for Education and Research on Macromolecules (CERM), University of Liege, Sart-Tilman B6a, 4000 Liège, Belgium*

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Abstract—A sandwich structure involving a honeycomb core filled with a carbon nanotube-reinforced polymer foam and glass fiber-reinforced composite face sheets has been developed in order to combine high electromagnetic absorption and high mechanical performance. The large electromagnetic absorption is attained by simultaneously minimizing the reflection and transmission, which, in terms of effective material properties, requires a low dielectric constant and a conductivity around 1 S m^{-1}. The sandwich offers also high stiffness versus density performance.

Keywords: Electromagnetic absorption; Electrical properties; Elastic behaviour; Nanocomposites; Foams

1. Introduction

Electromagnetic (EM) shielding is becoming a key issue in many areas, from the protection of living cells [1] to the mitigation of interferences in critical electronic devices. Often, a metallic surface is used simply to reflect the EM radiation from the system of interest or to maintain the EM field inside a close volume. Sometimes, however, a true reduction of the radiated EM power, up to full absorption, is needed, e.g. when self-reflection of the waves in a package affects the operation of the device [2] or when full or partial invisibility to incoming EM waves is needed. In that case, the aim is to select a material that provides optimum absorption.

EM absorption requires minimizing both the reflection and the transmission of the wave. The absorption capacity A, defined as the ratio of the absorbed power to the input power, depends, in addition to the material thickness, on the effective dielectric constant ε_{eff} and on the effective electrical conductivity σ_{eff} of the material or system. The analysis of the closed-form expression for the absorption A performed in Refs. [3,4] has shown that the best absorption is attained when ε_{eff} is as small as possible (hence, ideally equal to 1) and when σ_{eff} is between 0.1 and 10 S m^{-1} for frequencies between 1 and 100 GHz (while the thickness allowing to reach a given absorption increases with decreasing frequency). The optimum value of σ_{eff} depends on the exact value of the frequency. For lower frequencies, the thickness must be quite large to achieve, for instance, 90% EM absorption: thicknesses of ~10 and ~100 cm are required to absorb 90% of the incoming power at frequencies of 1 and 0.1 GHz, respectively. It turns out, as shown in Figure 1, that no single material possesses the right combination of permittivity and conductivity to meet the objective of maximizing A, or simply, to absorb even a minute fraction of the EM radiation with realistic

* Corresponding author at: Research Center in Architectured and Composite Materials, ARCOMAT, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium. Tel.: +32 10472417; e-mail: thomas.pardoen@uclouvain.be

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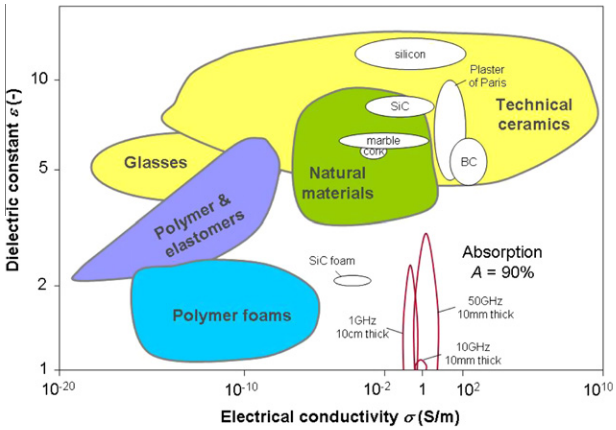

Figure 1. Schematic chart of dielectric constant vs. electrical conductivity showing the different families of materials as well as a few selected materials near the optimum region for high EM absorption. Data from Edupack software and Ref. [18]. Qualitative contours of iso-90% absorption are given for different material thicknesses. Precise values can be calculated with the analytical model developed in Refs. [3,4]. No single material enters the region of interest. Note that this chart is based on static conductivity while the conductivity varies with frequency.

thicknesses. The range of electrical conductivity allowing high absorption is indeed extremely narrow. The need for an architectured/hybrid material solution naturally emerges.

The strategy followed to build an architectured material with large A index first relies on a polymer material in order to start with a small dielectric constant, hence a small reflectivity. In order to reach the expected conductivity, around $1\ S\ m^{-1}$, the polymer is filled with carbon nanotubes (CNTs). A small amount of CNT is indeed known to significantly raise the conductivity at high frequency owing to the existence of electrical capacitances between the closely spaced nanotubes [5–12]. However, in parallel to the increase in the electrical conductivity, the dielectric constant also increases due to the presence of the CNT which adversely impacts the reflectivity. In order to further reduce the dielectric constant, open space is introduced in the nanocomposite by foaming while keeping the high conductivity introduced by the nanofiller, hence providing high absorption levels [13]. This material naturally possesses the main advantages of foams, i.e. low density and good thermal insulation.

However, polymer foams do not generally deliver the mechanical performance required in a variety of applications in which sufficient stiffness or resistance to static or dynamic loadings is needed. In order to improve the mechanical properties, the foam is introduced into a metallic honeycomb structure. Furthermore, the waveguide characteristics of the honeycomb combined with the conductive nanocomposite foam reduces the real part of the effective dielectric constant, leading to a synergistic effect for the EM absorption. This hybrid material can be bonded to two face sheets relying on a traditional sandwich approach. The face sheets must be selected so that they do not adversely affect the EM absorption. Note that the use of a foam-filled honeycomb inside a sandwich configuration for enhanced mechanical performances has been studied previously in the literature [14–16]. The objective of this paper is to describe the processing of such a sandwich structure and to show that a balance of high EM absorption and adequate stiffness can be achieved.

2. Processing of the architectured material

Several routes can be followed to process the CNT-filled-foam-in-a-honeycomb core (see Fig. 2). The starting point is a compound made of 0.2–2% CNT dispersed in a polymer matrix. The results presented later in this paper belong to a polycarbonate matrix filled with 1 wt.% multiwalled CNTs (Nanocyl™ NC 7000, 90%). Polyurethane and polycaprolactone matrices have also been tested. Two foaming strategies have been successfully used: supercritical CO_2 foaming [3,13] and chemical foaming. The supercritical CO_2 foaming consists in the impregnation of a large quantity of CO_2 within the polymer samples in a high-pressure reactor. After depressurization at low temperature, the samples are placed at high temperature in a hot press to induce the formation of foams with small cell size and high cell density. Chemical foaming requires the thermal decomposition of a foaming agent (here Hydrocerol HK40B, Clariant) incorporated in the polymer matrix, and generates larger and more heterogeneous pore sizes compared to supercritical CO_2 foaming. The results provided in this paper rely on chemical foaming. The core materials were prepared by foaming in situ inside the honeycombs using hot compression molding. Honeycombs made of 100 μm thick aluminium (5052) sheets comprising 2.3 or 5.5 mm sided hexagons, respectively, were used for the results presented hereinafter. Finally, the sandwich structure is produced by bonding glass fiber-reinforced polymer sheets (Epoxy/E-glass, plain weave composite 0.3 mm thick) on both sides of the core using a two-component epoxy glue (3M Scotch Weld DP 460).

3. Electromagnetic absorption

The EM-absorbing materials were characterized using a Anritsu Wiltron 360 vector network analyzer. The scattering parameters (or S-parameters), phase and magnitude, are measured as a characteristic of the device connected between the two ports: $|S_{11}|^2$ corresponds to the power reflected back at port 1, while $|S_{21}|^2$ is related to the power transmitted from port 1 to port 2, through the device. After eliminating the influence of the feeding probes on the S-parameters through calibration, the ratio of the power absorbed by the sample under test (P_{abs}) to the incident power (P_{in}) can be thus calculated as $P_{abs}/P_{in} = A = 1 - |S_{11}|^2 - |S_{12}|^2$. Figure 3 shows the variation of the absorption index A as a function of the frequency for the core alone (without face sheet) and a sandwich, with (a) $X = 5.5$ mm and (b) $X = 2.3$ mm. Glass fiber-reinforced composite face sheets have been selected owing to a low reflectivity. The difference between the core and sandwich EM absorption potential is indeed small (see Fig. 3). The slightly better behavior of the sandwiches comes from