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Computational Analysis of Metal Foams for EMI Shielding Using Comsol Multiphysics®

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Abstract:
With the rapidly increasing usage of electronic devices and wireless communication technology, generation and propagation of electromagnetic energy are becoming one of the major concerns, not only because it affects the functionality and integrity of the electronics and their components, but also for the potential health risks for the human body. New cellular materials obtained by additive manufacture are showing their shielding potential from electromagnetic interference, due to their unique combination of physical and electric characteristics.

In this work we study the behavior of a simplified-geometry open-cell metal foam as an attenuator of electromagnetic radiation by developing a finite element model using Comsol Multiphysics® 5.4. The analysis was carried out using the Radio Frequency module. S-parameters and electric field distribution were calculated for a range of high-frequency values. The computational results were then validated comparing them with the experimental measurements of the transmission coefficients in a 2-port network.

Keywords: electromagnetic interference (EMI), metal foams, computational simulation.

1. Introduction

The extensive development and rapid upgrading and renewing of electronically controlled devices and equipment that rely on wireless communication technologies for its normal operation [1], combined with the sustained increase in the working frequencies of digital systems, the generation and propagation of electromagnetic radiation released into the environment is a concern and a problem that need to be solved [2] [3]. These devices not only radiate energy but are also affected by electromagnetic waves incident in the air [4]. For this reason, the design and implementation of proper shielding materials against electromagnetic interference has become an essential requirement to ensure their continued functionality and integrity and, more importantly, to reduce the level of radiation the human body receives [5].

Aluminum metallic foams are known to have a unique combination of physical and mechanical properties, such as high strength, rigidity, and energy absorption [6] [7] which, combined with a high reflection coefficient and good electrical conductivity, makes them a potential shielding material against electromagnetic radiation (EM).

Multiple analysis methods based on modelling and simulation approaches have been addressed to study the shielding effectiveness of various materials. Particularly, different computational models have been proposed to approximate the electromagnetic behavior of commercially metal foams (Figure 1) [8] [9].

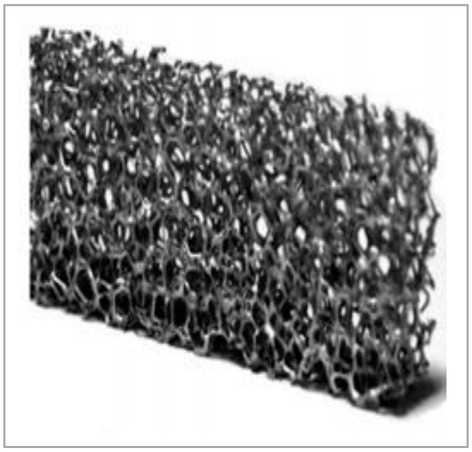

Figure 1. Commercially available aluminum foam.

For example, several of the analytical models developed make use of wire-mesh geometries, with matrices defined by uniformly distributed squares, which approximates the shape of the commercial foam cells [10] [11] [12] (Figure 2). In this case, by applying geometric symmetry considerations, computational models can be simplified to the study of a single cell of the material. Then, the results obtained are extrapolated to define and characterize the behavior of the rest of the structure.

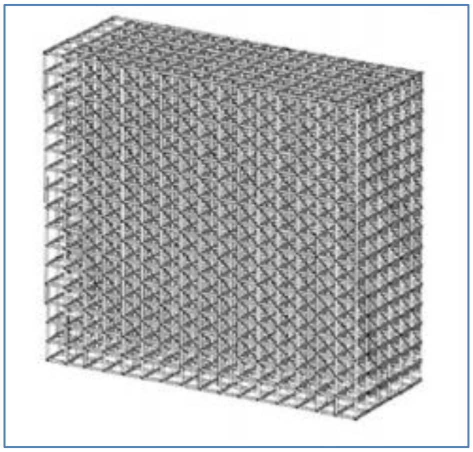

Figure 2. Wire-mesh 3D foam model.

These studies conclude that this type of material represents a feasible alternative as an attenuator of electromagnetic radiation. Also, these works indicate that the index of porosity and relative density, which characterizes open cell foams, is directly related to its effectiveness of attenuating EM energy. Particularly, the more porous (or less dense the material is), the less effective it is to attenuate EM waves.

In this work, we study the shielding capabilities against EM radiation of an open-cell aluminum foam fabricated by additive manufacturing techniques (3D metal printing). The EM behavior of a simplified geometry of the metal foam in the presence of EM fields was first analyzed with Comsol Multiphysics®. Shielding Effectiveness (SE) against this type of energy is then evaluated by measuring the transmission coefficients of a two-port network in a high frequency spectrum.

The structure of the paper is the following. The methodology is given in Section 2, while Section 3 describes the mathematical model and the use of Comsol Multiphysics®. The experimental and computational results are presented in Section 4. Finally, the main conclusions the work yielded are summarized in Section 5.

2. Methodology

The physical model of the aluminum foam was designed using SolidWorks® software. It consists of a cellular foam-like metal with a matrix of regularly distributed spheres, each one with a 5mm diameter. The internal composition and structure were obtained by settling a 4mm separation distance between the centers of each bubble. The final dimensions of the CAD model are 72x72x20mm^3, corresponding to the length, height, and thickness of the material, respectively. This configuration creates a symmetric matrix of 1620 cells, distributed in 18x18x5 spheres.

The additive manufacturing technique used for the model part fabrication was Direct Metal Laser Sintering or DMLS. This method was carried out in a 3D Systems 3D metal printer, model ProX DMP 200, using an AlSi10Mg aluminum alloy (Figure 2). The dimensions of the part obtained were 72x72x23mm^3 (support printing material on the bottom of the piece was not removed).

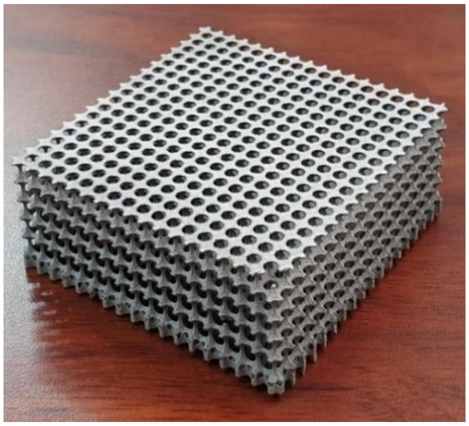

Figure 4. Open-cell aluminum foam.

The porosity index and the relative density of the metal foam physical model are estimated with SolidWorks®, having defined: a) the porosity index as the ratio between the volume occupied by air and the total volume of the material; b) the foam density as its mass divided by the total volume; and c) the foam relative density as the ratio between the foam density and the density of the solid material.

The actual relative density and porosity index of the manufactured material were obtained by measuring its mass with a Tanila scale, model KD-200. Then, the geometric dimensions were seized calculating, thus, the total volume. Finally, the foam relative density relationship described above was applied, where the porosity index was computed as 1 minus the relative density of the material.

The transmission coefficient measurements, with and without shielding material, were carried out in a Vector Network Analyzer (VNA) Rohde & Schwarz, model ZVL, using two Narda Microline pyramidal horn antennas, Standard Gain Horn 640 model with type N connectors, for the two-port network test.

The VNA was configured to measure the S_{21} parameter, with the transmitter antenna (Tx antenna) connected to port 1 and the receiving antenna (Rx antenna) to port 2 (Figure 5). The distance between antennas was 420mm. The analyzed cellular material was placed 20mm away from the receiving antenna mouth. The analyzed frequencies range went from 6GHz to 13.6GHz with measurements every 38MHz (this interval was determined by the frequency response of the horn antennas).

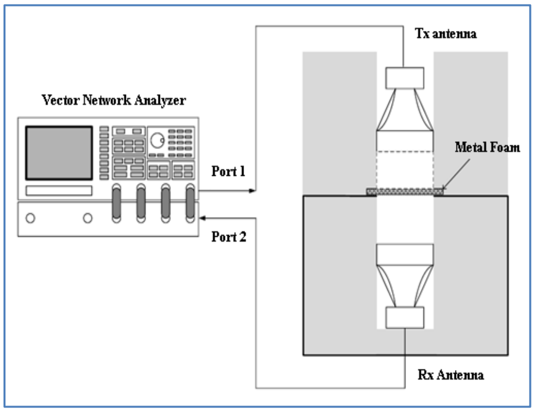

Figure 5. Experimental setup for SE measurements.

The shielding effectiveness of the metal foam, in decibels, was calculated with [13]

$$\mathrm{SE(dB)} = \mathrm{S}_{21,\text{without shield}} - \mathrm{S}_{21,\text{with shield}} \quad (1)$$

where $\boldsymbol{S}_{\boldsymbol{21},\ \textit{\textbf{without shield}}}$ and $\boldsymbol{S}_{\boldsymbol{21},\ \textit{\textbf{with shield}}}$ are the transmission coefficients without and with the shield material present, respectively.

3. Equations and solution with Comsol Multiphysics®

We modeled the electromagnetic response of the metal foam by using the Radio Frequency module of Comsol Multiphysics®. The formulations for high-frequency waves used in this module are derived from Maxwell-Ampère’s and Faraday’s laws,

$$\nabla x H = J + \frac{\partial D}{\partial t} \qquad (2)$$

$$\nabla x E = -\frac{\partial B}{\partial t} \qquad (3)$$

with $\boldsymbol{H}$ the magnetic field intensity, $\boldsymbol{J}$ the current density, $\boldsymbol{D}$ the electric flux density, $\boldsymbol{E}$ the electric field intensity, and $\boldsymbol{B}$ the magnetic flux density; where the governing wave equation for the electric field intensity $\boldsymbol{E}$ in the Electromagnetic Waves, Frequency Domain Interface can be written in the form

$$\nabla \times (\nabla \times \boldsymbol{E}) - k_0^2 n^2 \boldsymbol{E} = 0 \qquad (4)$$

where $\boldsymbol{n}$ is the refractive index, and the wave number of free space $\boldsymbol{k_0}$ is defined as

$$k_0 = \omega\sqrt{\varepsilon_0 \mu_0} = \frac{\omega}{c_0} \qquad (5)$$

with $\boldsymbol{\omega}$ the angular frequency, $\boldsymbol{\varepsilon_0}$ and $\boldsymbol{\mu_0}$ the free space permittivity and permeability, respectively, and $\boldsymbol{c_0}$ the speed of light in vacuum.

From the physical model (Figure 4) we extracted a single row of cells (Figure 6) with 8x8x20mm dimensions, since the designed internal matrix of the foam is symmetric. This simplified geometry was imported in Comsol Multiphysics® by the means of the CAD Import Module capabilities.

A unit cell was then built around the imported geometry applying Floquet-periodic boundary conditions on its four sides, creating an infinite 3D array of simplified cellular structures that act like the original model of the metal foam.

Two ports were placed on the bottom and upper faces of the unit cell (Figure 6) in order to reassemble the experimental conditions described in the Methodology section. Port 1 and Port 2 emulate the transmitter and the receiver antenna, respectively. The distance between ports was set to 420mm. The imported simplified foam model was placed 20mm above Port 2. The Electric Mode Field Amplitude in Port 1 was configured following the relation and values described in Table 1, where the Waveguide_Width parameter is equal to 25mm (size of the actual waveguide width of the horn antennas used). The elevation angle of incidence is 0, which means the electric field is normal to the geometry surface.

Table 1. Electric mode field amplitude.

E_0	0	**x**	V/m
	$\cos\left(\frac{\pi x}{Waveguide\_Width}\right)$	**y**	
	0	**z**	

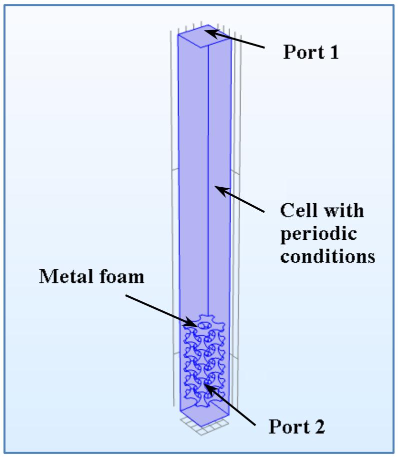

Figure 6. Simulation environment.

The mathematical equation for the component **y** of the Electric mode field amplitude matches the spatial propagation behavior exhibited by a classic pyramidal horn antenna.

Perfectly matched layers (PMLs) at the top of the unit cell was created in order to absorb higher-order modes generated by the periodic structure as well as the upward traveling excited mode from Port 1. The purpose of these PMLs is to attenuate the field in the direction normal to the unit cell upper boundary.

The material chosen for the metal foam was (built-in) Aluminum, and the domain outside and inside (the bubbles of) the cellular structure was filled with air. The electric and magnetic material properties required to solve the governing equations of the mathematical model are summarized in Table 2.

The frequencies analyzed (parametric sweep) went from 6GHz to 13.5GHz, with a 500Mhz interval between computed values.

Table 2. Electromagnetic properties of the materials.

Property	**Domain**	
	Air	*Metal Foam*
Relative permittivity	1	1
Relative permeability	1	1
Electrical conductivity	0	37.84e7 S/m

4. Results and discussion

The physical properties for the CAD model and the actual metal foam are summarized in Table 3, where the relative density and the porosity index exhibit a relative error of 18.71% and 3.27%, respectively, being the manufactured part denser that the designed 3D model. Differences between the values computed and measured of these parameters are a direct consequence of the non-removal of the support printing material.

Table 3. Physical properties of the metal foam.

Property	**Computed**	**Measured**
Total volume (mm^3)	103 600	119 232
Mass (g)	41.7574	57
Density (g/mm^3)	0.00040257	0.0004780
Relative density	0.1491	0.1770
Porosity index (%)	85.0832	82.2962

The transmission coefficients (or S_{21} parameter) with and without shield obtained using the 2-port network, as well as the simulated results for the counterpart scenario, are shown in Figures 7 and 8, respectively. The results obtained indicate that the general attenuation capability does not exceed the 20dB for most frequencies but displays a great performance at 12.35GHz. This behavior can be explained by the concept of cavity resonance, which says that an arrangement constructed with electrically conducting walls will function as a resonant cavity, where standing waves will exist exhibiting electromagnetic fields that are no uniform within the structure. The resonant frequency associated to this phenomenon is determined by the geometry, shape or dimensions of the shielded material [14].

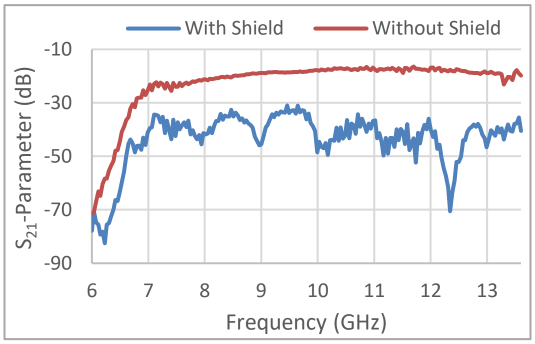

Figure 7. Transmission coefficients for the foam.

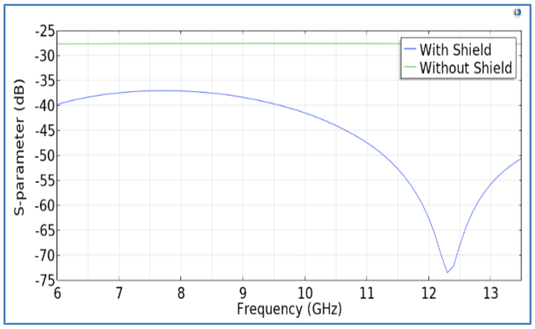

Figure 8. S_{21} parameter for the simulated model.

The norm of the electric field and power flow at 12.3GHz are shown in Figure 9 and Figure 10, respectively, where the intensity of the incident wave is strong near the upper face of the metal foam. It decreases toward the base of the cellular structure, where it is ultimately very weak. This behavior matches the results we obtained before for the specific frequency value analyzed.

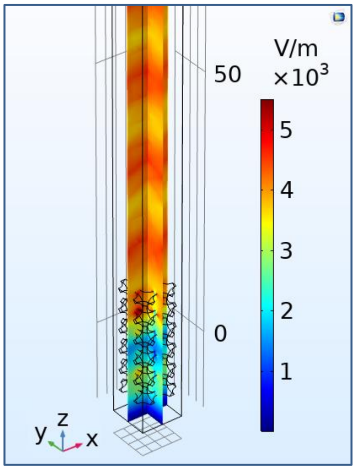

Figure 9. Electric field intensity.

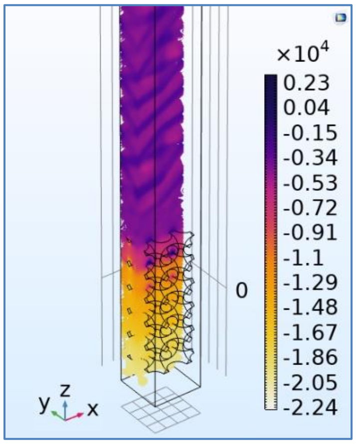

Figure 10. Power flow distribution.

Finally, the Shielding Effectiveness values computed for each frequency analyzed for both, the physical model simulated and the actual metal foam scenarios, are summarized in Figure 11. The results carry a relative error of 17.68% between them, comparable with the error exhibited by the relative density, where the SE of the manufacture material peaked at 53dB, while the maximum valor reached for the physical model are near 45dB. Precisely, this error magnitude is related directly to the proven fact that the less dense is a cellular structure, the less effective is for shielding electromagnetic radiation.

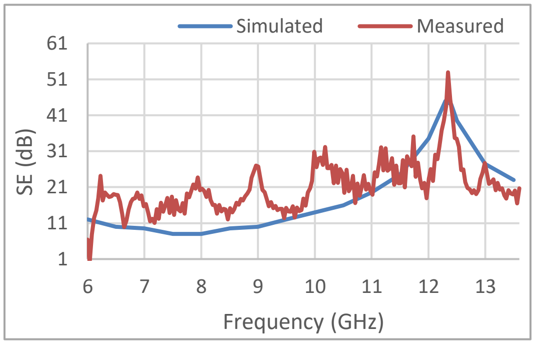

Figure 11. Shielding Effectiveness comparison.

5. Conclusions

The electromagnetic behavior of a simplified-geometry open-cell aluminum foam as an EMI shield material, manufactured with 3D metal printing techniques, has been modeled and simulated by using the Radio-Frequency module in Comsol Multiphysics®.

The numerical and experimental results suggest that this kind of material can be act as a resonant cavity, greatly attenuating the incoming EM radiation for certain frequency values.
The computational results obtained with Comsol Multiphysics® are encouraging for future studies including a resonant frequencies analysis.

6. References

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