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Computation of radar absorbing silicon carbide foams and their silica matrix composites

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Abstract

SiC-foams and their composites were studied as novel stealthy materials by numerical simulations. The reflection coefficients of various SiC-foams are found to be strongly dependent on the SiC volume fractions, electric conductivities and frequency. A foaming SiC allows to reach high level of electromagnetic wave absorbing ability when the SiC volume fraction and the conductivity at proper values comparing to SiC-particles and SiC-bulk, Which due to an increase of electromagnetic energy dissipation in foaming structures and an improvement of the conjugation condition with free space. It is of most importance that SiC-foams exhibit artificial magnetic properties that can absorb the magnetic energy of electromagnetic waves. The electromagnetic absorbability of the silica composites are significantly decreased compared to that of the SiC-foams alone for the larger impedance mismatch with free space.

Keywords: SiC-foam; Silica matrix composites; FEM simulation; Microwave absorption

1. Introduction

The absorbing materials are extensively utilized not only for military but also for commercial purpose. There are two commonly used methods. One is shaping the targets in order to scatter the incident electromagnetic (EM) wave, producing minimum reflection wave that can be detected by radar. Another is reducing the radar cross-section (RCS) by using radar absorbing materials (RAM) to cover the surface or using radar absorbing structures (RAS) to construct the components of the targets. This affects both the mission success and survival of a target in the battlefield.

Generally, the microwave reflection coefficient of a material depends on its dielectric permittivity ε, magnetic permeability μ [1], electrical conductivity σ [2], thickness and frequency. These parameters determine the impedance difference between the material and free space. Impedance changes abruptly at the interface between free space and either the bulk or film materials. To avoid such abrupt changes in impedance, multi-layered absorbing materials have been developed, which change the wave impedance by steps from layer to layer. However, such multi-layered absorbers relying heavily on magnetic losses do not function properly beyond Curie temperature. Moreover, the range of resonance frequency in which such absorbers are effective is at the MHz level. The efficiency of absorbers decreases rapidly in the range of gigahertz (GHz) and beyond. Here, SiC-foams and their composites are introduced as novel RAM for their stealthy properties. The absorption mainly depends on dielectric loss, and these materials can be utilized to overcome some of the shortcomings of existing RAM materials for their relatively stable complex permittivity from room temperature to high temperature.

SiC-foams, fabricated by a solid state sintering process using silicon carbide or other oxide powders through the polymer foam replication method [3,4], possess a

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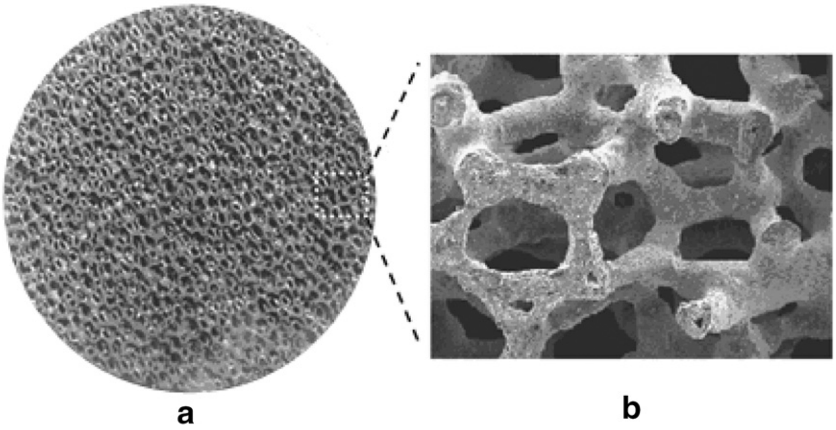

Fig. 1. (a) SEM image of a SiC-foam sample fabricated in Institute of Metal Research, Chinese Academy of Sciences. (b) Local region zooms in.

reticulated structure, as shown in Fig. 1. The SiC foams fabricated are highly versatile porous materials which are used primarily in molten metal filtration, hot gas filtration, catalysts support, and combustion, etc. Recently, such foams and their composites have found their way to act as stealthy materials, mainly due to their well matched impedance, high strength, light-weight, and effective EM wave absorbing capability, which are essential to a large range of applications especially at elevated temperatures.

In order to evaluate the performance of a RAM, reflection coefficients are often experimentally measured. However, experimental measurements are time-consuming and resource-wasting, and they are usually not reliable enough for optimization. Computer aided design and simulation can effectively resolve the uncertainty experienced in experiments, and improve the stealthy properties by optimizing the material and geometric parameters. For many types of microwave and millimeter-wave components and devices with arbitrary shape in two- or three-dimensions, a useful computational analysis may be conducted by calculating the EM field's distribution and other behavior of EM waves in the materials according to the principles of EM theory. Finite element method (FEM) [5–7] is a feasible technique to solve the constitutive equations, which is widely used in analysis of a complicated structure, and therefore, it was used to calculate microwave reflection coefficients of SiC-foams and their composites.

2. Theory and model

In electromagnetics [8–11], the behavior of EM wave can be described using partial differential equations. The field quantities electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{H}$ are related by Maxwell's equations. Wave equations in frequency domain are given by

$$\nabla^2\boldsymbol{E} + \omega^2\varepsilon\mu E - \mathrm{i}\omega\mu\sigma E = 0 \tag{1}$$

$$\nabla^2\boldsymbol{H} + \omega^2\varepsilon\mu H - \mathrm{i}\omega\mu\sigma H = 0 \tag{2}$$

μ is magnetic permeability, ε is electric permittivity, ω is angular frequency and σ is electric conductivity.

According to the transmission theory [12], the input impedance Z_1 at the interface between air and an absorber, shown in Fig. 2, is

$$Z_1 = Z_0\frac{Z_2 + Z_0\tanh(\gamma d)}{Z_0 + Z_2\tanh(\gamma d)} \tag{3}$$

where $Z_0 = \sqrt{\mu/\varepsilon}$ is the impedance of the absorber, and the propagation constant $\gamma = \alpha + \mathrm{i}\beta = \frac{\sigma}{2}\sqrt{\mu/\varepsilon} + \mathrm{i}\omega\sqrt{\varepsilon\cdot\mu}$, the units of α and β are $\mathrm{Np\,m^{-1}}$ and $\mathrm{rad\,m^{-1}}$, respectively. d is the thickness of the absorber. Z_2, the impedance at a distance d, is null because the back plate is a perfect electric conductor (PEC). So $Z_1 = Z_0\tanh(\gamma d)$. The impedance of air is $Z_a = \sqrt{\mu_0/\varepsilon_0}$ and the impedance matching condition is $Z_1 = Z_a$. This condition allows the incident wave to penetrate the medium, and the complex propagation constant determines the degree of wave attenuation or absorption, which can be derived from the following field equations:

$$E = E_0\mathrm{e}^{-\alpha r - \mathrm{i}\beta r} \tag{4}$$

$$H = H_0\mathrm{e}^{-\alpha r - \mathrm{i}\beta r} \tag{5}$$

r is the propagation distance.

Based on the theories discussed above, the EM absorbability of SiC-foams and their composites can be calculated [5,6,8,9,13,14]. A rectangular waveguide, which schematic is shown in Fig. 3, was designed in the simulation. The waveguide walls are considered to be made of a perfect conductor, implying that $\mathbf{n}\times\boldsymbol{E} = 0$ on the boundaries. Port

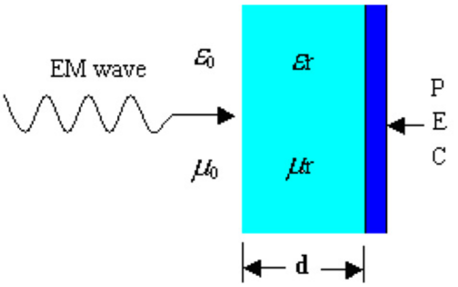

Fig. 2. Schematic of a single-layered electromagnetic wave absorber.