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A review of absorption properties in silicon-based polymer derived ceramics

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ABSTRACT

Design and development of advanced materials for electromagnetic applications and bringing these materials into use is one of the most challenging tasks of materials engineering. Silicon-based polymer derived ceramics (PDCs) are natural candidates for these demanding applications due to their very attractive microstructure and properties. Compared with sintered technical ceramics, such as SiC, Si_3N_4, Al_2O_3 or ZrO_2, polymer derived ceramics offer the possibility of flexible plastic-technical processing, for instance by means of injection molding or extrusion without the employment of additional binder systems. The chemical synthesis permits a purposeful optimization of the polymers with respect to workability, ceramic yield and composition by the substitution of different elements in the basic structure as well as the organic side groups. In many cases the microstructure of PDCs characterized by homogeneous distribution of semiconducting or conducting nano-phases in the amorphous matrix. This can lead to the good microwave absorbing properties. Thus, those materials may not only satisfy the impedance matching but also rapidly attenuate electromagnetic waves. The absorption properties of PDCs can be easily tailored by the design of the molecular precursor, changes in morphology, and volume fraction of the filler particles. Different classes of preceramic polymers are briefly introduced and their absorption properties with adjustable phase compositions and microstructures are presented in this review.

1. Introduction

The need for microwave absorbers and radar-absorbing materials is ever growing in both civilian and defense-oriented applications because of the increasing use of high operating frequencies and bandwidths, especially the X-band (8.2–12.4 GHz) in electronic systems [1–3]. As an excellent radar-absorbing material, composite should satisfy the following requirements: (i) it should have a strong absorbing capability and impedance matching characteristic, which means it should have a minimal reflection coefficient (RC), (ii) it should have a wider efficient absorption bandwidth (EAB, the corresponding frequency range with which the RC is smaller than −10 dB), (iii) it is expected to have a low density and high temperature stability when it satisfies the above two requirements, (iv) good mechanical property also becomes a gradually important requirement for radar-absorbing material [4–7].

A previous study indicated that ferrites and metal powders are the most commonly used absorbing materials in megahertz range because of their good electrical conductivities, magnetic and/or dielectric loss. However, their intrinsic disadvantages (Snoek's limit and high density) restrict their widespread application in high frequency range. Polymer-based nanocomposites attract great attention as EM absorbers with low density, broad absorption band and high EM loss, however, they cannot be used at high temperatures due to their lower decomposition temperatures. Low density ceramics can offer superior absorption properties in the gigahertz frequency range, excellent chemical stability from ambient to peak operation temperatures, corrosion and radiation resistance. Recently, materials such as carbon, SiC, Mn_2O_3, and ZnO have attracted great interest as EM absorbing materials in the GHz frequency range due to their unique chemical and physical properties [8–11].

Carbon-based materials, especially C nanostructures, 2D graphene and quasi-1D CNTs, are reported as the high-performance absorbing materials because of their soperior intrinsic

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properties, such as lower density, higher conductivity and higher specific surface area [12–14]. Silicon carbide (SiC), as a wide band gap semiconductor, possesses good microwave absorption properties [15]. The hybrid materials involving carbon (as the conductive phase) and SiC (as the semi-conductive phase) both disperses in an electrically insulating matrix, thereby offering more possibilities to achieve an promising dielectric loss, according to Lichteneker and Rother's law [16] and previous investigations [17–19]. PDCs processing route is an effective way to attain those hybrid materials.

Compared with current technology to produce ceramics, the result of the polymer derived ceramics (PDCs) route shows better characteristics, such as excellent thermomechanical properties, stability, good usability and workability [20]. Changing the chemistry and the architecture of the preceramic precursors, suitable chemical modification of the preceramic precursors, and tuning the microstructure of the PDCs all can lead to an enormous improvement in the properties of PDCs and thereby increase their potential applications [21]. Specifically, the absorption properties of such composites can be tailored through changes in composition, morphology, and volume fraction of the filler particles. This paper offers a perspective on the experimental efforts toward the development of microwave absorbers based on polymer derived ceramics.

2. Principle to design electromagnetic absorption ceramic

Fundamental knowledge of causes of absorption and the design of absorbers has been published by many researchers for several decades. When the electromagnetic wave is incident on the surface of absorption materials, energy loss will occur through the interactions of the electromagnetic field with the material's molecular and electronic structure [4]. The absorption materials transform electromagnetic energy into heat. The generated heat is related to the conductive and dielectric losses of materials. In order to obtain improved EM absorption properties, absorbing materials may have dielectric loss by polarization, and an appropriately high conductivity to attenuate the incident electromagnetic wave [2,22,23]. Generally, the absorption coefficient (A) and reflection coefficient (RC) are used to evaluate the performance of microwave absorption.

Fig. 1 shows a schematic illustration of the EMW propagation process through EM absorbing materials described by parameter ε', $\tan\delta$ and sample thickness d [24]. The power absorbed (P_A) in the material is obtained from the power balance between the power respectively incident in the air region 1 (P_I), the power reflected at input interface ($x = 0$) air/composite (P_R), and the power transmitted into region 3 (P_T): $P_I = P_R + P_A + P_T$. The absorption capacity or absorption coefficient A is used to evaluate the capability of a material to attenuate EM. A is defined as the ratio between absorbed powder P_A and incident powder P_I, $A = P_A/P_I = 1 - |S_{11}|^2 - |S_{21}|^2$ [25–27]. When the sample is tested in a wave-guide chamber, the value of A can be also expressed as

$$A = 2\pi d \frac{\left(\varepsilon^{1/2} \tan\delta\right)}{\lambda}$$

where ε is ε', λ is the wavelength of microwave and d is sample thickness. Absorption coefficient A depends on the effective relative permittivity, dielectric loss of the material and the sample thickness.

The EMW absorbing properties of a material is also characterized from relation curves of reflection coefficient (RC) versus frequency. When the RC of an EM absorbing material is smaller than −10 dB, only 10% of EM power is reflected and 90% is absorbed. The corresponding frequency range within which RC is smaller than −10 dB is defined as the effective absorption bandwidth (EAB). EM absorbing materials are always expected to have not only minimum RC and a wide effective absorption bandwidth, but also small thickness, light weight, and low cost [28]. Weight reduction and optimization of the operating bandwidth are two important issues of the most important parameters characterizing an EM absorbing material in terms of real applications.

Based on the transmission-line theory and metal backpanel model [29], RC can be determined from the relative complex permeability and permittivity.

$$\mathrm{RC} = 20\log_{10}\left|\frac{(Z_{in} - 1)}{(Z_{\rm in} + 1)}\right| \tag{2}$$

$$Z_{\rm in} = \sqrt{\frac{\mu}{\varepsilon}} \tanh\left(j2\pi \frac{\sqrt{\mu\varepsilon} f d}{c}\right) \tag{3}$$

where $Z_{\rm in}$, $\varepsilon = \varepsilon' - j\varepsilon''$ and $\mu = \mu' - j\mu''$ is the normalized input impendence, permittivity and permeability of the material; d and c represent thickness (m) and the light velocity in vacuum (3×10^8 m/s). Here μ was taken equal to 1 because in this paper the materials exhibit negligible magnetic properties.

Fig. 2 shows a schematic illustration of the EMW propagation process through EM absorbing materials based on the metal backpanel model [18]. One part of the incident EMW can be absorbed, the other can be reflected on the two surfaces ($x = 0$ and $x = d$). When the thickness of EM absorbing materials (d) is approximately a quarter of the propagating wavelength (λ) multiplied by an odd number, that is, $d = n\lambda/4$ ($n = 1, 3, 5, 7, 9, \ldots$), the signal reflected by the left surface ($x = 0$) has a phase opposite to the signal reflection coming from the right surface ($x = d$), resulting in destructive inter-

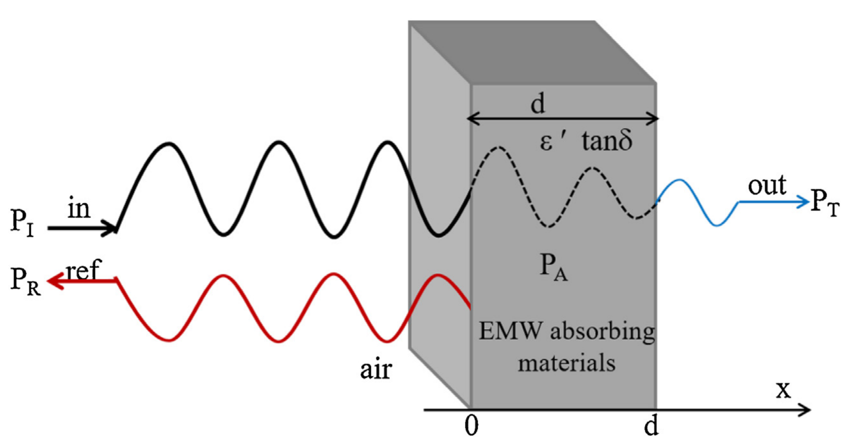

Fig. 1. Schematic illustration of EMW propagation process through EM absorbing materials.