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Microwave absorption enhancement of rectangular activated carbon fibers screen composites

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ABSTRACT

The radar absorbing materials composited of activated carbon fibers (ACF) as wave-absorber and glass fibers (GF) as impedance modifier were successfully prepared. The structure parameters of rectangular ACF felt screen, the influences of GF-piece and the reflection properties were investigated. It was observed that the effective bandwidth (the reflection loss below −10 dB) increased with the aspect ratio (a/b) increasing, but decreased with aperture spacing (δ) increasing. A double absorption peak (16.1 dB and 14.2 dB) for the optimized configuration ($a/b = 3$, $\delta = 5$ mm, $a = 30$ mm) appeared at 5.8 GHz and 16.9 GHz, and a wide absorption bandwidth (4–17.6 GHz) could be achieved. When a 30 mm × 15 mm rectangular aperture was filled by GF-piece of 20 mm × 10 mm, the effective bandwidth was improved to 12.1 GHz. The composites with a wide absorption bandwidth could be achieved via designing the proper element parameters and adjusting the composition of ACF and GF.

1. Introduction

Stealth technology is essential for increasing the weapon survivability in contemporary warfare by reducing reflection [1]. And with the rapid growth of electronics devices, it becomes essential to limit and shield electronic equipment against unwanted electromagnetic interference [2,3]. Recently, the excellent radar absorbing materials (RAMs) for stealthy defense system and electromagnetic interference, with outstanding microwave absorbing properties in a wide effective bandwidth (reflectivity of lower than −10 dB) under light weight, have been designed [4–7]. To accommodate the application desire, researchers have paid much attention to studying on the ACF felt screens (ACFFS), in analogy to traditional metallic frequency selective surface (FSS). FSS is a two-dimensional periodic array of conducting patches or aperture elements used in microwaves and optics, and generally patterned on, or embedded in a dielectric sheet, with pass-band or stop-band properties [8–10]. The FSS can be divided in two classifications, including inductive FSS with periodically arrayed aperture elements and capacitive FSS with periodically arrayed patch elements [11]. Moreover, there are three important characteristic parameters of an FSS: resonant frequency, effective bandwidth, and reflection loss (RL), and they mainly depend on the structure parameters (such as shape, size and distribution) of the element as well as material types [12,13]. That is because the area of the dielectric loss medium changes with the FSS structure parameters, and the electromagnetic wave propagation behavior also converts in the absorbing material composed of FSS, including transmission, reflection, diffraction and interference, and resonance effect, etc.. For example, the resonant frequencies of radar absorbing structure (RAS) of E-glass/epoxy composites decrease when the length or periodicity of FSS rectangular element increases, but that of RAS increase slightly when the rectangular element width increases [11]. Recently, carbon fibers (CF) preprocessed by the appropriate electromagnetic modification are used to replace the traditional material of FSS, which is metal. There have been many studies on absorbing abilities of CF [14–20]. Furthermore, embedding the ACFFS structure

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into RAMs is an effective approach to high efficiency RAMs with low density, thin thickness as well as absorption over broad microwave frequency bandwidth [10,17]. The alteration of the material is based on the following considerations: (i) ACF felt is born with the special electromagnetic properties and excellent mechanical properties; (ii) the porous characteristic irregular-shaped cross-sections of ACF are very advantageous for the absorption of electromagnetic wave; (iii) the density of ACF felt is lower than metal. So, in this work, ACF is chosen as the high energy-loss absorber of RAMs.

Apart from the high RL wave-absorber, the impedance-matching principle also plays an important role in improving the absorbing performance through matching the RAMs impedance to free space [21–23]. The natural impedance of FSS determined by element shape, size and configuration can be adjusted to achieve impedance matching with free space through the suitable design of structure parameters [24,25]. Moreover, it is an effective approach to achieve impedance-matching that wave-transparent materials like glass fibers (GF) are appropriately and efficiently embedded into absorbing layer [8,26,27]. Energy absorption capability of carbon-epoxy and glass-epoxy composites was reported by *Stanislaw Ochelski* [28]. Lee discussed the different designs of RAMs by CF and GF with dielectric transmission properties, and put forward that the mixture structure could be used to prepare microwave impedance adjuster [29]. Therefore, it is reasonable to propose that the outstanding RAMs with good impedance matching and low RL might be obtained by efficiently combining absorbing-agent (e.g. ACF felt in this work) with wave-transparent material (e.g. GF in this work).

Firstly, we reported the studies on the absorbing abilities by adjusting the rectangular element size and periodicity, according to the resonance effect of FSS. Secondly, the studies on the absorbing performance of the RAMs embedding the GF-piece as impedance modifier into rectangular ACFFS were carried out. Furthermore, the absorbing mechanism of RAMs containing rectangular ACFFS and GF-piece/ACFFS epoxy composites were discussed, respectively. Our research efforts are expected that RAMs for military applications met low density, thin thickness and a broad bandwidth below −10 dB by designing absorbing layer.

2. Experimental

2.1. Design of absorbing layer

According to the transmission line theory and impedance-matching principle [30], the theoretical RL for a multilayer RAMs was given as follows:

$$\mathrm{RL} = 20\lg\left|\frac{Z_{\mathrm{in}}(N) - Z_0}{Z_{\mathrm{in}}(N) + Z_0}\right| \tag{1}$$

where Z_0 is the impedance of the free space, $Z_{in}(N)$ is the input impedance of the RAMs expressed as the equitation (2).

$$Z_{in}(N) = Z_c(N)\frac{Z_{in}(N-1) + Z_c(N)\tanh[\gamma(N)d(N)]}{Z_c(N) + Z_{in}(N-1)\tanh[\gamma(N)d(N)]} \tag{2}$$

where $Z_c(N)$, $\gamma(N)$ and $d(N)$ are the characteristic impedance, propagation constant and the width of the N-layer, respectively. The absorbing performance of multi-layer design is much better than single-layer, but the smaller $d(N)$ conforms to the international requirement. So a two-layer composite laminate composed of impedance-matching surface layer and absorbing layer is designed in this work. And,

$$Z_C(N) = \sqrt{\frac{\mu_\gamma\mu_0(N)}{\varepsilon_\gamma\varepsilon_0(N)}} \tag{3}$$

$$\gamma(N) = cw\sqrt{\varepsilon_0\mu_0\varepsilon_\gamma(N)\mu_\gamma(N)} \tag{4}$$

where, μ_r and ε_r are the relative permeability and the relative dielectric constant of absorbing materials, μ_o and ε_o are the relative permeability and the relative dielectric constant of absorbing materials of free space. It can be seen from the above formulas that the RL of the RAMs related to the input impedance of each absorbing layer at a given frequency. But the impedance of ACFFS layer in this paper depends on not only the intrinsic dielectric properties of ACF but also the frequency selectivity of FSS mainly caused by diffraction phenomena and resonance effect. Though the dielectric constant of ACF is changeless at a certain frequency, the loss acreage of the FSS surface changes with the elements structure parameters. Moreover, the diffraction phenomena and resonance effect are designed by aperture parameters such as the shape, size, materials and array periodicity of FSS element.

(i) Diffraction phenomena: If the vertical incident electromagnetic wavelength (λ) is close to the length (a) or width (b) of the rectangular aperture, diffraction phenomenon will take place, meaning that the incident microwave is gradually absorbed and decayed via multiple reflections between metal plate and the circuit screen [31].
(ii) Resonance effect: When the half wavelength ($\lambda_{1/2}$) is similar to length (a) or width (b) of the rectangular aperture, resonance effect will occur, meaning that the FSS screen produces strong frequency response and intense scattering in a certain direction as a result of the high absorption and attenuation [13, 32].

Based on the above mentioned, two configurations on the absorbing layer were designed in this work:

(I) The ACFFS with size of 200 mm × 200 mm was fabricated by cutting off some rectangular elements (shown in Fig. 1). Furthermore, the effects of the aspect ratio (a/b) and aperture spacing (δ) of rectangular ACFFS elements on the absorbing properties would be discussed in section 3.1.
(II) The absorbing layer structure of GF-piece/ACFFS was formed by embedding GF-piece with a certain size into the rectangular blanks of ACFFS (shown in Fig. 2), where the GF-piece sizes a' and b' are taken as parameters. It shows by equitation (2) that the each-layer $Z_{in}(N)$ has an important impact on the absorbing properties. Thus this paper adopts this approach of ACFFS inserted with GF-pieces to adjust the impedance match of the absorbing composite laminate. In addition, it is necessary to describe the preparation process of GF-piece as follows. The homogeneous GF were closely expanded on the surface of demoulding paper and evenly coated by epoxy resin mixed with curing agent in weight ratio 5:1. After degassed by vacuumizing under 45 °C for 6 h, the solidified GF/epoxy resin composite panel was cut into pieces of required specimen dimensions (a', b'). The design parameters of the absorbing layer and the labels used to identify the samples subsequently in this article are given in Table 2, and the tolerances were ±0.5 mm.