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Complex permeability and permittivity variation of carbonyl iron rubber in the frequency range of 2 to 18 GHz

Abstract: *The complex dielectric permittivity (ε) and magnetic permeability (μ) of Radar Absorbing Materials (RAM) based on metallic magnetic particles (carbonyl iron particles) embedded in a dielectric matrix (silicon rubber) have been studied in the frequency range of 2 to 18 GHz. The relative permeability and permittivity of carbonyl iron-silicon composites for various mass fractions are measured by the transmission/reflection method using a vector network analyzer. The concentration dependence of permittivity and permeability on the frequency is analyzed. In a general way, the results show that ε´ parameter shows a more significant variation among the evaluated parameters (ε", μ", μ'). The comparison of dielectric and magnetic loss tangents (ε"/ε" and μ"/μ', respectively) shows more clearly the variation of both parameters (ε and μ) according to the frequency. It is also observed that higher carbonyl iron content fractions favor both dielectric and magnetic loss tangents.*

Keywords: *Carbonyl iron, Silicon, Permeability, Permittivity, Radar Absorbing Materials (RAM).*

INTRODUCTION

Magnetic granular composites consisting of metallic magnetic particles embedded in a dielectric matrix have been widely used in electromagnetic applications such as electromagnetic wave absorber (also named Radar Absorbing Material, RAM) and electromagnetic shielding materials (Park, Choi and Kim, 2000). With the fast advancement of wireless communication and defense industry, radar absorbing materials are becoming more and more important in both civil and military applications, respectively (Liu *et al*., 2003; Feng, Qiu and Shen, 2007; Yusoff *et al*., 2002).

In general, RAM can be divided into two types: dielectric and magnetic ones. For single-layer microwave absorbers that have mainly magnetic losses in comparison to those that have mainly dielectric losses, broader bandwidth and higher absorption at smaller layer thickness can be achieved (Giannakopouou, Kontogeorgakos and Kordas, 2003). In this way, it can be cited carbonyl iron as a typical magnetic particle used in the magnetic RAM processing, attending the microwave frequency range. This magnetic filler type presents as main characteristics high Curie temperature (~1000K), good thermal stability, that allows its application at higher temperatures and high specific saturation magnetization intensity ($4\pi M_s$) (Deng *et al*., 1999). Thus, this magnetic particle has been widely used in the electromagnetic shielding and in RAM processing (Liu *et al*., 2003; Yong, Afsat and Grignon, 2003).

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This paper shows a study involving the evaluation complex magnetic permeability (μ = μ' - jμ'') and dielectric permittivity (ε = ε' - jε'') behaviors of an elastomeric RAM processed with different carbonyl iron contents, in the frequency range of 2 to 18 GHz.

EXPERIMENTAL

Carbonyl iron powder was chosen as absorbing filler and silicon rubber was used as polymeric matrix. Both components are commercially available. The densities of the employed carbonyl iron and silicon matrix are 7.8 and 1.28 g/cm^3, respectively. The carbonyl iron contents into the processed elastomeric RAM were 30, 35, 40, 45, 50, 55, 60, 65 and 70% in mass concentration. The elastomeric RAM were prepared by conventional mechanical mixture of the two raw materials. The homogeneous mixtures were molded in a coaxial die with inner diameter of 3 mm and outer diameter of 7 mm. The polymer curing was performed at room temperature for about 24 hours. At the end, flexible cylindrical composite specimens were produced.

The S parameters (scattering parameters) were measured and used to calculate the complex magnetic permeability and dielectric permittivity of all the prepared RAM samples. The measurements were performed according to the transmission/reflection method using an HP 8510C vector network analyzer, adapted with an APC7 coaxial transmission line, in the frequency range of 2 to 18 GHz. Figure 1 shows a schematic representation of the measurement system utilized.

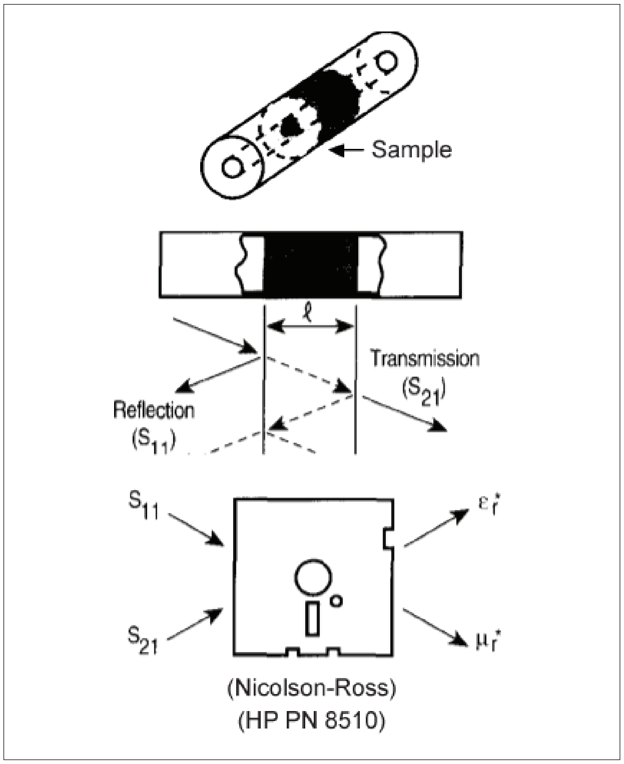

Figure 1: Representation of the transmission/reflection line Source: Bartley (2006).

The Nicolson-Ross modeling was applied in μ and ε calculations (Bartley and Begley, 2006).

RESULTS AND DISCUSSION

The real (storage) and imaginary (loss) permeability (μ' and μ'') and dielectric permittivity (ε´ and ε´´) behaviors are shown in Figures 2 and 3, respectively. Figure 4 shows the dielectric ($\tan \delta_e = \varepsilon''/\varepsilon'$) and magnetic ($\tan \delta_m = \mu''/\mu'$) loss tangents.

Figures 2 and 3 show that μ' and ε' components for the pure silicon rubber (0% mass concentration) present the lowest values. With the increase of the frequency, μ' values approach to 1.0 and ε´ varies around 2.6. The imaginary components (μ'' and ε'') also present the lowest values for these parameters (from 0.0 to –1.2 and from 0.0 to 0.7, respectively). In the same way, the loss tangents present the lowest values. These behaviors mean that the pure silicon matrix presents low magnetic and dielectric losses.

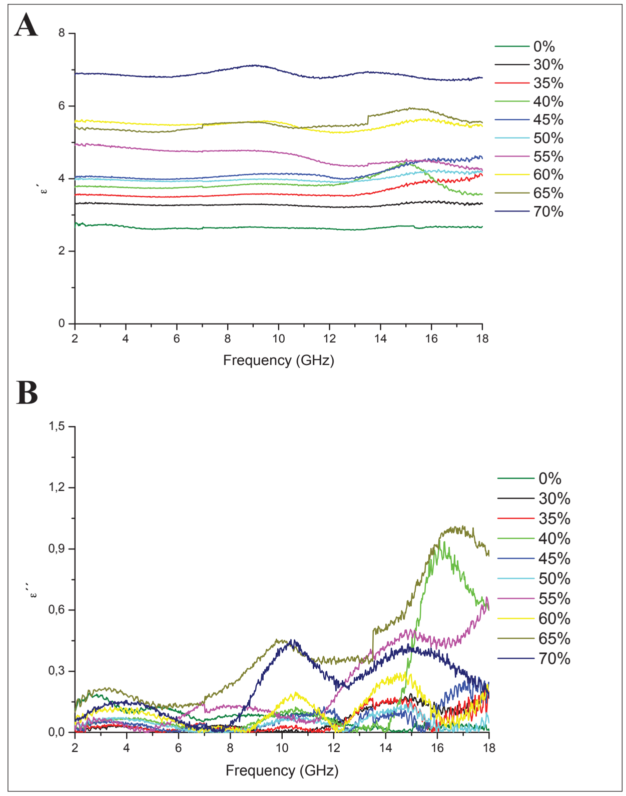

Figure 2: (a) Real and (b) imaginary dielectric permittivity of RAM (30 to 70% mass concentration) studied.

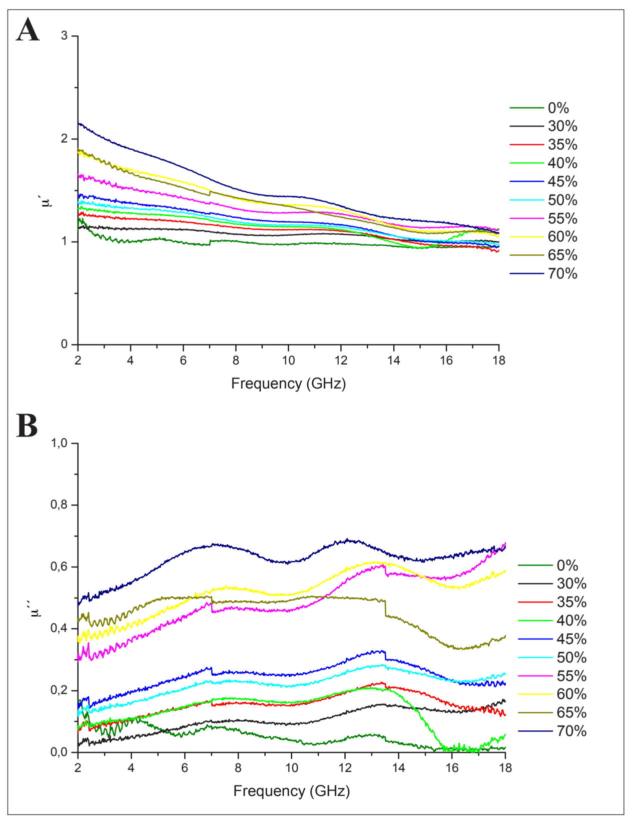

Figure 3: (a) Real and (b) imaginary magnetic permeability of the RAM (30 to 70% mass concentration) studied.

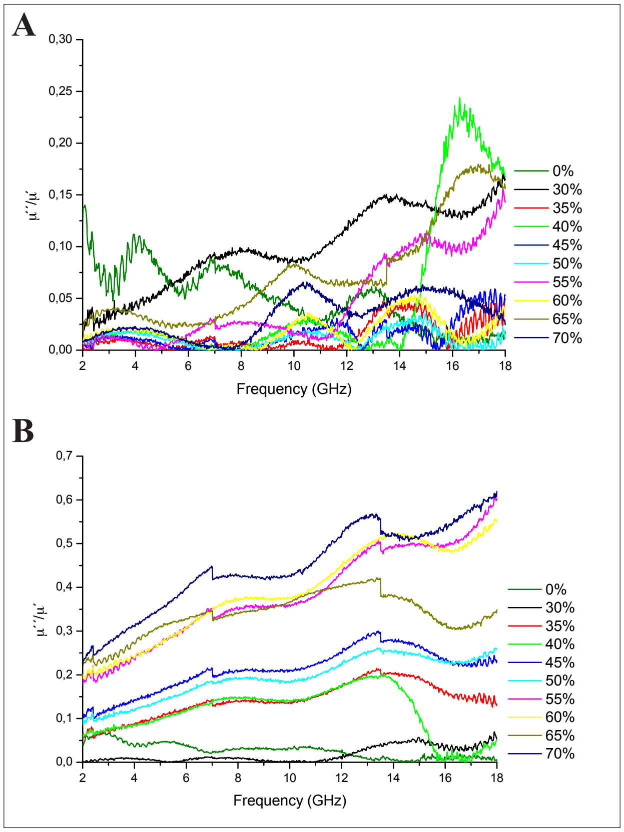

Figure 4: (a) Dielectric and (b) magnetic loss tangents of the RAM (30 to 70% mass concentration) studied.

Figure 3a shows that the real permeability (μ') values present a slight increase with the magnetic filler concentration increase into the RAM sample. For example, at 2 GHz, μ' is equal to 1.2 and 2.2 for the samples with 30 and 70% of carbonyl iron, respectively. On the other hand, this magnetic parameter decreases gradually until nearly 1.0, as the frequency increases. This observation is expected considering the typical behavior of magnetic materials with the frequency increase. It is known that this property decreases with the frequency increase due to the decreasing of both effects domain-wall motion and relaxation effects (Gama, 2009). Similar behavior is reported in the literature (Feng *et al*., 2006).

In general, the imaginary permeability (μ'') (Fig. 3b) presents a behavior similar to that observed for μ' (Fig. 3a). In this case, the increase of the imaginary parameter with the increase of magnetic filler concentration is also verified. However, considering the frequency increase, this parameter presents a behavior distinct from that observed for μ'. In this case, μ'' generally shows a slight increase until 14 GHz and, afterwards, this property decreases.

Comparing Figures 2 and 3, it is observed that the real permittivity (ε') presents a more accentuated increase with the carbonyl iron concentration increase in relation to that observed for μ'. Moreover, for a same mass fraction, the ε' parameter keeps almost constant with the frequency variation. The ε' variation with the carbonyl iron mass fraction is attributed to the polarization of the dielectric dipoles of the filler in the RAM. In this case, it is considered that the dipoles are in-phase with the oscillation of the electrical field vector of the electromagnetic wave. On the other hand, the dielectric losses (ε'') show an increase with both filler concentration and frequency. This behavior is more accentuated for the mass fractions above 55% and suggests that the loss processes during the dipole oscillation, under the electromagnetic wave influence, is more significant for higher frequencies, in accordance with Feng *et al*. (2006).

The magnetic loss tangent (μ''/μ') plots (Fig. 4b) show a slight increase concomitant to the frequency increase that is attributed to spin inversion losses (Feng *et al*., 2006).

The dielectric loss tangent (ε''/ε') curves (Fig. 4a) present a conclusive behavior only for the more concentrated samples (65 and 70%) that show an increase of this parameter concomitant to the frequency increase. Less concentrated samples present, in a general way, values in the range of 0.00 and 0.05.

Nelson (2005) reported that the dielectric losses present different loss mechanisms with the increase of frequency. When the frequency is relatively low (below GHz), the losses are determined mainly by the conductance and are independent of the frequency. Conversely, in frequencies in the microwave range, the losses involve two loss mechanisms: polarization relaxation and electrical conductance (Gama, 2009; Nelson, 2005). Thus, the two dielectric loss peaks at about 10.0 and 15.0 GHz (Fig. 4a) can be attributed to these two loss mechanisms.

CONCLUSIONS

The results of this study involving the electromagnetic properties of radar absorbing materials based on carbonyl iron/rubber show the dependence of both complex magnetic permeability (μ) and dielectric permittivity (ε) parameters on the frequency, in the range of 2 to 18 GHz. Firstly, the complexity involving the behavior of these parameters in the microwave frequency range is observed . It is also observed that ε' parameter shows the most significant variation among the evaluated parameters (ε'', μ'', μ'), with the carbonyl iron concentration. The comparison of dielectric and magnetic loss tangents (ε''/ε' and μ''/μ', respectively) shows more clearly the variation of both parameters (ε and μ) with the frequency. It is also observed that higher carbonyl iron content fractions favor both dielectric and magnetic loss tangents. Finally, based on the literature data, it is possible to suggest that the dielectric loss mechanisms for the RAM, in the microwave range, involve polarization relaxation, electrical conductance and spin inversion for magnetic losses.

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