Novel magnetic microwires-embedded composites for structural health monitoring applications

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We report the results of a systematic study of the magnetic, mechanical, magnetoimpedance and field tunable properties of glass-coated amorphous Co₆₈.₇Fe₄Ni₁B₁₃Si₁₁Mo₂.₃ microwires and composites containing these microwires. The magnetic microwires possess good magnetic and mechanical properties. The magnetoimpedance ratio in the gigahertz range varies sensitively with applied fields below the anisotropy field but becomes unchanged for higher applied fields. The good mechanical properties are retained in the magnetic microwires-embedded composites. The strong field dependences of the effective permittivity and transmission parameters in the gigahertz range indicate that the present composites are very promising candidate materials for structural health monitoring and self-sensing applications. © 2010 American Institute of Physics.
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Fiber reinforced composites (FRCs) are widely used for a variety of domestic and industrial applications. In aircrafts and automobiles, FRCs are being used extensively to reduce weight and improve fuel economy and performance.¹ However, effective detection of in-service damage to such composites remains a challenging issue and a regular inspection is time-consuming and expensive. As a result, advanced smart composite structures are expected to have integrated sensors arrays to interrogate potential damage to the structure.² The majority of work to date has been focused on embedding optical fibers within a material or structure for this purpose.²,³ However, a diameter mismatch between the reinforcing fibers and the optical fibers significantly degrades the mechanical performance of the composite as well as accuracy of detecting systems.¹,³ Therefore, developing new techniques alternative to optical fibers is essentially desired.

Recently, the independent discoveries of giant magnetoimpedance (GMI) and giant stress-impedance effects in soft magnetic amorphous glass-coated microwires have provided refreshing and exciting opportunities for the design and manufacture of smart composite materials.⁴–⁷ The tunable properties of these composite materials afford them a wide variety of applications, such as microwave absorber, field tunable microwave surfaces and self-sensing media for the remote wireless nondestructive test of structural materials. In this paper, we report a systematic study of the magnetic, mechanical, MI, and microwave properties of the glass fiber-reinforced composites containing continuous magnetic microwires. The results obtained reveal that the proposed composites are very promising for applications in structural health self-monitoring and stress sensing.

The glass-coated amorphous microwires of Co₆₈.₇Fe₄Ni₁B₁₃Si₁₁Mo₂.₃ with a metallic core diameter of 18.59 µm and a glass layer’s thickness of 2.8 µm were fabricated by a modified Taylor–Ulitovski process.⁸ The wire-composites were prepared by embedding the microwires into the E-glass 913 prepregs following the procedure detailed in our previous work.⁵ Instron 1466 with the load cell of 1 kN and Instron 3343 with the maximum load of 30 kN were employed to test the tensile properties of the microwires and composites, respectively. The free-space measurements were conducted as described in Ref. 9. Magnetic measurements were carried out along the axis of the microwire by LakeShore VSM at magnetic fields up to 5 kOe. The MI measurements were conducted by the HP8753E network analyzer. The MI ratio ΔZ/Z is defined as

\[
\frac{\Delta Z}{Z} = \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \times 100% ,
\]

where Z(H) and Z(H_{\text{max}}) are the impedance values of the microwire in the measured external magnetic field and maximum magnetic field to saturate the impedance, respectively.

Figure 1 shows a cross-section scanning electron microscope (SEM) image, the magnetic and mechanical properties and MI effect in the gigahertz range for a Co₆₈.₇Fe₄Ni₁B₁₃Si₁₁Mo₂.₃ microwire. Clearly, the microwire exhibits soft ferromagnetic characteristics, with a coercivity of 0.1 Oe, a saturation magnetization of 12.5 kGs, and an anisotropy field of 11 Oe. As also shown in the inset of Fig. 1(a), the stress-strain curve exhibits the Young’s modulus of 123.75 GPa, tensile strength of 1246 MPa and fracture strain

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of 2.97%. These results indicate that the microwire has good mechanical properties. In Fig. 1(b), in the investigated frequency range of 1–18 GHz, the MI ratio first increases with increasing magnetic field \( H \) until \( H=H_K \) (the anisotropy field) and then becomes almost constant for higher magnetic fields \( (H>H_K) \). This demonstrates a close correlation between the magnetization process and microwave frequency MI behavior. Overall, the results obtained indicate that the excellent magnetic, mechanical and MI properties of the micro-wires are desirable for engineering smart structural magnetic microwires-embedded composites.

To study the influence of embedded magnetic microwires on the mechanical properties of a fiber-reinforced composite, we characterized and compared the stress-strain responses of the composites without magnetic microwires and with 10 and 50 magnetic microwires. The results are shown in Fig. 2. The shape of the stress-strain response curves have little variance. While the coefficient of variation (CV) for the Young’s modulus of blank composites, composites with 10 wires and 50 wires are 3.1, 1.1, and 3.0, respectively. Upon performing comparison of the average value of each type of sample, the CV turns out to be 2.6. These results indicate that the good mechanical properties are retained in the magnetic microwires-embedded composites.

Next, the field tunable microwave response of the magnetic microwires-based composites was studied by modeling the effective permittivity and free-space measurement of the transmission/reflection spectra in an external magnetic field. The continuous-wire composite possesses a characteristic plasma dispersion behavior of the effective permittivity \( \varepsilon_{\text{eff}} \), which is expressed as

$$\varepsilon_{\text{eff}} = \varepsilon - \frac{f_p^2}{f^2},$$

(2)

where \( \varepsilon \) is the permittivity of the matrix, \( f_p \) is the so-called plasma frequency, which depends on both the spacing between the microwires \( (b) \) and the microwire’s radius \( (a) \). It can be calculated by:

$$f_p^2 = \frac{c^2}{2\pi^2 b^2 \ln \left( \frac{b}{a} \right)}.$$  

(3)

Since the plasma frequency is dependent on the wire impedance, the effective permittivity can be tuned by the magnetic field or stress through the impedance. Therefore we varied the periodicity of microwires (the interwire spacing) to study its influence on the field tunable properties of the prepared composites.

Figure 3 shows the transmission spectra (S21) of the composites with different wire periodicity \( (b) \). Overall, as \( H=0 \), all the samples show two maximum and one minimum cups at frequencies of \( \sim 8, 15, \) and \( 12 \) GHz, respectively. These cups become more pronounced for composites with higher \( b \). Noticeably, the amplitude of S21 significantly reduces as the magnetic field is applied. For \( H>500 \) A/m, an additional dip appears to occur at \( \sim 3 \) GHz and this dip shifts to a lower frequency as \( b \) is increased. For the samples investigated, the amplitude of S21 reduces strongly with \( H < 500 \) A/m and it becomes almost constant for \( H > 500 \) A/m. This implies there exists an upper limit of the field tunability of the composites, which can be related to the effective anisotropy field of a multiwire system. It is also noted that the field tunability of the transmission parameter is diminished as the frequency is increased. In the vicinity of the plasma frequency, the transmission parameter becomes independent of the external magnetic field. This indicates that the field tunable properties are limited not only by the magnetic field but also by the frequency, both of which should be carefully considered in practical applications.

To further clarify this issue, we show in Fig. 4(a) and its inset the magnetic field dependence of field tunability \( (n_{S21}) \) and S21 at 4 GHz, a frequency near the minimum of S21 in the presence of field of 1 kA/m and below the plasma frequency. The field tunability varies with magnetic field and decreases with increasing wire periodicity until \( H \) exceeds.
This can be understood as increasing amount of wires and an elevated interaction between the wires due to decreasing periodicity encouraged the response to applied magnetic field. The maximum tunability is shifted to a decreasing periodicity encouraged the response to applied field. Figure 4(b) illustrates the magnetic field dependence of the field tunability at the plasma frequency, which is theoretically expected to excite the maximum response to electric field. However, the best field tunability occurs below the plasma frequency, which can be attributed to the different dynamic dielectric response and magnetic response. The application of external magnetic field reduces the transmission until c.a. 500 A/m where maximum absorption can be inferred.

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FIG. 3. (Color online) Transmission spectra (S21) for composites with varying wire periodicity. (a) b = 3 mm, (b) b = 7 mm, and (c) b = 9 mm.

FIG. 4. (Color online) Field tunability of transmission parameter S21 as a function of external field for composites containing continuous wires with different wire spacing b = 3, 7, and 9 mm at 4 GHz (a); plasma frequencies (b). The ordinate profiles are divided by the factor 0.001. Inset graphs are the corresponding field dependence of S21.

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