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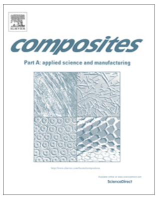

Embedded ferromagnetic microwires for monitoring tensile stress in polymeric materials

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ABSTRACT

Considerable efforts have been made to develop testing non-destructive methods for polymer composite materials. We would like to introduce researchers in the field of smart materials to a new method of monitoring internal stresses. The method can be classified as an embedded sensing technique, where the sensing element is a glass-coated ferromagnetic microwire with a specific magnetic anisotropy. With a diameter 10–100 μm, the microwire impedance acts as the controlled parameter which is monitored for a weak alternating current (AC) in the MHz range. The microwire impedance becomes stress sensitive in the presence of a weak constant axial bias magnetic field. This external parameter allows the impedance stress sensitivity to be easily tuned. In addition, a local bias field may also allow the reconstruction of stress profile when it is scanned along the microwire. The experimental results are analysed using simple magnetostatic and impedance models.

1. Introduction

Ferromagnetic microwires coated with glass can be used in several niche applications due to their specific magneto-anisotropic properties [1–3]. There are two types of microwires. The first type, known as bistable microwires, is characterised by an almost rectangular magnetic hysteresis loop measured along the microwire axis. These microwires, demonstrating natural ferromagnetic resonance, have found applications in microwave absorbing materials [4–6]. The second type of microwires is characterised by a narrow inclined hysteresis loop. The most remarkable property observed in these microwires is the so-called magneto-impedance (MI) effect: a large change in the microwire high frequency impedance under the influence of a longitudinal magnetic field [7,8]. The Mohri et al. review [9] describes implemented magnetic sensors based on MI.

In the embedded sensing techniques, some special particles or fibres are used which act as mediators between internal parameters of the medium and a readout device. Depending on the physical principle of this intermediary function, different physical quantities can be utilised as the measurement parameters which include: current, voltage, resistance or impedance, electric or magnetic fields, permeability or permittivity, reflected or transmitted electromagnetic waves (amplitude and phase). The method of monitoring the internal tensile stresses, developed in the present work, consists in embedding a MI glass-coated microwire into a polymer matrix and measuring its impedance using a weak high frequency current in the MHz range. As opposed to the usual MI, the tensile stress is used as the control parameter instead of the magnetic field. Before we proceed, it would be useful to conduct a comparative analysis of several embedded sensing methods which are similar to our method either by the geometry of inclusions or some physical principles.

The undisputed leader in non-destructive testing of composites is the method using embedded optical fibres [10,11]. The silica or polymer optical fibre may play the role of a sensor by itself or could transmit signals between the tested area, where the light interacts with a substance, and a readout device. Along with the extraordinary sensitivity, the optical method can also measure a wide range of parameters such as strain, temperature, pressure, humidity, and vibration. In addition, it is immune to electromagnetic interference. The experience gained by the integration of optical fibres into a polymer matrix is useful to us because their diameters (7–50 μm) are close to those of microwires. Since microwires are coated with glass, the bonding of matrix–microwire and matrix–fibre interfaces should be comparable assuming similar surface treatments. Despite modest diagnostic capabilities as compared with optical

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fibres, the microwire-based sensor proposed in our work can be made tuneable and the instrumentation has much lower cost.

In impedance-based spectroscopy [12–16], the effective impedance of the mixture of conductive reinforcing fibres (steel or carbon) and a weakly conductive matrix is measured in a specific frequency range (normally MHz) between a pair of patch contacts attached to the sample surface. Since the volume fraction of fibres (<3%) is usually below the percolation transition, the presence of a weakly conductive matrix is absolutely necessary to ensure the effective conductivity. An external stress does not change the electrical properties of non-magnetic conductive fibres. The piezoimpedance effect is caused by the fibre–matrix interface which has a capacitive nature due to the oxidation or polarization layers forming on the surfaces of steel and carbon fibres, respectively. Thereby, this method can scarcely be used in polymer matrixes as the conductivity is too small. On the contrary, the stress sensitivity of ferromagnetic microwires is caused only by their internal magnetic properties, and hence they can be used in any dielectric matrix allowing their embedding.

In magnetostrictive tagging, Terfenol-D magnetic microparticles (<300 μm in size) are added to the composite matrix to produce the effective magnetic properties [17,18]. Since Terfenol-D particles are almost nine times denser than the matrix resin, they tend to settle during cure. To prevent this process, the sample is placed between the poles of a permanent magnet creating a homogeneous magnetic field perpendicular to the sample plane. Samples manufactured using this technique have aligned particle clusters and demonstrate an enhanced magnetostrictive response when they are loaded. Stress transferred through the matrix to the particles causes a change in the direction of equilibrium magnetisation due to the inverse magnetostrictive effect. Stress monitoring measures the longitudinal or transverse component of the magnetic field near the sample surface using a magnetometer. This inverse magnetostriction effect is also used in our method. However the measured quantity is a high frequency MI of microwires that depends on the direction of magnetisation. The use of ready-made microwires eliminates the necessity of forming the magnetic properties during cure. Moreover, the MI microwires have a very narrow hysteresis loop that eliminates the problem of calibration when measuring a cyclic load.

Investigation of the matrix parameters which may affect the magneto-impedance of embedded microwires is of crucial importance for the development of not only the contact stress sensors, but also microwave smart materials. In the GHz range, microwires homogeneously distributed inside the matrix can be interrogated remotely using microwave beams. The short microwire inclusions will scatter the incident microwave in a similar manner to the miniature dipoles [19], while the long microwire strings will respond as the cold plasma of free electrons [20]. A local magnetic field, stress, and temperature will change the impedance of microwires and, as a consequence, the transmitted and reflected microwaves. The volume fraction of microwires required to introduce a tuneable microwave functionality is very small (much less than 1%) and thus reduces the impact of sensor inclusions on the mechanical properties of matrix. Composites based on ferromagnetic micro- and nano-microwires are being studied experimentally and theoretically by several research groups (see e.g. [21–26]). Despite the growing interest in tuneable microwave composites, to our knowledge only one work [27] has been published where the effect of tensile stress on the free-space microwave properties of the wire-filled composites was demonstrated. Difficulty in carrying out such experiments is caused by the need to integrate a loading frame with microwave antenna measurements.

In our present work, we return to contact impedance measurements with a ferromagnetic microwire embedded into a commercial epoxy resin matrix. Our experiments are designed not only to demonstrate the physical effects, but also to address a number of practical issues that pertain to the embedded sensors. In particular, we show how the magnetic and mechanical response of microwires are related to the matrix elastic properties.

2. Magnetostatic and impedance models for glass-coated microwires

In this section we introduce the magnetostatic and impedance models used in Section 3 to analyse experimental results. The Gaussian-cgs system of units will be used within the formulation of theoretical models, while SI units are more convenient for the interpretation of experimental data. Unless it is otherwise, the physical dimensions specified in the brackets would refer to SI units.

2.1. Magnetostatic model for glass-coated microwires

Glass-coated microwires are produced using the Taylor–Ulitovskiy casting method [1,2]. As a result of quenching, an amorphous or polycrystalline metal core is obtained in the glass envelope. The initial process of quenching and the difference in thermal expansion coefficients of glass and metal create a tensorial residual stress, $\hat{\boldsymbol{\sigma}}$, inside the metal core which is responsible for the magnetic anisotropy [28–30]. The components of $\hat{\boldsymbol{\sigma}}$ can be further modified by an annealing treatment. In as-cast glass-coated microwires, the axial tensile stress σ_a produced by the glass shell is predominant over other residual stresses. For glass-coated microwires made of a Co-based alloy, which have a small negative magnetostriction, the predominant residual tensile stress σ_a will result in a circular magnetisation $\mathbf{M}_0$ in the near-surface layer of the metal core. In turn, this circular magnetised shell is divided into cylindrical domains with opposite magnetisation directions.

The direction of $\mathbf{M}_0$ can be controlled by the combined action of an external axial magnetic field H_{ex} and an external axial stress σ_{ex}. The total residual stress on the surface of the microwire metal core also needs to be taken into account. It can be decomposed into the axial tension σ_1 ($\sigma_1 = \sigma_a$) and the torsion (pure shear) which is a combination of tension and compression with equal intensity σ_2 perpendicular to each other and at 45° to the microwire axis [31]. In the frame of the Stoner–Wohlfarth model [32], the total magnetostatic energy per unit volume (erg/cm^3, cgs) can be written in the following form [33]:

$$U_t(\theta) = -M_0\left(\frac{1}{2}\mathrm{sgn}(\lambda)H_K\cos^2(\alpha+\theta) + H_{ex}\cos(\theta) + H_b\sin(\theta)\right) \tag{1}$$

$$K = \frac{3}{2}|\lambda|\tilde{\sigma} \tag{2}$$

$$H_K = \frac{2K}{M_0} = \frac{3|\lambda|\tilde{\sigma}}{M_0} \tag{3}$$

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{2\sigma_2}{\sigma_1 + \sigma_{ex}}\right) \tag{4}$$

$$\tilde{\sigma} = \sqrt{(\sigma_1 + \sigma_{ex})^2 + 4\sigma_2^2} \tag{5}$$

where α is the angle of magnetic anisotropy measured from the circular direction, $\mathrm{sgn}(\lambda)$ is the sign of the magnetostriction constant λ, K is the anisotropy constant (erg/cm^3, cgs), H_K is the anisotropy field (Oe, cgs), $H_b = 2I_b/ca$ (Oe, cgs) is the circular DC magnetic field on the surface of metal core induced by a DC bias current I_b in the microwire, θ is the angle between $\mathbf{M}_0$ (emu/cm^3, cgs) and the wire axis, $M_0 = |\mathbf{M}_0|$ is the module of $\mathbf{M}_0$, the parameters $\sigma_{1,2}$ (dyn/cm^2,