CoFe-microwires with stress-dependent magnetostriction as embedded sensing elements

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Abstract. Testing internal stress/strain condition of polymer composite materials is of high importance in structural health monitoring. We are presenting here a new method of monitoring internal stresses. The method can be referred to as embedded sensing technique, where the sensing element is a glass-coated ferromagnetic microwire with a specific magnetic anisotropy and stress-dependent magnetostriction. When the microwire is remagnetized the sharp voltage is induced which is characterized by high frequency harmonics. The amplitude of these harmonics sensitively depends on various stresses. The microwire of composition Co₁₋₁Fe₅B₁₁Si₀Cr₃ with the metallic core diameter of 22.8 µm show abrupt transformation of the magnetization process under applied tensile stress owing to the stress-dependent magnetostriction.

1. Introduction.
Magnetostriuctive materials are widely used for stress and strain sensing. When a mechanical force is applied to a magnetostriuctive material, its magnetization state changes. This can be measured and inversely translated into a corresponding indication of stress or strain change. In many cases it is assumed that a good magnetostriuctive material should have a large magnetostrictive constant λ as Terfenol-D (Tb₁₋₁₋ₓDₓ₁₋ₓ₋ₓFe₂₋ₓ₋ₓ, x ≈ 0, 0 < y < 0.2) with λ ≈ 1.6·10⁻³ [1]. The situation can be different for amorphous or nanocrystalline materials where the intrinsic crystalline anisotropy is small. In this case, the main source of the anisotropy is due to anisotropic stress-magnetostriction coupling effect. It is well known that the magnetic structure in amorphous microwires with small magnetostriction λ ≈ 10⁻⁷ – 10⁻⁶ can be easily changed by a moderate stress [2-4]. Therefore, the magnetization process will be highly stress-dependent which can be used for sensitive stress sensing, for example, based on magnetoimpedance effect in near-zero magnetostrictive wires [5-6].

The stress sensitivity of the magnetization state in low magnetostrictic metal glasses may be further enhanced by the dependence of the saturation magnetostriction on the applied tensile stress σₑ [7-9]. Typically, the behavior is described by a linear relationship:

\[ \lambda_s(\sigma_e) = \lambda_s(0) - \alpha \sigma_e \]

where the parameter α is found to be in the range of (1 – 6)·10⁻¹⁰ MPa⁻¹. Similar effects on stress dependence of the saturation magnetostriction were recently observed in nanocrystalline alloys [10].

A number of mechanisms were proposed to explain such magnetostriction behavior. In many cases, the phenomenon of stress-dependent magnetostriction can be attributed to local atomic
rearrangements resulting in the redistribution of local anisotropy axes. The coexistence of two amorphous phases, elastically coupled, with different magnetostriction to each other may also lead to the stress dependence of magnetostriction. The purpose of this paper is not to elucidate a particular mechanism of the stress dependence of magnetization, but to demonstrate how this phenomenon can be used in embedded stress sensors. The sensing principle is based on the stress-sensitivity of the harmonic spectrum originated by the wire remagnetization process.

2. Experimental details
Glass-coated Co$_{71}$Fe$_{5}$B$_{11}$Si$_{10}$Cr$_{3}$ amorphous wires with small magnetostriction constant have been studied. The wires were produced by the modified Taylor-Ulitovski technique [11,12] based on direct casting from the melt. The wires with different geometry were used: having the total diameter of 29.5 and 41.5 $\mu$m and the metallic core diameter of 23.9 and 36.3 $\mu$m, respectively for samples labeled as No (1) and No (2). For structural characterization, differential scanning calorimetry (DSC) measurements were performed using (DSC 204 F1 Netzsch) calorimeter in Ar atmosphere at a heating rate of 10 K/min. The mass of the samples was 10-15 mg. The extent of crystallization, Curie temperature and crystallization temperature were estimated from DSC curves using standard IT application.

The magnetization curves were measured by an inductive method with two differential coils under the effect of external load by hanging weights up to 35 g. The magnetization coil was excited by a current of frequency 500 Hz, which produced a magnetizing field with the amplitude of 1000 A/m. The induced voltage vs time was digitally integrated to obtain a hysteresis loop. The wire was inserted into a narrow magnetization/detection coil having the inner diameter of 3 mm and the length of 5 cm. This stress is redistributed between the metal core and glass shell which have different Young’s moduli ($E_m = 130$ GPa, $E_g = 70$ GPa) and cross-sections ($A_m$, $A_g$), for metal core and glass shell, respectively. The stress $\sigma_{ex}$ in the metal core can be estimated by using the method of consistent deformations caused by a gravitational force $F$:

$$\sigma_{ex} = \frac{E_m F}{E_m A_m + E_g A_g}$$

Magneostriiction was measured by small-angle magnetization rotation technique [13,14].

The harmonics of the voltage generated at remagnetization are measured with the help of a lock in amplifier (Signal Recovery 5210) and function generators [15].

3. Result and discussion
The DSC curves are shown in Figure 1. It is seen that the crystallization proceeds in two stages for both types of samples; however, for sample (1) with smaller diameter the main peak is much narrower. This indicates a partial crystallization of sample (2). From the ratio of the peak areas the proportion of the crystalline phase has been evaluated as 12.5%. The Curie temperature is defined from the position of the inflexion point which is clearly seen for sample (1) at 364.4 $^\circ$C as shown in insert of Figure 1. For sample (2) inflexion is not noticeable which also supports the conclusion about its partial crystallization. The partial crystallization of sample (2) can be attributed to its larger diameter.

![Figure 1: DSC curves for samples (1) (solid red curve) and (2) (dashed blue curve). Insert shows the inflexion point on the DSC curve for sample (1).](image-url)
The results for the saturation magnetostriction are shown in Figure 2. For sample (2) the value of $\lambda_s$ is positive and much larger owing to partial crystallization. For sample (1), the magnetostriction is negative and the absolute value increases with increasing $\sigma_{ex}$. For linear portion, the gradient of this increase is $2.7 \cdot 10^{-10}$ $MPa^{-1}$ which is consistent with previously reported results [16,17]. The value of the magnetostriction near zero stress is questionable since reliable measurements to avoid the effect of the off-axis anisotropy require the application of a certain stress. However, linear extrapolation gives a value close to zero (smaller than $10^{-6}$). The sign is unclear but considering the hysteresis loops without stress suggests that $\lambda_s$ is positive for $\sigma_{ex} = 0$.

![Figure 2: Saturation magnetostriction as a function of applied tensile stress for as-prepared Co$_{71}$Fe$_5$B$_{11}$Si$_{10}$Cr$_3$ wires two different diameters. Linear extrapolation (shown by blue line) for sample 1 gives $\lambda_s$ close to zero at $\sigma_{ex} = 0$.](image)

Indeed, when no stress is applied the hysteresis loops for both samples are of bistable type and almost identical with small coercitivity of about 25 A/m. The value of remanence close to saturation magnetization confirms the existence of the axial anisotropy nearly in the entire wire. Applying a tensile stress results in sharp transformation of the hysteresis for sample (1): for stress higher than 200 MPa the loop becomes inclined. For sample (2), the loop remains a rectangular form but the coercivity increases. The change in remanence and coercivity under the effect of tensile stress is shown in Figure 3.

![Figure 3: Effect of tensile stress on remanence (a) and coercivity (b) of Co$_{71}$Fe$_5$B$_{11}$Si$_{10}$Cr$_3$ wires with different diameters.](image)

In all types of wire samples, the voltage induced by the wire re-magnetization is characterized by the generation of high harmonics. However, only for wire sample (1) their amplitudes sensitively change under the effect of stress as shown in Figs. 4 (a, b) and the sensitivity with respect to stress increases for higher harmonics. It is interesting to notice that for wire sample (2) with a bistable type of hysteresis for all applied stresses and the coercivity increasing with $\sigma_{ex}$, there is no dependence of the harmonic spectrum on $\sigma_{ex}$.

For practical applications, it is interesting to investigate the stress dependence of the harmonics ratio since this parameter is not dependent on a particular measurement scheme. This was done for sample (1) which demonstrates a considerable stress sensitivity of the harmonic spectra. Figure 5 shows the stress dependences of higher frequency harmonics normalized to the amplitude of the third harmonic. The normalized harmonics change by 10-15% per 100 MPa in the stress sensitive region ($\sigma_{ex} > 200$ MPa) depending on the harmonics number. The change in the induced harmonic spectra may give...
information about the strain/stress state inside materials which otherwise is very difficult to measure. The methods to avoid insensitive stress-range should be further investigated.

Figure 4: Amplitudes of high harmonics as a function of applied stress: (a) for wire sample (1) and (b) for wire sample (2). The amplitudes are normalized by their values at zero applied stress.

Figure 5: Ratio of higher harmonics amplitudes to the amplitude of the third harmonic as a function of applied stress for wire sample (1).

In summary, we have proposed to use the effect of stress-dependent magnetostriction for the development of embedded wireless stress sensors which is based on sharp transformation of the hysteresis loops and stress-sensitive harmonic spectrum.

L. V. Panina acknowledges the support for this work under Russian Federation State Contract for organising a scientific work.

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