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A high performance strain gage based on the stressimpedance effect in magnetic amorphous wires

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ABSTRACT

The paper presents a study on the possibilities of using the Co based magnetic amorphous wires (MAWs) with nearly zero magnetostriction for measuring strains by exploiting the stressimpedance (SI) effect occurring on them. It is known that the SI is a particularization of the magnetoimpedance (MI) effect when a MAW is driven by an ac current and is subjected to mechanical stresses under constant magnetic field. Several parameters of influence have been investigated in order to obtain the best performances for a strain gage (SG) that is intended to be developed for finally building a high performance landslide transducer. Using a MAW of 20 mm length which is driven by a current of 10 mA and of frequency of 1 MHz, under induced initial torsional stress of 5π rad/m and a residual axial tensile stress of 55 MPa, we obtained a high sensitivity SG showing a gage constant of about 2100 and a linear range of ± 200 ppm.

1. Introduction

There are many research and industrial areas in which SGs are basic sensing elements for measuring, directly or indirectly, physical quantities like strain, pressure, torque, acceleration, displacement and force. Strain gages are devices whose impedance is changing according to the strain applied to them. The sensitivity of an SG to a strain is measured by its gage constant, *k*, which is defined by the relative change of impedance, reported to the corresponding strain. The most commonly used SGs in technical applications are based on metal or semiconductor materials as sensing element. The metallic SGs are characterized by small sensitivity ($k \cong 2$), but good linearity and stability with temperature over the measurement range. Higher sensitivities are shown by semiconductor based gages ($k \cong 200$) because of their piezoresistive effect [1], but they prove to be more expensive, more sensitive to temperature changes and more fragile than metallic gages. A new category of materials appeared in 80s in the form of magnetic amorphous wires. They are metallic glasses that are obtained by in-rotating water spinning method [2] or by Taylor–Ulitovsky method [3]. Their composition is based on a metal phase like Fe, Co, Ni, Cr, Mn, Cu, Nb, alloyed with Si and B in different proportions. They exhibit excellent magnetic properties and effects that make them suitable to be employed as sensitive elements for measuring various quantities such as: magnetic sensors, stress sensors, torque sensors, position sensors, non-destructive testing sensors, biosensors, etc. (several examples are given in Refs. [4–7]). The MAWs presenting high permeability and nearly zero magnetostrictivity ($\lambda_s < 0.1$ ppm) exhibit the MI effect, which consists in a sudden variation of the wire impedance as soon as it is subjected to a magnetic field and it is driven by an ac current. Even if the MI effect is defined by the influence of the magnetic field on the wire impedance, since this effect is tightly related to the anisotropy induced by the axial and circular mechanical stresses applied to the wire, it is obvious that these stresses may lead to impedance modifications provided that the magnetic field remains constant. In this sense, the SI effect evolves from the interaction between circular magnetization in the wire structure and the internal and external stresses induced into the wire [8]. As a consequence, SI effect may be successfully utilized in building devices suitable to measure quantities related to mechanical actions and, in particular, deformations.

An important advantage of the MAWs is their excellent elasticity. The value of maximum tensile strength is around 3–4 GPa with an elastic deformation ratio of more than 95% [9].

Several attempts for building SGs using SI effect were reported. Shin et al. [10] reported a gage constant of 1800 obtained using a FeCoSiB film at a frequency of 50 MHz. Uchiyama and Meydan [11] estimated a *k* of more than 2000 for a 21 μm diameter glass-covered Co-based amorphous wire. In this case, a linear dependence of the impedance on the strain was observed for a strain interval of −0.01% to 0.01% by annealing the wire with a dc current of 50 mA for 20 min.

In this paper we investigate the behaviour of a 120 μm diameter Co based nearly zero magnetostrictive MAW from the point of view of its impedance variation under applied stress in different conditions. The aim of this approach is to obtain the maximum efficiency of the SI effect for building high performance stressimpedance

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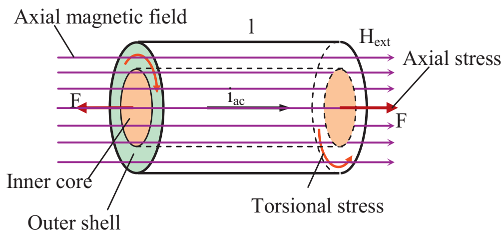

Fig. 1. Schematic internal domain structure of a Co-based MAW.

strain gages (SISG) that will be subsequently used for developing a new sensor for landslides measurement and monitoring. At present, the commercially available SGs are not convenient for our task because of their low sensitivity to strain. We test the SISG for different lengths and residual torsional stresses as well as for different annealing treatments and temperatures when ac currents of variable frequencies and intensities flow through it.

2. Short presentation of MI and SI effects

MI effect is, by convention, defined as variation of MAW impedance when subjected to a variable magnetic field, whereas SI implies same impedance variations, but when mechanical stresses are applied to it, thus leading to wire deformation. The impedance change ratio per Oersted in MAWs may be, in certain conditions, higher than that found in giant magnetoresistive (GMR) materials. Moreover, under some specific conditions, hysteresis may be avoided in MI effect. Since discovered, the MI and SI effects were intensively studied in amorphous wires [12–18], wires and microwires covered by glass [19–22], various composites [23,24] or in single or multilayered films [25–27].

In MI, as well as in SI effects, for a certain composition and under the influence of a static magnetic field, the impedance variation, ΔZ, is a consequence of the dynamic magnetization process inside the wire structure, that is strongly influenced by the current frequency, but also by the internal axial or circumferential stresses "frozen" during the wire fabrication process or induced from exterior by mechanical actions [28,29]. The MAW internal structure looks like an axially magnetized core surrounded by a circumferentially magnetized shell, as shown in Fig. 1 [30,31]. The outer shell exhibits a circumferential anisotropy in terms of opposite magnetization in adjacent magnetic domains.

The wire impedance variation mainly depends on the ac current frequency. As for example, for frequencies under about 100 kHz, the MI is given by variations of reactive component of the impedance (magnetoinductive effect) whereas for higher frequencies, the skin effect occurs at the wire surface. In this case, the skin penetration depth is given by:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_{\Phi}(H_x\xi, \sigma)}} \tag{1}$$

where ρ is the material resistivity, ω is the current pulsation, μ_{Φ} is the circular permeability in the wire shell depending on the axial magnetic field, H_x, and axial and torsional stresses ξ and σ.

The basic equation that governs the MI effect is [17]:

$$Z = R_{dc}kr\frac{J_0(kr)}{2J_1(kr)}, \quad k = \frac{1+j}{\delta} \tag{2}$$

where R_{dc} is the wire resistance in dc current, J_0 and J_1 are Bessel functions, r is the wire radius and δ is the skin depth.

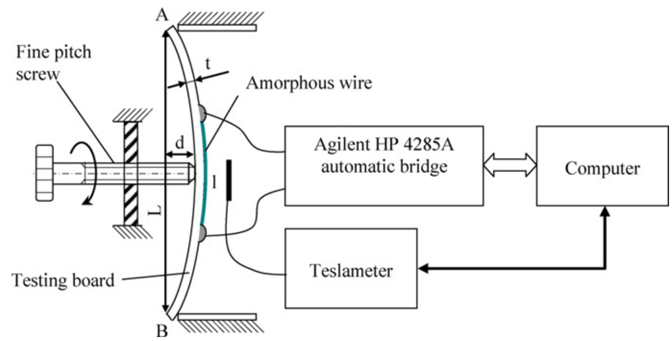

Fig. 2. Experimental setup for tracing the SISG characteristics.

Explicitly, (1) provides the two components of Z for a MAW of length l:

$$\underset{\sim}{Z} = R_{dc} + j\omega L, \quad L = \frac{l\mu_{\Phi}(H_x, \xi, \sigma)}{8\pi} \tag{3}$$

for $f \leq 100$ kHz and

$$\underset{\sim}{Z} = \frac{r}{2\sqrt{2\rho}}R_{dc}(1+j)\sqrt{\omega\mu_{\Phi}(H_x, \xi, \sigma)} \tag{4}$$

for $f > 100$ kHz.

One may observe from the above equations that, for low frequencies, the impedance variation is given mainly by variation of the inductance L that depends, in turn, by the magnetic field intensity and axial and torsional stresses, whereas for higher frequencies, both active and reactive components are affected by these parameters.

In the next sections we present the results obtained by experimentally tracing the dependence of Z on several factors of influence in order to investigate how these dependences may be used to build and optimize the operation of an SG whose performances will be assessed in terms of sensitivity, linearity and temperature dependence.

3. Experimental procedure

In order to trace the characteristics of the future designed SISG, we utilized the experimental setup shown in Fig. 2. The main element in this approach is the testing board (Fig. 3), on which the MAW is bonded so that it supports the strain ε under the action of the bending force produced by a fine pitch screw progress. We utilized in our experiments Co-based amorphous wires, kindly supplied by the National Institute of Research & Development for Technical Physics Iasi, of composition $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ and of 120 μm diameter. The bending of the board is carried out under the action of the screw with a step of 0.508 mm/turn. The displacement d of the screw produces the bending of the board and, implicitly, the wire axial deformation.

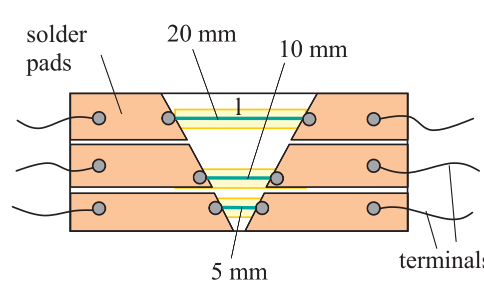

Fig. 3. Experimental board for testing the MAW sample behaviour under strain action.