Combined Mechanical Stress – the Key Parameter of Fine Tuning of Magnetic Microwires for Sensor Application

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Abstract— **The experimental observation of the spiral domain structure has opened a new possibility of the fine control of the domain structure with different magnetization states in magnetic microwires, which are the base elements of the magnetic sensors. Here, we demonstrate that the tuning of magnetic domain structures in amorphous microwires can be engineered by the combination of tension and torsion mechanical stresses.**

Keywords-soft magnetic materials; amorphous magnetic wires; magneto-optic Kerr effect.

I. INTRODUCTION

Amorphous magnetic wires present a number of properties suitable for technical applications, such as Giant Magneto-Impedance (GMI) effect or magnetic bistability associated with fast domain wall propagation [1]–[4]. Consequently, various types of magnetic wires have been widely investigated during the past years [1]–[7].

While the separate application of different types of mechanical stresses is the usual practice, the combination of two different mechanical stresses could be considered as a new step permitting the fine tuning of the magnetic properties of the microwires.

Our study aimed at performing wide and complex magnetic and magneto-optical investigations of glass covered magnetic microwires under the simultaneous presence of tension and torsion stresses. Also, we have paid special attention to the domain walls motion in the wire being under stress. The essential element of our study is the simulation of the magnetic structure based on the theoretical analysis proposed in [8]. As a result, the spatial distributions of the vector of magnetization and the domain structures have been obtained in the cylindrically shaped magnet. The main idea of our work is the search of new magnetic states, in particular on the surface of microwire, which could be created only by the combination of torsion and tensile stresses.

The paper consists of 4 parts. Section 2 is devoted to the experimental description. Section 3 presents the results of the experiments. In Section 4, the conclusions are presented.

II. EXPERIMENTAL DETAILS

We studied glass-coated microwires (as cast and current annealed) with a $Fe_{3.85}Co_{67.05}Ni_{1.44}B_{11.53}Si_{14.47}Mo_{1.66}$ composition, a metallic nucleus diameter of d = 25.5 µm and a total diameter, including the glass coating, of D = 26.5

μm. The microwires were prepared by the Taylor–Ulitovsky method.

We represent the normalized magnetization, M/M_s as a function of the axial magnetic field, H, where M is the magnetic moment at a given magnetic field and M_s is the magnetic moment of the sample at the maximum magnetic field amplitude.

The study of the magnetization reversal on the surface of microwires has been performed by means of the optical polarizing magnetometer using the longitudinal Magneto-Optical Kerr Effect (MOKE) configuration [9].

Domain wall (DW) propagation is measured by using Sixtus–Tonks-like experiments. The magnetic field, *H*, is generated by a solenoid applying rectangular shaped voltage. Three pick-up coils are mounted along the length of the wire and propagating DW induces an electromotive force EMF in the coils (see scheme in Figure 1). Each pick-up coil is 2 mm long, the internal diameter is 1 mm, winding thickness is also 1 mm and it has 200 turns.

A pair of Helmholtz coils provided an axial magnetic field H_{ax}. The mechanical torsion stress has been applied. One of the wire ends was mechanically fixed, while the second end was rotary stressed to apply the stress with different angles. Also, tensile stress has been applied during the experiments.

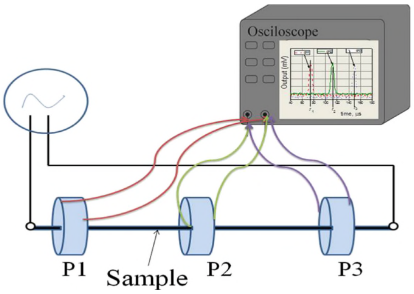

Figure 1. Schematic picture of modified Sixtus–Tonks setup.

III. MAGNETIC MEASUREMENTS

Figures 2 and 3 show the magnetic hysteresis loops obtained in the presence of torsion and tension stresses in as-cast and annealed microwires.

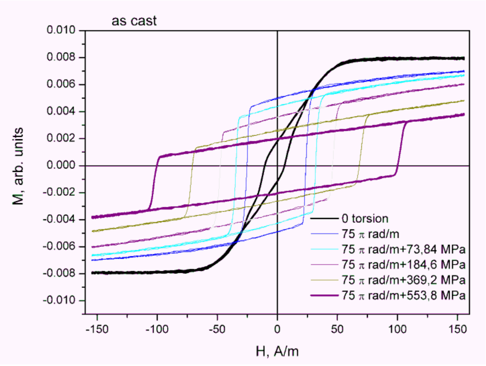

Figure 2. Hysteresis loops of as cast wire in the presence of torsion and tensile stresses.

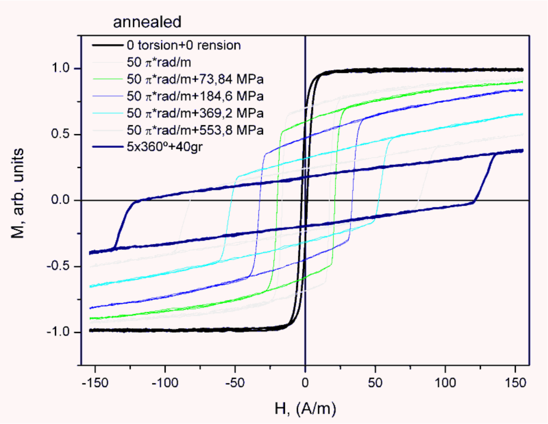

Figure 3. Hysteresis loops of annealed wire in the presence of torsion and tensile stresses.

Without stress, as-cast wire demonstrates a non-rectangular hysteresis loop while the annealed wire demonstrates an almost rectangular curve. In the presence of the stresses, the transformation of hysteresis in the two studied wires looks similar.

First, in the presence of the torsion stress, the hysteresis loop becomes clearly expressed as rectangular curve. Evidently this is related to the bistability effect. At the same time, it is known that the torsion stress induces the formation of the inclined helical structure. So, we could consider that here we observe the so called, helical bistability. Second, the application of tension induces the decrease of the remanent magnetization and the increase of the coercive field.

The observed decrease of the remanent magnetization and the increase of the coercive field must be attributed to the redistribution of internal stresses upon applied external stress and negative magnetostriction coefficient, λ_s, of the studied microwire. Thus, arising of the axial magnetic anisotropy upon torsion can be originated by negative λ_s – values. Such torsion induced axial magnetic anisotropy gives rise to magnetic bistability (rectangular hysteresis loops, see Figure 2). On the other hand, tensile stress, σ, dependence of the switching field, H_s, has been previously observed in microwires with spontaneous and stress-induced magnetic bistability [10][11]. Experimentally, roughly $H_s \sim \sigma^{1/2}$ has been explained considering the H_s relation to the domain wall energy involved in the re-magnetization process of magnetically bistable samples [11]. We can assume a similar mechanism in the present case considering that the magnetic bistability is induced by the torsion stresses and the tensile stress dependence is attributed to the stress dependence of the domain wall energy. On the other hand, considering commonly accepted domain structure of magnetic wires consisting of the axially magnetized inner core and outer domain shell [12], we can deduce that the outer shell volume increases upon tensile stresses. Such modification of the domain structure can be obtained from the relation between the radius of the inner axially magnetized core, R_c, and the wire radius R given by the squire-ness ratio, M_r/M_s as [12]

$$R_c = R(Mr/Ms)^{1/2}, \qquad (1)$$

Therefore, the observed tensile M_r/M_s stress dependencies must be associated with rising of the outer shell volume due to negative λ_s values of the studied microwire.

Figures 4 and 5 demonstrate the field dependencies of the DW velocity measured in two studied wires in the presence of the combination of the stresses.

The highest value of the velocity (about 1200 m/s) was obtained in as-cast wire in the presence of only torsion stress. The additional application of the tension increases the start field, shifting in such a way the velocity dependence along the field axis. Also, the decrease of the value of the velocity is observed.

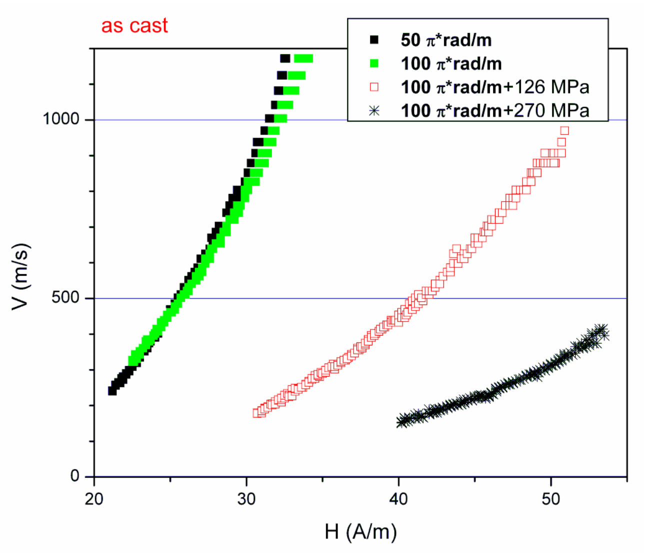

Figure 4. Magnetic field dependence of the DW velocity in the presence of torsion and tensile stresses (as cast wire).

The annealed wire shows a significantly lower value of the velocity (about 400 m/s) when the stresses were not applied. The application of the stresses causes the decrease of the velocity. The lowest value was obtained for the case of the combination of two types of the stresses.

The obtained dependencies of the DW velocity have found the explanation in the frame of the conception of the stress induced transformation of the magnetic structure in as-cast and annealed microwires, demonstrating the clear correlation with the magnetic hysteresis loops.

Measurement uncertainties of Sixtus–Tonks experiments were determined by the thickness of the pick-up coil and do not exceed the size of the experimental points in Figures 4 and 5.

Figure 6 shows the results of the simulation obtained for the different values of parameter ρ (ρ = R_c/R) that correspond, according to our approaching, to different values of torsion stress.

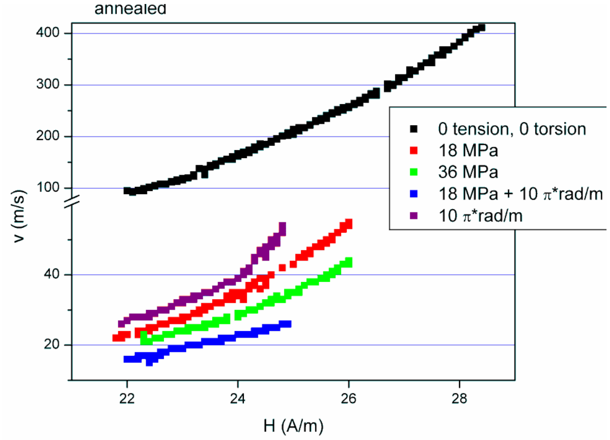

Figure 5. Magnetic field dependence of the DW velocity in the presence of torsion and tensile stresses (annealed wire).

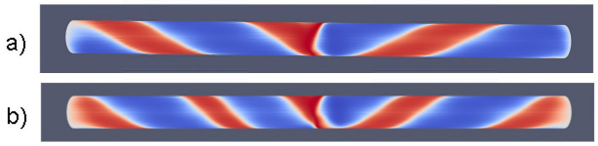

Figure 6. Calculated spiral domain structure obtained for different values of the parameter ρ: a) ρ=0.4, b) ρ=0.8.

The formation of the spiral DW on the wire surface is determined by the competition of different energy contributions: magnetic anisotropy, exchange and the magnetostatic energy. The angle of the DW inclination changes with parameter ρ.

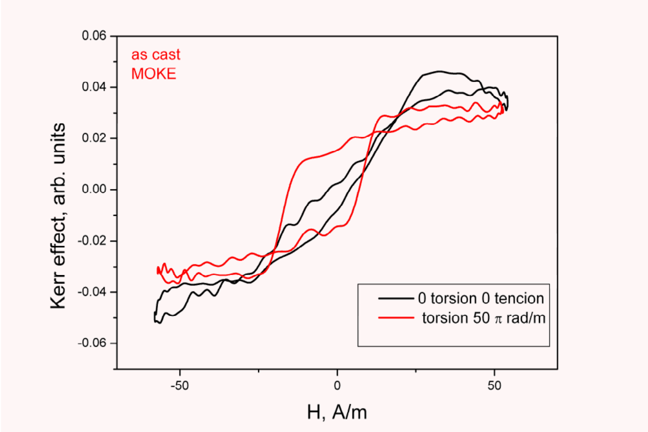

Figure 7. MOKE hysteresis loops of as cast wire in the presence of torsion stress.

Figure 7 demonstrates the independent confirmation of our concept. Here, we can see the torsion stress induced transformation of MOKE hysteresis loop. Torsion stress induces the appearance of a rectangular hysteresis loop. It means the formation of helical structure in the surface of the microwire. Therefore, the torsion stress produces the spiral helical structure in almost the whole thickness of the microwire.

IV. CONCLUSIONS

In this work, we propose a new method of control of the magnetic structure in magnetic microwires, which are the base elements of the magnetic sensors. The combination of the torsion and tension stresses gives a new understanding of the transformation of the magnetic structure. The combination of magnetic and magneto-optical techniques with the Sixtus–Tonks experiments permits us to select the predicted magnetic structures. The results of magnetic simulation confirm the validity of our conception.

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