Magnetic and sensitive magnetoelastic properties of Finemet nanostructured ribbon

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Abstract. Soft-magnetic Fe73.5Cu1Nb3Si13.5B9 (Finemet) ribbon has been fabricated by using melt-spinning techniques. After annealing at suitable temperature the ribbon changes from an amorphous to crystalline state which related to the formation of Fe nanocrystallites. Study on the magnetic and magnetoelastic properties of the ribbon is presented. Furthermore, based on the fabricated ribbon stress sensors are simply constructed. The sensors showed high sensitivity of 3.8 mV/MPa as well as a wide working range up to 17 MPa. These sensors are potential for practical applications such as detecting small stress and movement in civil structures.

Keywords: Magnetic and magnetoelastic properties, Finemet, nanostructured materials.

1. Introduction

Recently, interest in the development of magnetoelastic sensors has greatly increased because of their wide applications, such as for small magnetic field detection, stress, strain, pressure, displacement, and vibrations sensors [1-7]. It is well-known that a magnetostrictive material changes its size when placed in an external magnetic field. By applying a mechanical stress to the material, one observes an inverse magnetoelastic effect (namely the Villari effect) in which the magnetization direction varies leading to the variation of the induction and magnetic permeability. Consequently, an electromotive force is induced in a pick-up coil surrounding the material.

Fe-based amorphous alloys exhibit a good magnetic as well as magnetostrictive softness. In addition, they have also good mechanical properties. In the as-prepared alloys, however, the permeability easily reaches maximum at low stress and then the sensitivity is reduced at high stress. In order to extend the working range, suitable heat treatments or (Fe, Co)-based amorphous ribbons are usually used [8].

In this paper we present the study on crystallographic and micro-structure, magnetic and magnetoelastic properties of Fe73.5Cu1Nb3Si13.5B9 (Finemet) ribbon. In addition, the dependences of the stress sensor sensitivity on frequency and annealing temperature are also investigated.

2. Experimental

Fe73.5Cu1Nb3Si13.5B9 ribbon has been prepared by using melt-spinning technique. The purity of the starting elements was at least 99.9%, excepting Si and B (99.5%). In the melt-spinning process, the
bulk alloy was melted at 1450°C in a quartz tube under an Ar pressure of 0.5 atm and produced in ribbon form by rapid quenching on a Cu roller rotating at the speed of 2100 turns/minute. The typical dimensions of the as-prepared ribbon were 10 mm in width and 20 μm in thickness. Different strips cut from the same ribbon with 5 mm in width and 15 mm in length were submitted to the magnetoelastic measurement. For other analysis, the size of the ribbons were around 5×5 mm². Conventional annealing treatments have been performed in vacuum at different annealing temperatures (T_a) up to 550°C for 1h.

The crystallographic structure of the samples was characterized by using an X-ray diffractometer (XRD) Siemens D-5005 with CuKα wavelength. The microstructure was observed by means of a field emission scanning electron microscopy (FE-SEM) Hitachi S-4800. The magnetic hysteresis loops of the samples, measured at room temperature along and perpendicular to the ribbon surface, were carried out by using a vibrating sample magnetometer (VSM) Lake Shore 7404.

For magnetoelastic analysis, stress sensors have been constructed using the above 15 mm-length ribbon and a two-coil system, as shown in figure 1. At one end of the ribbon the excited coil produces an alternating magnetic field

\[ H = H_0 \sin(2\pi f_0 t) \]

in which \( H_0 \) is the amplitude of the exciting magnetic field and the frequency is tuned to the fundamental resonance frequency \( f_0 = v/2l \) (\( v \) is the sound velocity, \( l \) is the length of the ribbon) [9, 10]. Due to the magnetoelastic effect, the magnetic field induces an alternating strain \( \varepsilon \) that determines a local excitation propagating through the ribbon as a magnetoelastic wave. Then the magnetic component of the generated wave induces an electromotive force in the pick-up coil located at the opposite end of the ribbon. As a consequence of the inverse magnetoelastic effect, an alternating voltage can be detected as

\[ V(t) = V_0 \sin(2\pi f_0 t + \varphi) \]

where the voltage amplitude, i.e. the stress sensor’s signal \( V_0 \), can be expressed as

\[ V_0 = H_0 \mu k \left( \frac{E}{\rho} \right)^{1/2} \]

in which \( \mu, E, \rho \) and \( k \) are the ribbon’s magnetic permeability, Young’s modulus, mass density and magnetomechanical coupling factor, respectively.

When a stress is applied along the ribbon length, one can measure the change in the sensor’s signal \( V_0 \) as a function of external stress \( \sigma \).

**Figure 1.** Image of a used typical stress sensor.
3. Results and discussion
For as-prepared Finemet ribbon, a flat XRD pattern is observed indicating its amorphous state. After increasing annealing temperatures up to $T_a = 350^\circ$C, the XRD patterns are still almost flat although nanocrystallites may have formed during the heat treatment. Only at $T_a$ around 500$^\circ$C, some peaks clearly appear which corresponds to Fe nanocrystallites. These samples, however, were too brittle for other measurements.

The FE-SEM images of the ribbons, presented in figure 2, also confirmed the XRD result. As can be seen from this figure, the as-prepared sample has a homogeneous structure of amorphous state. Meanwhile after annealing at $T_a = 350^\circ$C for 1h the sample displays signs of crystallization. The influence of these different microstructures on the properties of the studied ribbons will be discussed later.

![Figure 2. FE-SEM images of the as-prepared Finemet ribbon (left-hand side) and after annealing at 350$^\circ$C for 1h (right-hand side).](image)

The in-plane and perpendicular magnetic hysteresis loops of the as-prepared and annealed ribbons, measured at room temperature, are plotted in figure 3. All samples show soft magnetic behavior in the in-plane, with the coercivity around 1 Oe. With increasing the annealing temperature, the saturation magnetization $M_s$ increases from 95 to 129 emu/g for the as-quenched ribbon and 350$^\circ$C-annealed one, respectively (see also table 1). This observation can be explained in terms of the formation of Fe nanocrystallites in the annealed sample.

![Figure 3. In-plane and perpendicular magnetic hysteresis loops of the as-prepared (left-hand side) and annealed ribbons (right-hand side).](image)
Figure 4 represents the stress sensor’s signal $V_0$ responding to longitudinal applied tensile stress $\sigma$ of the ribbon annealed at 250°C, measured at different frequencies. With increasing the applied stress, firstly the sensor signal linearly increases and then reaches saturation state. Besides, the stress sensor’s signal and therefore its change in the linear part, $\Delta V_0$, exhibit higher values at high frequency. From the slope of the linear part of the $V_0-\sigma$ graph, one can calculate the sensitivity of the stress sensor.

**Table 1.** Characterized parameters of the stress sensors based on Finemet ribbon.

| Sample       | $M_s$ (emu/g) | Maximum sensitivity (mV/MPa) | $\Delta V_0$ (mV) | Linear working range (MPa) |
|--------------|---------------|------------------------------|-------------------|-----------------------------|
| As-prepared  | 95            | 4.0 @ 150 kHz               | 17.8              | 4.5                         |
| $T_a = 150^\circ C$ | 98            | 3.1 @ 120 kHz               | 54.5              | 17.5                        |
| $T_a = 250^\circ C$ | 118           | 3.8 @ 180 kHz               | 82.0              | 21.5                        |
| $T_a = 350^\circ C$ | 129           | 1.4 @ 50 kHz                | 29.2              | 21.5                        |

![Figure 4](image.png)

**Figure 4.** Stress dependence of sensor signal of 250°C-annealed ribbon at different frequencies.

![Figure 5](image.png)

**Figure 5.** Stress sensor signal of as-prepared and annealed ribbons.

In figure 5 the stress dependences of the sensor signals of the as-prepared and annealed ribbons are plotted. These measurements are taken at frequencies around 150 kHz (excepting 350°C-annealed ribbon having a frequency of 50 kHz) at which the sensors exhibit maximum sensitivity. As indicated in table 1, the sensor using as-prepared ribbon displays highest sensitivity of 4.0 mV/MPa with a linear working range from 0 to 4.5 MPa. Meanwhile for the 250°C-annealed ribbon, a considerable change in the voltage amplitude $\Delta V_0 = 82$ mV is obtained, resulted in a comparable sensitivity of 3.8 mV/MPa. Furthermore, the working range is also extended four-times, from 0 to 21.5 MPa. This sensitivity is in the same order as the previous result for Fe-Co-Si-B ribbon [8]. The results obtained on the Finemet ribbon meet the requirements for application as high-sensitivity stress sensors.

**4. Conclusions**

The stress sensor is constructed using the as-prepared and annealed Finemet ribbons. The sensor based on 250°C-annealed ribbon exhibits a high sensitivity of 3.8 mV/MPa as well as a linear stress dependence up to almost 22 MPa. These stress sensors are potential for practical applications such as detecting small stress and movement in civil structures.
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