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THE INFLUENCE OF MICROSTRUCTURE ON COMPRESSIVE STRESS CHARACTERISTICS OF THE FINEMET-TYPE NANOCRYSTALLINE SENSORS

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Due to the low magnetocrystalline anisotropy nanocrystalline alloys are very promising as core materials for magnetoelastic stress and force sensors. In this paper the compressive stress characteristics of the FINEMET-type ($Fe_{73.5}Si_{13.5}Nb_3Cu_1B_9$) nanocrystalline sensors is investigated as a function of the parameters of nanocrystalisation process. Special force converter was developed to achieve uniform distribution of stress through the length of magnetic circuits. The stress sensitivity of nanocrystalline alloys was found to be higher at small values of the magnetizing field.

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1. Introduction

The mechanical stress changes the magnetization process of the soft magnetic material. This effect, known as magnetoelastic Villari effect, is especially important in the case of FINEMET-type ($Fe_{73.5}Si_{13.5}Nb_3Cu_1B_9$) nanocrystalline alloys, where the magnetocrystalline anisotropy is low due to the exchange averaging [1] and the proportion of magnetoelastic energy in the total free energy is especially significant. As a result such materials are expected to be highly stress-sensitive.

Magnetoelastic Villari effect may be observed as a change of the value of flux density B achieved in the nanocrystalline core for a given value of magnetizing field H [2]. The magnetoelastic Villari effect enable construction of the novel, cost-effective as well as highly sensitive stress, and force sensors. These sensors may operate in a wide range of temperatures, limited only by the Curie temperature.

To optimize the magnetoelastic Villari effect in the nanocrystalline materials it's dependence on structural properties is necessary to be investigated. In this paper a toroidal sensor prepared from Finemet ribbon will be investigated as a function of the nanocrystallizing heat treatment.

2. Experimental

In construction of the highly sensitive magnetoelastic sensor cores with closed magnetic circuits should be utilized. Open magnetic circuit would lead to decreasing of sensitivity of the sensor due to the appearance of demagnetization energy in total free energy of the core.

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The idea of novel method of the applying the compressive stress to the ring-shaped sensing element is presented in Fig. 1. In this method the compressive force F is applied to the ring-shaped cores perpendicularly to the magnetizing field H [3]. In such case uniform, compressive stress σ can be reached on the all length of the magnetic circuit of the sensing element. Moreover commercially available, ring shaped cores can be used as the magnetoelastic stress and force sensors.

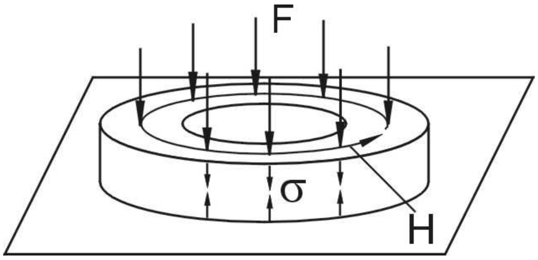

Fig. 1. Sketch of applying the compressive stress to the ring-shaped stress sensor.

The special device [4] for applying stresses to the sensing element is presented at Fig. 2. Base backings (1) allow a ring core (3) to be subjected of the compressive force F. Due to the special, nonmagnetic cylindrical backing (2) the distribution of stresses in the core is uniform. Measuring and magnetizing windings are placed in grooves (2a) at the cylindrical backings (2).

In this method of applying stresses both of bulk material rings and ribbon ring cores can be investigated. Because of uniform distribution of stresses in the sample the local high stresses are absent. So a brittle material can also be investigated.

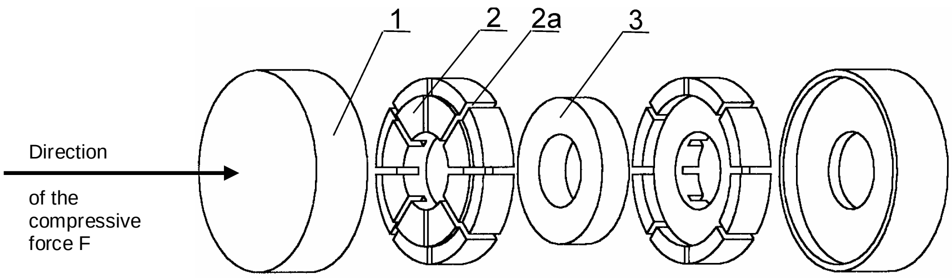

Fig. 2. Device for applying the compressive stress to the ring-shaped sensing element (Patent pending P-345758) [4]. 1 – base backing, 2 – nonmagnetic cylindrical backing, 2a – grooves for windings, 3 – magnetoelastic sensing element.

Presented method creates the new possibilities in the field of both construction of magnetoelastic stress and force sensors, as well as investigation of the influence of stresses on the functional properties of the cores of the inductive components of mechatronic devices.

The hysteresis loop were determined using digitally controlled measuring installation. This system enabled both applying the mechanical stresses to the sample as well as measuring of the magnetic properties of the sensing elements. PhilipsX'pert powder diffractometer with Cu_{α} radiation was used to determine the crystalline/residual amorphous fraction in the two phase nanocrystalline FINEMET samples obtained after different annealing treatments.

3. Results

The magnetoelastic investigation was carried out on FINEMET type $Fe_{73.5}Si_{13.5}Nb_3Cu_1B_9$ alloy. The nanocrystallline structure [5] was achieved by thermal annealing in three different conditions: sample no 1 was annealed in 510 °C for 0.5 hour, sample no. 2 in 530 °C for 1 h and sample no. 3 in 540 °C for 1 h. The X-ray diffractograms are presented in Fig. 3.

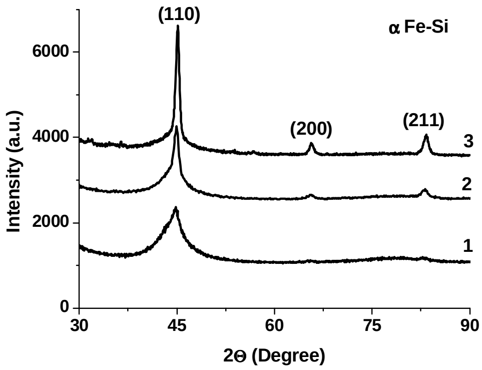

Fig. 3. X-ray diffraction patterns after different annealings: 1) 510°C /0.5h, 2) 530 °C/1h, 3) 540 °C/1h.

The volume fraction, x, of the nanocrystalline phase was estimated using a peak fitting module which enabled to decompose the first peak into the (110) reflection of the α-Fe(Si) crystalline phase, fitted by pseudo-Voigt function, and an amorphous phase halo, fitted by a Gauss function. The ratio of the integral intensities was taken equal to the ratio of the corresponding phases. In addition the gravity center and the half with at half amplitude have been determined for 3 other reflections in order to estimate the grain size (by Halder –Wagner method) and residual strain (by Hall-Williamson method). The sample annealed at 510 °C for 0.5 h remained practically amorphous; the proportion of the crystallized phase could not be appreciated. For the samples annealed at 530 and 540 °C the crystalline fraction was about 49.% and 75%. For these latter samples the average grain size and average residual strain was also determined and was found to be about 12 and 20 nm, and 0.05% and 0.4 %, respectively.

The influence of compressive stresses σ on the magnetic hysteresis loop B(H) of the ring-shape sensing element is presented in Fig. 4. The compressive stresses σ produce the decrease of the flux density B and considerable change of the form of the hysteresis loops.

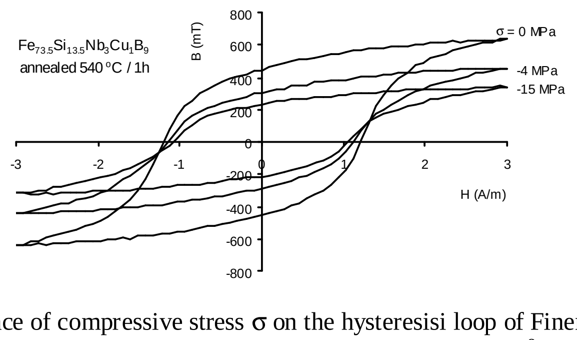

Fig. 4. The influence of compressive stress σ on the hysteresisi loop of Finement type $Fe_{73.5}Si_{13.5}Nb_3Cu_1B_9$ alloy in nanocrystalline state (annealed in 540 °C for 1 h).

In the Fig. 5 the influence of the compressive stress σ on the value of relative changes of the flux density B(σ)/B(σ=0) presented for a magnetizing field H_m three times higher than coercive field H_c of each sensing element. The most significant decreasing of permeability (up to 40 %) were observed for the fully nanocrystallized sensing core material.

Presented relative changes of flux density B(σ)/B(σ=0) as a function of the compressive stress describe magnetoelastic, functional properties of the sensing element. These properties determine character and value of output signal from the magnetoelastic sensor with sensing elements annealed at different temperatures.

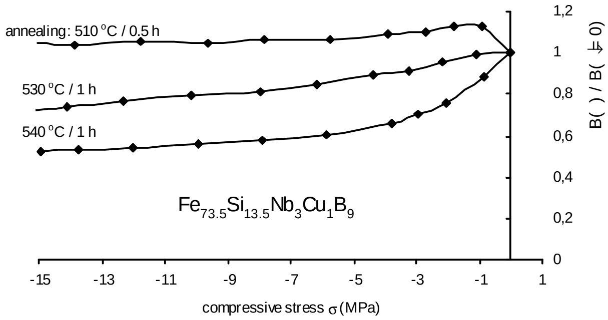

Fig. 5. Relative changes of flux density B(σ)/B(σ=0) as a function of the compressive stress σ, for ring-shaped sensing elements annealed at different temperatures.

4. Discussion

The presented results of the X-ray studies confirmed that thermal annealing conditions have significant influence on the structure of nanocrystalline sensing elements. It was observed that the increasing of annealing temperature causes increasing amount of nanocrystalline phase in the alloy.

Moreover, it was observed that increasing of annealing temperature (and increasing of nanocrystalline phase) causes the increasing of stress sensitivity of the sensing elements. The highest stress sensitivity was observed in the case of fully nanocrystalline core, annealed in the temperature 540 °C for 1 hour. In the case of sensing element annealed in such conditions the changes of value of flux density B up to 40% was observed. Moreover for sample annealed at the temperature of 540 °C for 1 hour monotonous magnetoelastic characteristic was observed. For this reason such sensing elements are more suitable than sensing elements annealed at lower temperature, where the maximum on the magnetoelastic characteristic (so called Villari reversal) was observed.

It should be also highlighted that fully nanocrystalline material (annealed at the temperature 540 °C for 1 hour) is commonly used for cores of the inductive components. Observation that such material has the highest stress sensitivity is very important from the practical point of view. For this reason should be taken in consideration by both constructors and users of inductive components based on the nanocrystalline magnetic cores.

In the same compositions the authors from [6] have found that addition of RE elements strongly influences the phase structure during annealing of melt spin ribbons and this can suggest a possibility to control the properties of FINEMET nanocrystalline sensors.

5. Discussion and conclusion

1. The highest stress sensitivity was observed in a case of fully nanocrystalline sensing elements (annealed in the temperature 540 °C for 1 hour).
2. Magnetoelastic characteristic of fully nanocrystalline sensing element is monotonous.

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