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Temperature Dependence of the Magnetostriction and the Induced Anisotropy in Nanocrystalline FeCuNbSiB Alloys, and their Fluxgate Properties

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Abstract - Making use of the stress induced magnetic anisotropy in some iron-rich FeCuNbSiB nanocrystalline materials we studied the thermal dependence of their magnetostriction which becomes zero below the Curie temperature. The choice of a suitable composition and annealing temperature results in materials with zero magnetostriction at room temperature. Due to the low magnetostriction these materials have very promising fluxgate properties which were studied as well.

I. INTRODUCTION

Nanocrystalline FeCuNbSiB alloys, produced by crystallizing amorphous alloys [1], have promising application potentials mainly due to their softness. A second feature which makes them attractive is their ability of being tailored according as which magnetic properties are the most suitable for the application in question.

Here we focus on the properties which are important for applications as core material in high-sensitive magnetic field sensors, the so-called fluxgates. These sensors require magnetic materials with high susceptibility, low magnetostriction and low Barkhausen noise. To some degree these requirements are conflicting because a high susceptibility (easy magnetization axis) inherently is accompanied by domain wall movements which constitute the origin of the Barkhausen noise. In low-susceptibility (hard magnetization axis) materials, on the contrary, the magnetization process may be dominated by coherent spin rotations which are free of Barkhausen noise.

A magnetic anisotropy in FeCuNbSiB nanocrystals may be induced during the crystallization process by applying a magnetic field of which the direction becomes the easy axis direction [2]. The anisotropy may also be induced by applying a mechanical stress during the crystallization. In this case the direction of the tensile stress axis becomes the hard magnetic axis.

The magnetostriction undergoes a substantial change upon the formation of the nanocrystalline state. Depending on the composition and the annealing temperature the magnetostriction coefficient λ_s decreases from about 23×10^{-6} to a value between 10×10^{-6} and -2×10^{-6} [2].

In the present work we studied the magnetostriction and the induced anisotropy in materials with either positive or negative magnetostriction coefficients in the nanocrystalline

state. The influence of crystallization on the fluxgate properties (Barkhausen noise) was furthermore studied in fluxgates of the ringcore type.

II. MAGNETOSTRICTION AND ANISOTROPY

The magnetostriction in FeCuNbSiB nanocrystalline materials, produced by annealing amorphous ribbons, depends on the thermal treatment. Figure 1 shows, for two compositions with different Si/B ratios, the annealing temperature dependence of the magnetostriction coefficient λ_s measured at room temperature.
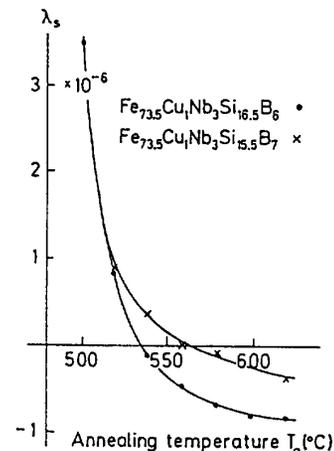

Fig.1 Annealing temperature dependence of λ_s measured at room temperature for two nanocrystalline materials after 1 h annealing.

Anisotropic nanocrystalline materials were produced by annealing under a mechanical tensile stress amorphous ribbons of the compositions $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ($\lambda_s > 0$) and $Fe_{73.5}Cu_1Nb_3Si_{16.5}B_6$ ($\lambda_s < 0$). The induced magnetic anisotropy has a hard axis along the ribbon axis [3], thereby making it possible to determine negative as well as positive magnetostriction coefficients from the applied stress (σ) dependence of the magnetic susceptibility χ:

$$\lambda_s = (-1/3)\mu_0 M_s^2 d\chi/d\sigma$$

where M_s is the saturation magnetization.

The magnetostriction λ_s, the saturation polarization J_s ($=\mu_0 M_s$), the susceptibility χ, the coercivity H_c and the remanence to saturation ratio J_r/J_s were measured in the nanocrystalline phase from room temperature up to the temperature used to (nano)crystallize the ribbons. Figure 2 shows the temperature dependence of these parameters for $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$.

For this alloy the Curie temperature in the amorphous phase is $T_C^{am} = 313$ °C. Below T_C^{am} the magnetization curve is practically without hysteresis, and linear up to saturation, giving a well defined susceptibility χ. This means that the induced anisotropy is $K_u = \frac{1}{2}J_s^2/\mu_0\chi$, and we find that the anisotropy decreases monotonically from 661 J/m³ at room temperature to 174 J/m³ at T_C^{am}. Above T_C^{am} a pronounced hysteresis developes up to a maximum before the temperature of nanocrystallization.

A similar behavior is observed for the negative magnetostriction alloy ($T_C^{am} = 318$ °C), except that $|\lambda_s|$ reveals a maximum before reaching zero, see figure 3. At room temperature this alloy has a very small positive magnetostriction crossing zero at about 50 °C.

In both cases we were looking for a balance in magnetostriction between the α-FeSi grains (negative) and the residual amorphous matrix (positive) [2]. If the balance exists we expected in both cases to find a negative magnetostriction
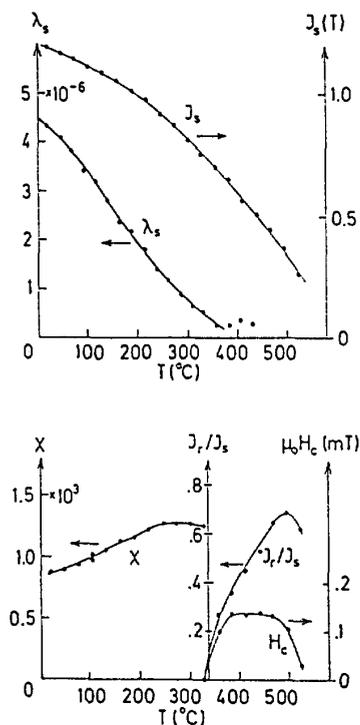

Fig. 3. $Fe_{73.5}Cu_1Nb_3Si_{16.5}B_6$. Temperature dependence of various magnetic properties after stress annealing 1 h at 530 °C with applied stress = 70 MPa.
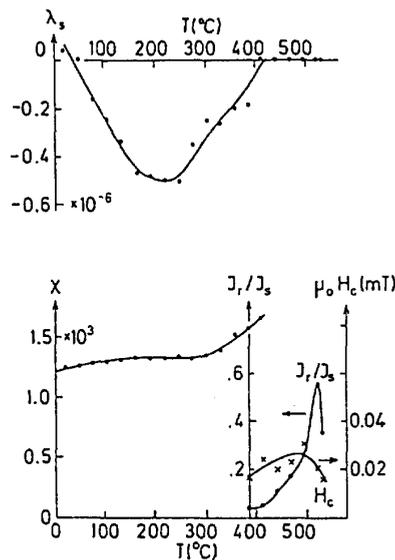
above the amorphous Curie temperature. This behavior, however, was *not* observed in our experiments which revealed magnetostrictions very close to zero at temperatures between the amorphous and the crystalline Curie temperatures.

III. FLUXGATE PROPERTIES

The properties studied so far indicate that these materials may be suitable as core material in sensitive fluxgate sensors of which the core should have a low (zero) magnetostriction. If a high field resolution is required the core must furthermore have a low magnetic (Barkhausen) noise level which was studied in a fluxgate of the ringcore type, see figure 4.

The sensor was produced with a 0.022 mm thick, 2 mm wide ribbon of amorphous $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ as core material. The ribbon was wound with 7 wraps inside a stainless steel support, and the innermost wrap was kept in position by an open-ring shaped spring of stainless steel.

Because of the brittleness of the crystallized sample the crystallization process must be performed after mounting the ribbon in the bobbin. Attempting to suppress the Barkhausen noise we furthermore want the presence of a (weak) hard ribbon axis anisotropy. This was induced by exposing the sensor to a transverse field during the crystallization.

Fig. 2. $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$. Temperature dependence of various magnetic properties after stress annealing 1 h at 530 °C with applied stress = 70 MPa.

Fig. 4. Ringcore fluxgate. The 17 mm ringcore which is supplied with 220 excitation windings, excitation coil is situated in a 25 x 25 x 8 mm³ detector coil supplied with 400 windings.

Detector coil
Support with excitation coil
Magnetic core
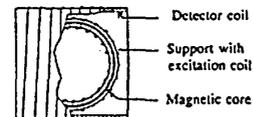
The anisotropy may influence the sensitivity of the fluxgate. For a hard ribbon axis material with constant relative susceptibility χ up to the saturation magnetization M_s it is easily shown [4] that the output detector voltage E from the sensor excited with the angular frequency ω is given by

$$E = (8/\pi)\mu_0 H_a NA\omega\chi \sum_{n=2,4,...} a_n \sin(n\omega t)$$

with

$$a_n = (-1)^{n/2}\sin(nM_s/\chi H_{ex})$$

where H_a is the applied (external) field, N is the number of detector turns, A is the cross section area of each core and H_{ex} is the amplitude of the sinusoidal excitation field.

In this expression the multiplier preceding the summation includes χ whereby the voltage E (sensitivity) apparently is reduced due to the induced hard ribbon axis anisotropy. In our case, however, the susceptibility after the transverse field annealing is so large ($\chi \sim 10.000$) that the dependence on χ cancels through the small a_n-values.

The sensor, situated in a zero-field chamber consisting of a 6 layer μ-metal shielding, was used in the feedback magnetometer described in reference [4].

The magnetometer output for the amorphous core sensor (*before* crystallization) is shown in figure 5(a). The sensor is exposed to a 16 nT field of square waveform. The noise in this signal is 3.0 nT (rms 0.06-10 Hz) as measured by an FFT analyzer.

After crystallization (1h at about 550 °C) in a transverse field (perpendicular to the ring plane) we obtain the magnetometer output shown in figure 5(b). The output is obtained at conditions identical with those leading to figure 5(a), but the noise level has decreased from 3.0 nT rms for the amorphous core to 0.055 nT rms for the crystallized core.

A second sensor with $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ as core material was produced with the same core cross section as the one in figure 5. Experiments like those described above showed qualitatively the same behavior, and an improvement of the noise level to 0.040 nT, probably due to the zero magnetostriction for the annealed material.

IV. CONCLUSION

From the temperature dependence of the magnetostriction coefficient it can be concluded that the magnetic behavior of FeCuNbSiB nanocrystalline materials is more complicated than a simple superposition of the properties for the individuel constituents. The magnetostriction becomes zero far below the Curie temperature.

The nanocrystalline materials have very promising fluxgate properties. Their noise level is comparable to the best permalloy materials.

Fig. 5. Output from the magnetometer supplied with a fluxgate sensor containing a $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ribbon as core material. The sensor is exposed to a 0.08 Hz magnetic field (16 nT p-p) of square waveform.
a) as quenched (amorphous)
b) annealed 1 h at about 550 °C in transverse field

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[4] O.V. Nielsen, J.R. Petersen, A. Fernando, B. Hernando, P. Spisak, F. Primdahl, and N. Moser, "Analysis of a fluxgate magnetometer based on metallic glass sensors," *Me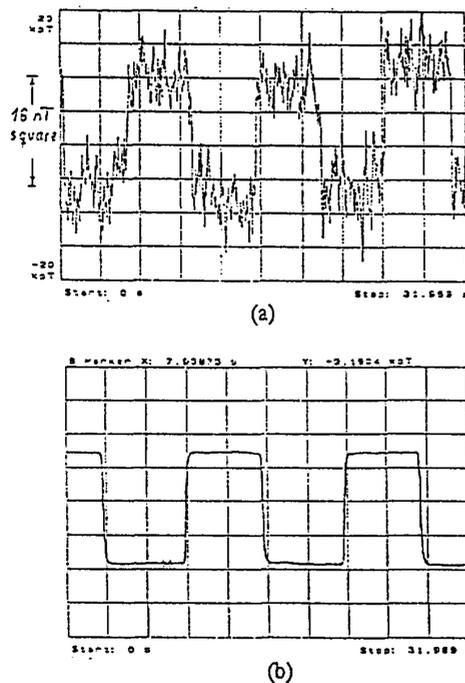as. Sci. and Technol.*, vol. 2, pp. 435-440, 1991.