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The temperature dependence of the magnetoelastic characteristics of cores for force sensors utilizing $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy

ROMAN SZEWCZYK[1,*], ADAM BIEŃKOWSKI[2] and JACEK SALACH[2]
[1]Industrial Research Institute for Automation and Measurements, Al. Jerozolimskie 202, 02-486 Warszawa, Poland
[2]Institute of Metrology and Measuring Systems, Warsaw University of Technology, sw. A Boboli 8, 02-525 Warszawa, Poland
[*]Corresponding author. E-mail: rszewczyk@onet.pl

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Abstract. This paper presents the results of investigation on the influence of temperature on magnetoelastic characteristics of the two ring-shaped cores, made of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy. The cores were annealed for 1 h at 350 and 400°C, respectively. The compressive force F was applied perpendicular to the direction of the magnetizing field H in the sample. Special cylindrical backing enables application of the uniform compressive stress σ to the wound ring sample. A resistive furnace heated the experimental set-up. Results presented in the paper indicate a significant influence of the temperature on the magnetoelastic characteristics of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy. Information about the magnetoelastic characteristics of this material may be useful in the magnetoelastic sensor development. Also this will create new possibilities in the development of physical model of magnetoelastic effect.

Keywords. Magnetoelastic effect; amorphous alloys; temperature.

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1. Introduction

The magnetoelastic effect may be defined as the changes of flux density B in the material (achieved for a given value of magnetizing field H_{m}) under the influence of mechanical stresses σ, caused by external force F. The $B(\sigma)_{H_{\mathrm{m}}}$ characteristics describe magnetoelastic properties of the material [1]. Sometimes a peak on the $B(\sigma)_{H_{\mathrm{m}}}$ characteristic may be observed. This extreme is known as the Villari point [2]. It was confirmed, that for compressive stress σ causing the Villari point, magnetostriction λ_s of the material changes its sign [3].

Changes of the magnetic state of the material subjected to stresses from external forces are very important from the practical point of view. Magnetoelastic effect is particularly important in the case of amorphous alloys [4–6]. Due to the lack of magnetocrystalline anisotropy [7] (caused by amorphous structure), as well as large initial permeability [8] (connected with the small value of the total anisotropy of the material) amorphous magnetic alloys are very sensitive to stresses caused by external forces [9]. It should be noted that such external forces might be applied to the amorphous alloy accidentally during the assembly process of inductive components with amorphous core or by thermal expansion of the material during the normal operation of the component. Stresses applied to the material may be especially large in the case of miniature components where even small forces may cause significant stresses.

On the other hand, a significant magnetoelastic effect observed in the amorphous alloys may be technically utilized in the development of robust and cost-effective force sensors [10]. Such sensors exhibit distinguished changes of measuring signal under the external force. It should be mentioned that even the signal from semiconductor strain gauges changes less than 1%, whereas permeability of amorphous alloys subjected to stresses may change up to 80% under stresses up to 10 MPa [11].

One of the most significant limitations in the practical, industrial application of amorphous alloys as cores of force sensors is the temperature dependence of their magnetoelastic characteristics. It is commonly known that magnetic properties of amorphous alloys depend significantly on temperature, even if the temperature is much lower than the Curie temperature [8]. Unfortunately, the results of experimental investigation on the temperature dependence of magnetoelastic characteristics of amorphous alloys were not presented before.

Lack of such experimental results is an important barrier in the development of stress and force sensors with amorphous alloy cores. Moreover, the information on the temperature dependence of magnetoelastic characteristics may be important for theoretical analyses of the physical background of the magnetoelastic effect.

2. Experimental method

Investigation on the temperature dependence of the magnetoelastic characteristics requires a methodology enabling achievement of uniform stresses σ in the ring-shaped amorphous core. Moreover, the investigated core has to be wound by a magnetizing and sensing winding, to measure the magnetic hysteresis loop. Method enabling magnetoelastic tests of the ring-shaped amorphous alloy core was developed previously [11]. A device for the practical realization of magnetoelastic investigation is presented in figure 1.

The compressive force F is applied to the investigated ring-shaped core (1) through base backings (3). Measuring and magnetizing windings are placed in grooves (2a) of the special, non-magnetic cylindrical backings (2).

This method allows measurement of magnetoelastic characteristics of both bulk material rings and ribbon ring cores. It should be highlighted that device based on the idea presented in figure 1 enables also measurements of the influence of torque on magnetic characteristics of the ring-shaped cores [13].

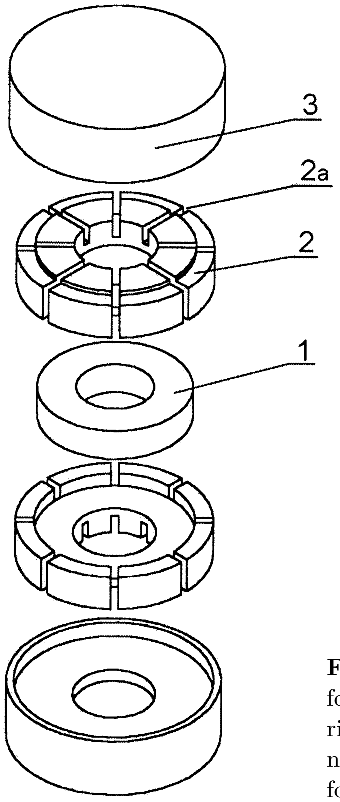

Figure 1. Schematic diagram of the device for applying uniform compressive stress to the ring core [12]. (1) Investigated ring core, (2) non-magnetic cylindrical backing, (2a) grooves for windings, (3) base backings.

Practical realization of the device for magnetoelastic tests of ring-shaped cores made of amorphous alloys is presented in figure 2. Device (5) presented in figure 1 was mounted in a resistive furnace (2). The furnace uses bifilar resistive coil to avoid the generation of additional magnetic field during the heating. Temperature of the core was measured using a resistive thermometer, whereas compressive force F was generated by a hydraulic press (1) and measured by strain-gauge transducer (3). Compressive force F was transmitted to the device through ball joints (6) to avoid bending of the device that could have resulted in the generation of additional, non-uniform stresses in the investigated core.

3. Results

The experiment was performed on the two ring-shaped $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous ribbon cores. The thickness of the ribbon was about 25 μm. Cores were annealed at 350 and 400°C respectively. The outside diameter of the sample was 32 mm, the inside diameter 25 mm and the height 8 mm. Measurements of the magnetoelastic characteristics were performed at 100 and 140°C for both the samples.

The influence of the compressive stress on the quasistatic hysteresis loop of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy cores is presented in figure 3. As can be seen,

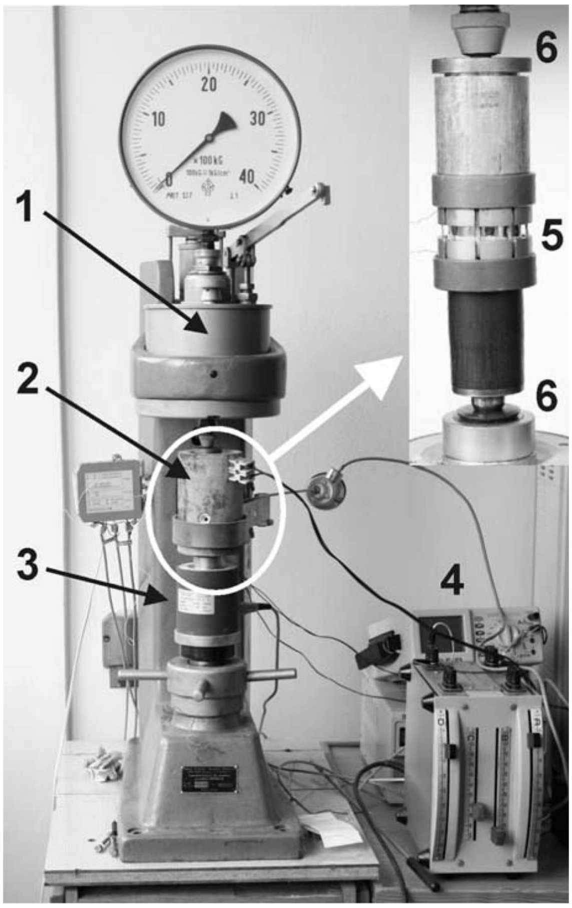

Figure 2. System for magnetoelastic tests of ring-shaped cores: (1) hydraulic press, (2) resistive furnace with device presented in figure 1, (3) strain-gauge force transducer, (4) furnace control unit, (5) core in backings (as presented in figure 1) and (6) ball joints.

increasing the compressive stress σ from 0 to 10 MPa causes an increase of the flux density B, from 135 to 415 mT for the sample annealed at 350°C (figure 3a), and from 340 to 620 mT for the sample annealed at 400°C (figure 3b).

The temperature dependence of the magnetoelastic characteristics, given as the changes of the flux density B under the influence of compressive stress σ (for constant values of the magnetizing field H_{m}), is given in figure 4. For both the cores, the magnetoelastic characteristics are monotonous. However, for the core annealed at 350°C for 1 h (figure 4a) crossings between characteristics measured at 100 and 140°C were observed for both magnetizing fields H_{m}. This phenomenon was not observed in the case of the core annealed at 400°C (figure 4b), probably due to the decrease of total anisotropy K_{an} in the core annealed at higher temperature as well as due to the decrease of the temperature sensitivity of anisotropy in this core. In

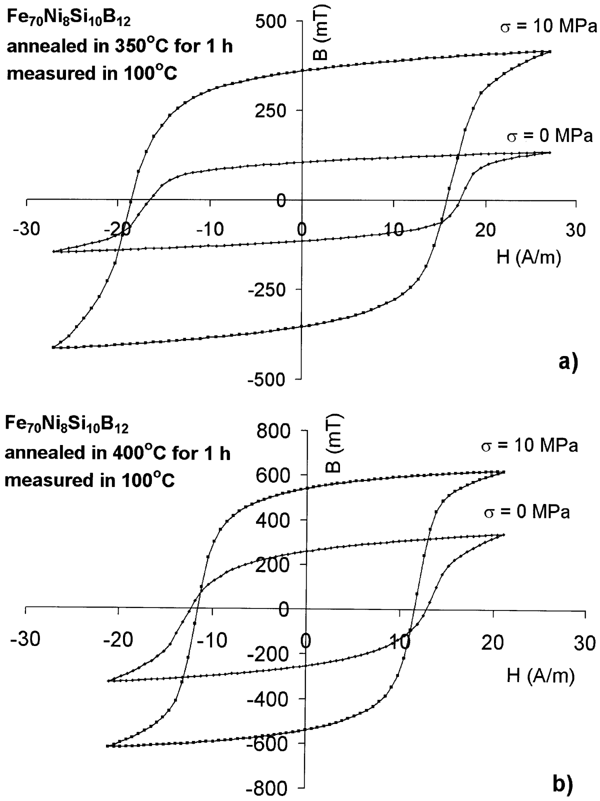

Figure 3. The influence of compressive stress σ on the magnetic hysteresis loop $B(H)_\sigma$ of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy cores annealed at (**a**) 350°C and (**b**) 400°C for 1 h (measured at 100°C).

this case the magnetoelastic characteristics $B(\sigma)_H$ are similar, but shifted by about 50 mT.

It should be pointed out that the presented experimental results confirm high stress sensitivity of cores made of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous ribbon, annealed at 350 and 400°C. For both the cores subjected to compressive stresses σ up to 10 MPa, increase of flux density about 140 and 95%, respectively was observed. These results confirm the fact that amorphous alloys have a great potential in the development of magnetoelastic force and stress sensors.

4. Conclusion

The methodology presented in the paper creates new possibility of testing the temperature dependence of magnetoelastic characteristics. In this methodology, uniform distribution of stress from compressive force is achieved and the temperature is controlled by the resistive furnace with bifilar coil.

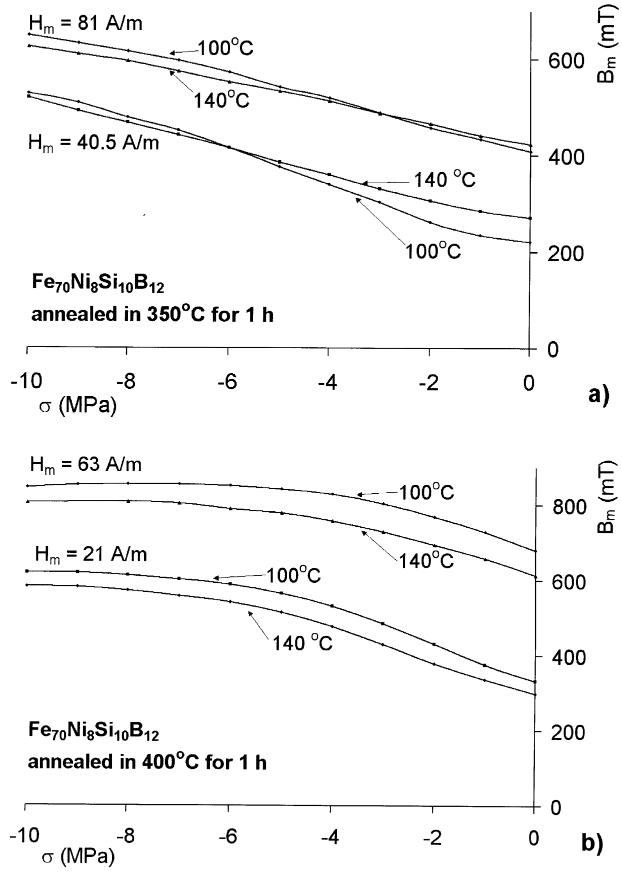

Figure 4. The temperature dependence of magnetoelastic characteristics $B(\sigma)_{H_m}$ of $Fe_{70}Ni_8Si_{10}B_{12}$ amorphous alloy cores annealed at (**a**) 350°C and (**b**) 400°C for 1 h.

The results of this investigation confirm the high stress sensitivity of amorphous ribbon cores made of $Fe_{70}Ni_8Si_{10}B_{12}$ annealed at 350 and 400°C. Under the influence of compressive stress up to 10 MPa, value of the flux density B in the core increases up to about 140%.

Unfortunately, the experimental results indicate that it is difficult to predict *a priori* the influence of temperature on the magnetoelastic characteristics of amorphous alloys. This fact is especially noticeable for the core annealed at 350°C where magnetoelastic characteristics measured at 100 and 140°C cross each other. This observation implies the necessity of using more sophisticated models (such as Jiles–Atherton–Sablik model) for the calculation of the temperature correction factors of magnetoelastic force sensors.

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