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Complex Magnetoimpedance in Joule-Heated $Co_{71,1}Fe_{3,9}Si_{10}B_{15}$ Microwires

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Complex magnetoimpedance study is an alternating current technique that can be used to probe some properties of magnetic materials. We report on complex impedance measurements in low-negative magnetostrictive ferromagnetic CoFeSiB microwire. In these wires, the domain structure consists of two parts: an inner core, with domains oriented to the longitudinal direction of the wire, and an outer shell with circumferentially oriented domains. This magnetic structure is modified by AC current flowing through the microwire which produces an additional circumferential magnetic field $H_{\Phi}$and significantly affects magnetic structure inside the wires. The additional circular magnetization process in wires was studied by impedance measurements as a function of the amplitude and the frequency of the AC current after gradual Joule heating. Changes in the magnetization processes are reflected in the real permeability values and loss factor values.

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1. Introduction

Glass-coated ferromagnetic microwires are desirable for a variety of technological applications. Co-rich amorphous alloys with nearly-zero magnetostriction coefficients has gained a special importance in the field of applied magnetism because exhibit soft magnetic properties and highest giant magnetoimpedance (GMI) effect. The impedance in ferromagnetic conductor is strongly dependent on its magnetic permeability. The main factors contributing to the permeability are domain configuration and the preponderant magnetization process. In low-negative magnetostrictive wire, the domain structure consists of two parts: an inner core, with domains oriented to the longitudinal direction of the wire, and an outer shell with circumferentially oriented domains. This is the consequence of mutual influence between the tensile stress, induced in the wire production process, and the negative magnetostriction that leads to an alignment of the magnetic moments in a circumferential direction. The magnetic structure is modified by AC current flowing through the microwire which produces an additional circumferential magnetic field. Therefore, the circular magnetization process in wires can be studied by impedance measurements as a function of the amplitude and the frequency of the AC current. Experiments using complex impedance give information about the magnetization processes. The real and imaginary parts of impedance can be transformed into imaginary and real parts of permeability and the obtained results can be interesting in terms of the domain wall dynamics study [1].

In our paper, we report on complex impedance measurements as a function of the circumferential magnetic field H_{Φ} produced by AC current flowing through the microwire. Effects of the gradual change in the structure and crystallization as a consequence of the Joule-heating in the circular permeability dependences were studied.

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2. Theory

Magnetic field H_{Φ} generated by AC current has a circular geometry and significantly affects magnetic structure inside the wires with circumferential domain structure. This nonhomogeneous circular field increases amplitude with intensity of AC current and with the distance to the wire axis. The maximum H_{Φ} is therefore on the surface of the wire. The mean AC circular field H_{Φ} can be calculated using equation

$$H_{\Phi} = 3\sqrt{2} I_{AC}/\,(16\pi r)\,, \qquad (1)$$

where I_{AC} is the amplitude of the AC current and r is the radius of the wire [2, 3]. Complex impedance is given by equation

$$Z = R + \mathrm{j}X = R + \mathrm{j}\omega L. \qquad (2)$$

In the low frequency case, where the skin depth is larger than the radius of the wire, $\delta \gg r$, is $X = \omega L$, $\mathrm{j} = \sqrt{-1}$ is the imaginary number.

There is a relationship between complex impedance, complex inductance L and complex circular permeability μ. In the simplest case (permeability is proportional to inductance through geometrical factor G), real and imaginary part of permeability are obtained from impedance by the relation

$$\mu = \mu_{\mathrm{Re}} - \mathrm{j}\mu_{\mathrm{Im}} = GL = -jGZ/\omega, \qquad (3)$$

where the real part and the imaginary part of permeability are μ_{Re} and μ_{Im}, $\omega = 2\pi f$ is the angular frequency and G is the geometric constant [4].

In the case of ferromagnetic materials, the inductance L is proportional to the permeability of the material and the resistance term R is associated with the difficulty of domain reorganization. Real and imaginary μ components correspond to the effective magnetization and to the magnetic losses. They can be calculated using relations [2]:

$$\mu_{\mathrm{Re}} = X\frac{8\pi}{\omega l}, \quad \mu_{\mathrm{Im}} = (R - R_{DC})\frac{8\pi}{\omega l}, \tag{4}$$

where R_{DC} is the DC resistance of the alloy and l the sample length.

Losses in alternating magnetization are calculated using equation

$$\tan\delta = \frac{\mu_{\mathrm{Re}}}{\mu_{\mathrm{Im}}}. \tag{5}$$

3. Experiment

The experiments were carried out on amorphous ferromagnetic glass-coated microwires of nominal composition $Co_{70.5}Fe_{4.5}Si_{15}B_{10}$, prepared by the Taylor–Ulitovsky technique. The measured sample was of 9 μm in total diameter, 7 μm in metal core diameter and 5 cm long. The glass coating was mechanically removed from the sample ends and the electric contacts were attached with silver paste. The crystallization temperature T_X of the amorphous $Co_{70.5}Fe_{4.5}Si_{15}B_{10}$ microwire was determined by thermal analysis of the electrical resistance R_{DC} (Fig. 1). The variations in R_{DC} value during thermal treatment indicate structural transformation and modification of magnetic behavior in alloy. The impedance analyzer HAMEG RLC METER 8118 was used to determine the real and imaginary part of impedance. Measurements were realized at the frequency of 1, 10, and 100 kHz at room temperature. The same sample was first gradually Joule-heated for 10 min by AC current of 21, 40, 45, and 60 MA. Real and imaginary part of permeability was calculated from relationships (4), loss factor from Eq. (5).

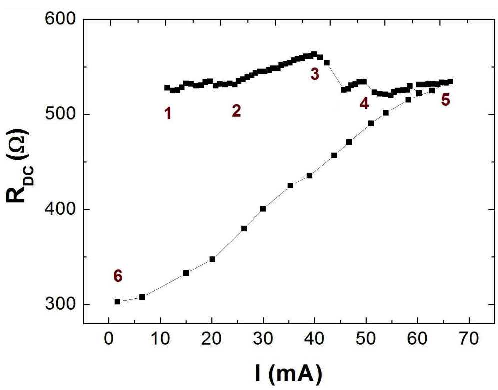

Fig. 1. Thermal analysis of the electrical resistance R_{DC}.

4. Results and discussion

The structural relaxation processes in amorphous alloy correlate with constant value of the resistance in the first stage of thermal treatment (1 → 2). After reaching current of about 25 mA, resistance increases as a consequence of the internal stresses relief and structure homogenization (2 → 3). Upon heating at the temperature

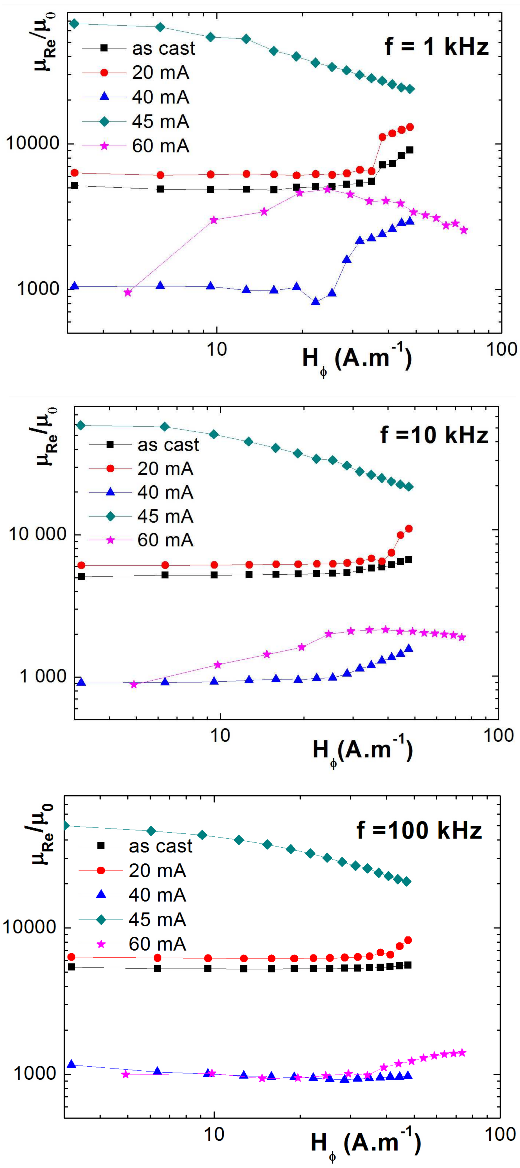

Fig. 2. Real part of the circular permeability as a function of circular magnetic field H_Φ at zero DC magnetic field for as cast sample and after different thermal treatment.

$T_x \sim I_x \approx 40$ mA, the amorphous alloy begins to crystallize and resistance starts to decrease (3 → 4). Heating at higher currents induces new internal stresses in alloy which are much stronger than that from amorphous wire and resistance increases again (4 → 5). Sample is fully crystalline after the Joule-heating at 65 mA during 5 min. The cooling part of $R_{DC}(I)$ dependence has a higher slope because of higher temperature coefficient of resistance for crystalline phase (5 → 6).

Figure 2 shows real part of relative permeability μ_{Re}/μ_0 as a function of the circular magnetic field H_Φ, at frequency of 1, 10, and 100 kHz for sample in as cast state and for the samples Joule-heated at 20, 40, 45, and 60 mA. Dependences in Fig. 2 show similar behavior for the as cast sample and sample Joule-heated at 20 mA at all frequencies which results from the fact that the annealing at 20 mA has produced only a stress relief without major modifications of the domain walls. At all frequencies relative permeability $\mu_{\rm Re}/\mu_0$ is almost constant for low field which is due to relaxation process. The insensitivity of permeability at the low circular fields indicates that domain walls are pinned to various defects or discontinuity of the structure, in the case of amorphous wires probably to the surface of the wire, and the magnetization process is associated with the bulging of the wall and its reversible oscillation. Since such processes are reversible, the permeability value is independent of the field amplitude. This dependence is similar to the typical behavior of initial permeability as a function of applied field [1].

A change of the structure after the Joule-heating at 45 mA leads to a higher values of real permeability which is usually found for alloys in the first state of the crystallization. Moreover, the annealing and subsequent cooling results in an induction of new stresses in the microwire from the glass-coating. This fact leads to overall decrease in the real permeability values with the H_Φ at all measured frequencies. Sample is full crystalline after heating at 60 mA and the dependences of permeability exhibits a maximum at lower fields in comparison with amorphous alloys.

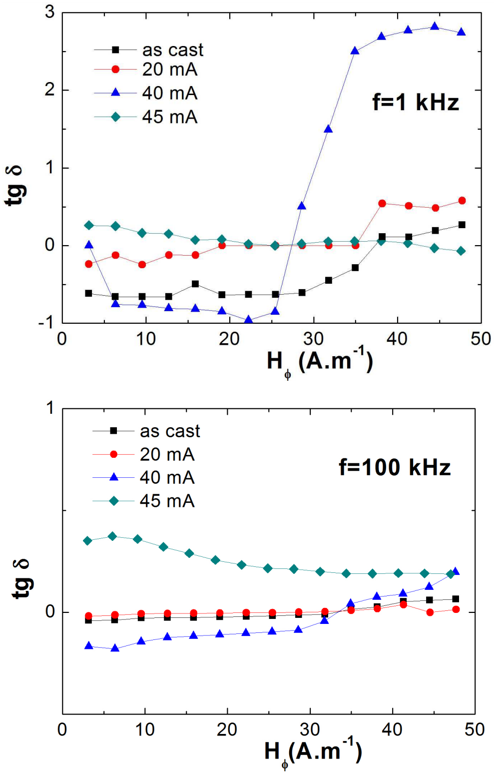

Fig. 3. Effect of the Joule-heating on loss factor tanδ measured at frequencies of 1 kHz and 100 kHz.

Influence of thermal treatment on the magnetic losses at two different frequencies (1 kHz and 100 kHz) is shown in Fig. 3. Dependences $\tan\delta = f(H_\Phi)$ exhibit slow increase for samples in as cast state and at low annealing current of 20 mA. After annealing at 40 mA a strong increase of losses was observed. This fact can be explained by the structural changes. The small grains which are created in the amorphous alloy can serve as remagnetizing nuclei in the magnetization processes. When the field H_Φ reaches a critical value, the formation of a huge amount of remagnetizing nuclei gives rise to a rapid increase of the eddy-current loss, which hinders the change of the magnetization with the field. After annealing at 40 mA, the maximum value of losses was observed for frequencies 1 kHz and 100 kHz at the same circumferential field 45 A m^{-1}. The frequency increase of the driving current to the 100 kHz plays decisive role in the observed permeability response.

The different characteristics of real part of permeability in Fig. 2 and tanδ values in Fig. 3 at the frequency 100 kHz manifest that the domain walls are unable to follow the field excitations, and spin rotation starts to be the dominant magnetization process.

5. Conclusions

The Joule-heating and the related anisotropy play decisive role in the observed permeability response. The change of the structure after the Joule-heating leads to the different magnetic properties of microwires which are reflected in the real permeability values and loss factor values.

Acknowledgments

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