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Magnetic properties and giant magnetoimpedance in FINEMET cold drawn microwires

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The influence of the diameter reduction and annealing conditions on the magnetic properties and giant magnetoimpedance (GMI) response of FINEMET wires with diameters from 50 μm down to 10 μm have been investigated. The results reveal potential ways to improve the soft magnetic properties of nanocrystalline microwires, the permeability reaching a maximum after annealing at 500˚C (5.3×10^5) and the GMI response being maximum after annealing at 550˚C (248%), with a great importance for future sensor applications based on these novel materials.

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1. Introduction

Amorphous and nanocrystalline magnetic microwires proved to be excellent candidates as sensitive elements in sensors for the detection and measurement of ultra-low magnetic fields [1-4]. These sensors can be also used to detect small displacements, vibrations, and mechanical deformation. Yoshizawa et al. [5] have proposed in 1988 the first nanocrystalline alloy with the composition $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$, patented under the trade name FINEMET. This nanocrystalline alloy was found to show the best magnetic softness, with very high value of the initial relative permeability (~10^5), very low coercivity (<1 A/m) and high saturation polarization (1.2–1.3 T) [6 - 8]. Knobel et al. [9] reported that conventional $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$ nanocrystalline wires show very large giant magnetoimpedance (GMI) response. The largest value of the GMI response was about 200% at a frequency of 500 kHz for the wire sample annealed at 600˚C for one hour. In another study, Chiriac et al. [10] reported that the GMI response was about 180% at a frequency of 50 MHz for a wire sample annealed at 550˚C for one hour.

In this paper we investigate the influence of the diameter reduction and annealing conditions on the magnetic properties and GMI response of cold drawn FINEMET wires with diameters between 10 μm and 50 μm.

2. Experimental

The FINEMET ($Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$) microwires with diameters between 50 μm and 10 μm were prepared by successive cold drawing of an amorphous wire with the initial diameter of 105 μm, which was prepared by in-rotating-water melt spinning. The cold drawn FINEMET wires were annealed in vacuum for one hour at temperatures between 300°C and 600°C, to relieve the stresses induced during the preparation and to favor the formation of the optimum nanocrystalline structure, specific to FINEMET alloys.

The coercivity, H_c, and relative magnetic permeability, μ_r, were measured in the longitudinal (axial) direction using a modified a.c. fluxmetric method in magnetic fields up to 30kA/m, at 50 Hz. The GMI response was recorded using an Agilent 4991A impedance analyzer at frequencies of the ac driving current between 10 and 250 MHz.

3. Results and discussion

The as-cast FINEMET amorphous wires with the nominal composition $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$ and 105 μm in diameter, prepared by in-rotating-water melt spinning, exhibit good soft magnetic properties, i.e. a relative permeability of 4×10^4, and a coercivity of 53 A/m.

Fig. 1 shows the coercivity and maximum value of the relative permeability vs. wire diameter for the cold drawn wires in as-cast state and after annealing at 500°C and 550°C for one hour. One observes that after cold drawing, both coercivity and magnetic permeability change significantly as compared to the as-cast state. Coercivity increases greatly after first stages of cold drawing reaching a maximum of 1400 A/m for the wire with 50 μm in diameter [10]. This behavior is mainly due to the high internal stresses induced in the wires during cold drawing. Subsequent cold drawing to even smaller diameters results in a continuous decrease in coercivity, down to 735 A/m for the wire with 10 μm in diameter (see Fig. 1 a). This behavior is due to the nonlinear changes in the distribution of internal stresses as a result of material removal when the diameter is reduced. These high values of the coercivity result in very low values of the magnetic permeability for all the as-cast samples (see Fig. 1 b).

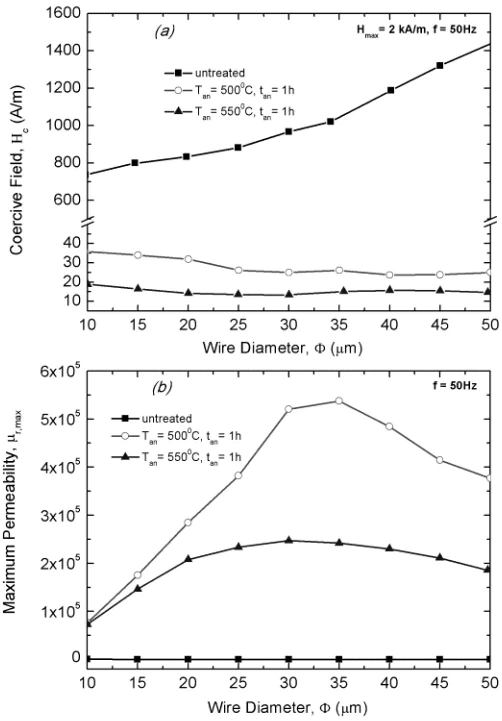

Fig. 1. Coercivity (a) and maximum value of the relative permeability (b) vs. wire diameter for the $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$ as-cast and cold drawn wires annealed for one hour at different temperatures.

Annealing at temperatures between 500°C and 550°C relieves the stresses induced during cold drawing process and favors the formation of the optimum nanocrystalline structure, specific to FINEMET alloys [10]. After annealing, coercivity decreases for all samples (see Fig. 1. a). For each value of the wire diameter, the minimum coercivity was measured for the samples annealed at 550°C. For the FINEMET microwires obtained by annealing from amorphous precursors, the formation of the nanocrystalline state is associated with the minimum coercivity [10]. The maximum magnetic permeability, 5.3×10^5 (see Fig. 1 b), was obtained for the wire with the diameter of 35 μm after annealing at 500°C for one hour, at a very small applied field (H_μ = 1.2 A/m). The maximum value of the magnetic permeability is obtained after annealing at a lower temperature (500°C) as compared to the minimum coercivity (550°C), due to residual internal stresses which remain from the preparation process, along with those induced during the cooling process, following annealing.

Fig. 2 illustrates the dependence of the amplitude of the GMI response, $\Delta Z/Z=(Z-Z_{H=max})/Z_{H=max}*100$ versus applied magnetic field, H, and the maximum amplitude of $\Delta Z/Z$ versus wire diameter, with the frequency of the ac driving current f as a parameter, for the cold drawn wires annealed for one hour at 550°C. One observes that the amplitude of $\Delta Z/Z$ increases when the diameter decreases for the samples annealed at temperatures up to 550°C. Such a specific behavior is the consequence of the formation of the nanocrystalline structure in the cold drawn wires subjected to the optimum annealing conditions [10]. At f = 10 MHz, the GMI response displays a maximum in the case of the wires with the diameter of 25 μm. The maximum value of the GMI response (248%) was obtained at f = 100 MHz for the wire with the diameter of 10 μm annealed for one hour at 550°C (see Fig. 2). The amplitude of the GMI effect is associated with the high frequency current penetration depth and the presence and volume of a region with high circular magnetic permeability at the wire surface [11, 13]. In microwires, the coupling between internal stresses and low magnetostriction gives rise to a specific core-shell domain structure [14-16], having an inner region with a longitudinal easy axis and an outer shell with a transverse easy axis of magnetization. The volume occupied by the axially and transversally magnetized regions depends on the wire diameter and on the internal and/or induced stress [14-17]. When the wire is thinner, the volume occupied by the outer shell is smaller and consequently the maximum impedance variation is obtained at higher frequency (see Fig. 2b).

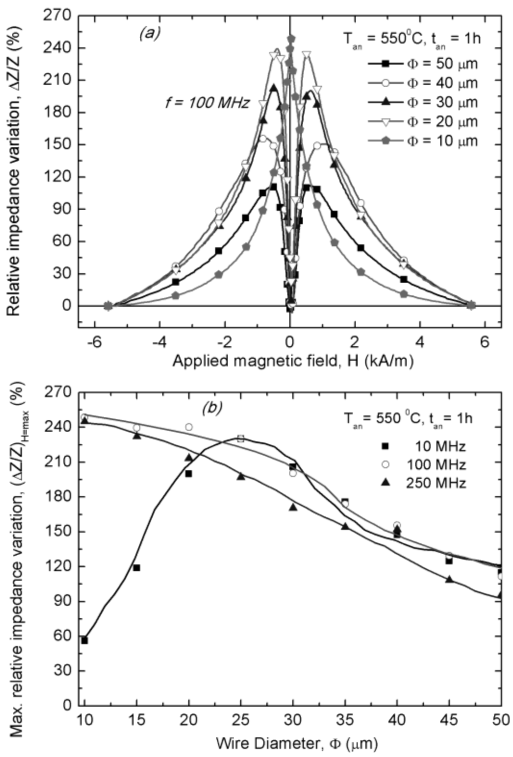

Fig. 2. Relative impedance variation, $\Delta Z/Z=(Z-Z_{H=max})/Z_{H=max}*100$ vs. applied magnetic field (a) and maximum relative impedance variation, $(\Delta Z/Z)_{max}$ vs. wire diameter at different frequencies f (b) for the $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_3$ cold drawn wires annealed for one hour at 550°C.

4. Conclusions

The influence of the diameter reduction and annealing conditions on the magnetic properties and GMI response of cold drawn FINEMET wires with diameters between 10 μm and 50 μm has been investigated.

By specific preparation process and suitable annealing conditions, the magnetic properties can be tailored to obtain excellent soft magnetic properties, e.g. very high relative magnetic permeability (up to 5.3×10^5), enhanced saturation magnetization (1.2 T), and a sensitive GMI response (up to 248%). Hence, these materials can be used for applications in novel magnetic sensors which require sensing elements with enhanced and optimized response.

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