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ORIGINAL PAPER

Tailoring of Magnetic Properties of Amorphous Ferromagnetic Microwires

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Abstract This article is a brief review of new different ways to tailor the magnetic properties of amorphous ferromagnetic microwires of two types: glass-coated and glassless. Metallic core of the studied samples was manufactured from CoFe-, Co-, and CoFeNi-based alloys by quenching and drawing or by the Taylor-Ulitovsky methods. We tested the following options to tailor the magnetic properties: changing of the parameters of manufacturing process, annealing, magnetostatic interaction in the array of wires. For the first time, it was found that a system of Co-based microwires with nearly zero magnetostriction coefficient exhibits a step-like hysteresis loop. The same behavior was found for single microwires with compositions of $Fe_{77.5}Si_{7.5}B_{15}$ and $Fe_{45}Co_{30}Si_{10}B_{15}$ produced under certain conditions. The effect of stress-annealing was investigated for $Fe_{67.5}Co_{7.5}B_{15}Si_{10}$, $Fe_{52.5}Co_{22.5}B_{15}Si_{10}$, and $Fe_{37.5}Co_{37.5}B_{15}Si_{10}$ glass-coated microwires.

Keywords Ferromagnetic microwire · Magnetostatic interaction · Magnetic properties

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1 Introduction

Recently, considerable attention has been paid to the investigation of a family of thin glass-coated and glassless amorphous ferromagnetic microwires (see for example, [1–4]). These thin, 1–30 μm in diameter, wires could present the following rather different properties: either extremely magnetically soft or magnetically bistable behavior, depending on the composition of the metallic core. High permeability is typical for wires with nearly zero magnetostriction, they present the coercivity below 0.06 Oe and exhibit giant magnetoimpedance effect (GMI). Rectangular hysteresis loop is a characteristic of bistable microwires with positive magnetostriction; they exhibit the fast domain wall (head-to-head or tail-to-tail type) propagation. The first type of the wires has been successfully used for creation of sensors with high sensitivity and quick action; the second one could be successfully used as elements of coding systems, logic, and memory devices. In the last decades, tendency toward miniaturization of modern magnetic sensors and devices has

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Table 1 Compositions and diameters of microwires

Metallic core composition	Diameter of the metallic core	Total microwire diameter
1. $Co_{30}Fe_{45}Si_{10}B_{15}$	13–24	15–29
2. $Co_{83}Fe_{7}C_{1}Si_{7}B_{2}$	30	–
3. $Co_{68.6}B_{14.8}Si_{10}Mn_{6.6}$	16.2	21.2
4. $Co_{68.7}Fe_{4}Ni_{1}B_{13}Si_{11}Mo_{2.3}$	17.0	23.6
5.$Co_{67.05}Fe_{3.85}Ni_{1.44}B_{11.53}Si_{14.47}Mo_{1.66}$	22.2	24.2

stimulated development of functional magnetic materials with reduced dimensionality and with controllable and tunable magnetic properties. Magnetic microwires were always a subject of the research on aforementioned subject (see for example, [5–8]).

During manufacturing process (either using Taylor-Ulitovsky method or other rapidly quenching methods) the quenching rate, the melt temperature, and the velocity of extraction affect the total diameter of the microwire, metallic nucleus diameter of microwire, and its crystalline structure (for example, [9, 10]). All these properties affect magnetic behavior of the microwires. Early reports (for example, [11–13]) point to two types of stresses in the metallic core of glass-coated microwires which, finally, have great influence on magnetic properties of the samples: (i) Quenching stress depending on diameter of the metallic core (i.e., on cooling rate and velocity of extraction) and (ii) stresses due to the difference between the thermal expansion coefficients of metal and glass (may be associated with the ratio of diameter of metallic core to diameter of glass-coated microwire, d/D). So, properties of as-cast glass-coated microwires depend on geometrical factors: d and d/D. Additionally, magnetic properties in as-prepared state depend on the chemical composition of alloy, particularly on the sign of magnetostriction coefficient [14]. But these properties can be changed by annealing (for example, [2, 15]), by removing the glass coating (for example, [16, 17]) or—using a bistable microwires array or sputtered second magnetic phase—by magnetostatic interaction (for example, [7, 18, 19]).

We report on different ways to tailor the magnetic properties of amorphous ferromagnetic microwires: by changing of the parameters of manufacturing process, by annealing (under the influence of stress), and by manipulating of magnetostatic interaction in a system of the wires (glassless microwires with negative magnetostriction constant).

2 Experiment Details and Sample List

We studied glass-coated or uncovered microwires manufactured by methods described elsewhere [10, 20, 21]. Parameters of microwires under consideration are listed in Table 1. Detailed parameters, lengths, and special treatments are given below.

Magnetic properties of the microwires were studied using two different methods. The first one is a vibrating sample magnetometer which allows one to decrease the increment of magnetic field down to 0.02 Oe and to perform very precise measurements of magnetization loops for amorphous ferromagnetic microwires with very low coercivity. The second one is a setup utilizing the induction method.

3 Results and Discussions

Three ways to tailor the magnetic properties of microwires have been studied: by changing of the parameters of the

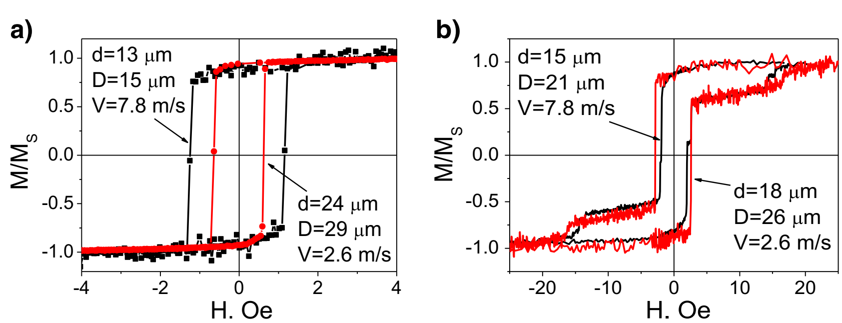

Fig. 1 Hysteresis loops measured for $Fe_{45}Co_{30}Si_{10}B_{15}$ microwires manufactured under **a** water quenching and **b** air quenching. In the figure, the following diameters and parameters are indicated: *d* is the diameter of the metallic core, *D* is the total glass-coated diameter, and *V* is velocity of extraction

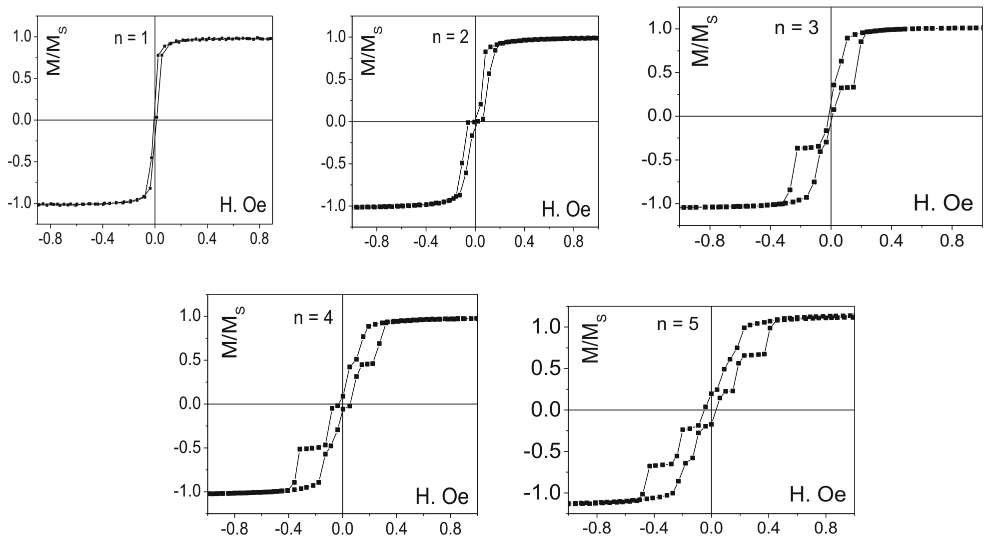

Fig. 2 Hysteresis loops of microwires arrays with different number of wires

manufacturing process, by annealing, and by manipulating of the magnetostatic interaction in a system of the wires.

Changing of the parameters of manufacturing process is the first important and frequently used way to change the magnetic properties of microwires. A set of the samples with different concentration of iron (samples 1–3 in Table 1) has been prepared. The different samples were obtained by changing conditions of the extraction: the rate and the atmosphere of cooling. Different shapes of hysteresis loops were observed for different metallic core compositions and parameters of the manufacturing process. In Fig. 1. the hysteresis loops measured for $Fe_{45}Co_{30}Si_{10}B_{15}$ microwires manufactured under water quenching or air quenching are presented.

Typical parameters of production of amorphous ferromagnetic microwires are the cooling rate of $10^6 - -10^7 \circ$C/s and the velocity of extraction of 6–9 m/s [9, 10]. Here, we demonstrated that even at smaller extraction velocity (down to 2.6 m/s), the samples exhibit nearly bistable hysteresis loop and amorphous structure. Consequently, as pointed out also in [1], if the quenching velocity is above some critical value, it does not considerably affect magnetic behavior and structural properties of the samples. On the other hand, partially crystalline sample can present step-like hysteresis loops even in a single microwire (Fig. 1b). as has been previously demonstrated in $(Fe_{69}Si_{10}B_{15}C_5)_{50}Cu_{50}$ microwires [22]. We checked by XRD the crystalline structure of the samples. Small values of coercive forces observed in Fig. 1a corroborate that fact. We have found out that the number of the crystalline phases depends on the cooling atmosphere. Under air cooling, bi-phase microwires with corresponding step-like hysteresis loops were obtained (see Fig. 1b). Moreover, the iron concentration influences formation of single or bi-phase microwires: (i) For $Fe_{45}Co_{30}Si_{10}B_{15}$ alloy, the single or bi-phase state depends only on the atmosphere of cooling but not on the velocity of extraction used in this work; (ii) for $Fe_{77.5}Si_{7.5}B_{15}$ alloy, the velocity of extraction does not cause the appearance of a second phase under water cooling, but bi-phase microwire at cooling rate $\leq$2.6 m/s is appeared under air cooling; (iii) $Co_{69}Fe_4Cr_4Si_{12}B_{11}$ microwires were found to be the single-phase amorphous bistable or single-phase crystalline microwires, depending of velocity of extraction and quenching rate (for low velocity and rate, crystalline phase was found).

Magnetostatic interaction can also be considered as a method of manipulation of the magnetic properties. A system of $Co_{83}Fe_7C_1Si_7B_2$ microwires containing 1–5 wires was investigated. The modification of hysteresis loops shape

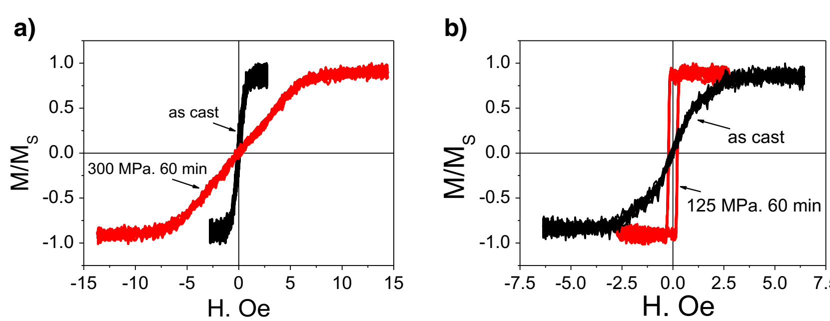

Fig. 3 Hysteresis loops of as-prepared and annealed samples of $Fe_{3.85}Co_{67.05}Ni_{1.44}B_{11.53}Si_{14.47}Mo_{1.66}$ microwire **a** under stress influence and **b** stress-free

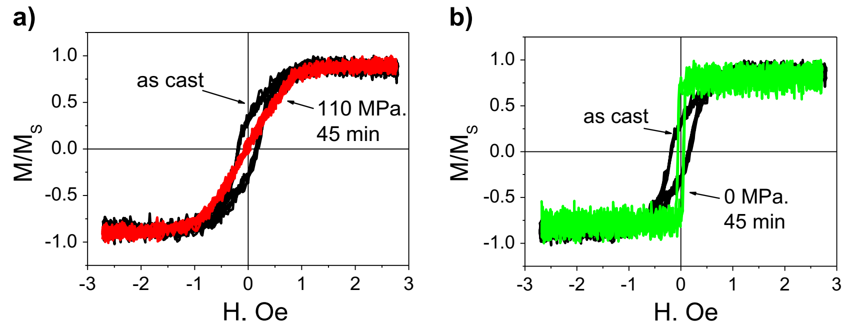

Fig. 4 Previously, unusually strong effect of stress annealing on magnetic properties of glass-coated microwires has been explained, considering back compressive stresses appearing from glass coating [6]

is presented in Fig. 2. The main feature of this experiment is the emergence of a step-like dependence with increasing of number of microwires in spite of the fact that a single microwire does not exhibit the bistable behavior. Future study of these wires is necessary to give the explanation of this phenomenon. But in this paper, we unveil for the first time the possibility to tailor the step-like hysteresis loops using the array of Co-based non-bistable microwires. So far, only an increase of the slope of the hysteresis loops has been reported for this type of microwires (for example, [19, 20]).

Magnetic properties for as-prepared and annealed under applied stress amorphous ferromagnetic glass-coated Co-based and CoFeNi-based microwires (see Table 1) were investigated. We have demonstrated that annealing of the microwires under stress allows one to change the magnetostriction coefficient [15] and thereby facilitating change of the magnetic properties. In Figs. 3 and 4. the results of the influence of stress annealing and conventional annealing are presented. For CoMn- and CoFe-based microwires, increasing of the annealing time and applied stress affect the magnetic properties in the following ways: For the $Co_{68.6}B_{14.8}Si_{10}Mn_{6.6}$ wire, increasing of time and stress at annealing causes a decrease of magnetic permeability. $Co_{68.7}Fe_4Ni_1B_{13}Si_{11}Mo_{2.3}$ microwire annealed at any time and stress at annealing presents magnetically bistable behavior. Influence of annealing on magnetic properties of FeCoNi-based microwire depends on the presence or absence of stress (see Fig. 4).

Hysteresis loops of as-cast and stress-annealed samples **a** $Co_{68.6}B_{14.8}Si_{10}Mn_{6.6}$ and **b** $Co_{68.7}Fe_4Ni_1B_{13}Si_{11}Mo_{2.3}$

Different ways to tailor the magnetic properties of amorphous ferromagnetic microwires, i.e., changing of the parameters of the manufacturing process, annealing, and appearance of magnetostatic interaction in a system of the wires were described. The study of magnetostatic interaction influence on the reversal process and magnetic properties of $Co_{83}Fe_7C_1Si_7B_2$microwires array were performed. For the first time, we observed the step-like hysteresis loops in the system of Co-based microwires with a nearly zero magnetostriction. For the first time, step-like hysteresis loops were observed in a single microwire with composition of $Fe_{77.5}Si_{7.5}B_{15}$ and $Fe_{45}Co_{30}Si_{10}B_{15}$ produced under certain conditions (without using of microwire system). The stress annealing was investigated for $Fe_{67.5}Co_{7.5}B_{15}Si_{10}$, $Fe_{52.5}Co_{22.5}B_{15}Si_{10}$, and $Fe_{37.5}Co_{37.5}B_{15}Si_{10}$. Dramatic change of the hysteresis loop form caused by stress-annealing was demonstrated.

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