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Magnetic Properties of CoFeSiB/CoNi, CoFeSiB/FeNi, FeSiB/CoNi, FeSiB/FeNi Biphase Microwires in the Temperature Range 295–1200 K

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We have studied the magnetic properties of two series of magnetically biphase microwires with 1 μm thickness of CoNi-based hard or FeNi-based soft shells with a core of FeSiB or FeCoSiB glass-coated microwires. The magnetic properties were analyzed as a function of temperature in the range from 295 K to 1200 K using a vibrating sample magnetometer. Analysis of the magnetization reversal of each phase with measuring temperature has been performed.

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1. Introduction

Nowadays, emerging areas in science such as biochemistry, microbiology or nanotechnology are widely investigated. Such areas in science are directly related with the fabrication and manipulation of nano- and micro-objects.

There are no many kinds of devices for the manipulation of nano- and micro-objects and all of them present some disadvantages. We can mention atomic force microscope or optical tweezers, magnetic tweezers. Optical tweezers, despite all its advantages can work with objects only in a liquid medium and only with partially transparent particles with sizes between 0.2 to 5 μm. The acting forces are small — units pN. The magnetic tweezers have in turn no restrictions on transparency and particle size, so it is possible to work in gases, liquids, and vacuum. But the presence of the residual field of the core affects the objects. Furthermore the working field of the magnetic tweezers and its implemented range of actions are limited. All details about these types of tweezers and actuators can be found in Ref. [1].

In our work, we propose to create the prototype of the manipulators based on magnetically bi-phase microwires. Main objective of our investigations is a development of the technique of controlling the bending of the bi-phase microwires with magnetic field. The working characteristics of such actuator are: working at large distances and with larger objects, a low fabrication cost, strong forces to move objects (tens pN), smallness and compact, and the possibility to work with nontransparent objects. Also it can have two operating regimes: control of objects by magnetic field or by mechanical forces.

Magnetically bi-phase microwires are the special class of microwires with controllable magnetization state by magnetic field [2]. They consist of a ferromagnetic core — amorphous glass-coated microwires, and a polycrystalline ferromagnetic shell. In order to determine the different ways to control and manipulate the magnetization state of bi-phase microwires, it is important to examine the various factors having a relevant influence: composition of the magnetic material components, the thickness of the shell and diameter of the core, the measuring temperature and applied stress. The influence of these parameters was partly investigated elsewhere [2, 3].

In this paper we have studied the high temperature magnetic behavior of bi-phase microwires with different core and shell components.

2. Experimental details

The microwires under consideration consist of two phases: a core (a single-phase glass-coated microwire) and a shell with different composition. The single phase glass-coated microwires were prepared by quenching and drawing technique (a first phase) [4]. Then a gold nanolayer was sputtered onto the Pyrex coating of the single-phase microwire to serve as an electrode for the subsequent electrodeposition onto the core of a second phase — a polycrystalline external shell [5].

Alloys with two different compositions were used for the preparation of the core: $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ ("CoFeSiB" for short — with near zero saturation magnetostriction) and $Fe_{77.5}Si_{7.5}B_{15}$ ("FeSiB" for short — with positive saturation magnetostriction). The diameters of the metallic core were $d = 8$ μm and $d = 12$ μm,

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the thicknesses of the Pyrex glass coating were $t_g = 6$ μm and $t_g = 14$ μm, respectively.

For the preparation of the shell were used $Co_{90}Ni_{10}$ and $Fe_{20}Ni_{80}$ alloys. The thickness of the external shell is 1 μm. The thickness control was performed by controlling of the electroplating time [6, 7]. Further details about the preparation can be found elsewhere [4–6]. The microwires lengths were 4.5 mm for CoNi shell and 4 mm for FeNi shell.

All measurements were performed using a vibrating sample magnetometer (Lake Shore) in the temperature range from room to 1200 K in Ar atmosphere. Magnetic moment versus temperature measurements were carried out in a magnetic field of 200 Oe for the samples with a FeNi shell and 1 kOe for the samples with a CoNi shell. A magnetic field was directed parallel to the microwires axis.

3. Experimental results and discussions

To trace the bi-phase microwires magnetic properties evolution we measured the hysteresis loops at different temperatures. Figure 1a–d shows the room temperature hysteresis loops, normalized to the maximum value of magnetic moment for each sample. The hysteresis loops have two steps. The first step of the hysteresis loops corresponds to the magnetization reversal of amorphous magnetically soft metallic core. It is observed at very low field. The second jump corresponds to the magnetization reversal of the polycrystalline core. It occurs in higher fields: 50–200 Oe for magnetically hard CoNi shell and 1–15 Oe for magnetically soft FeNi shell. The hysteresis loops steps became smaller and less pronounced when the temperature is increasing up to the Curie temperatures of the core where step-behavior has disappeared. The Curie temperatures of the cores — amorphous microwires — were estimated from the temperature dependences of magnetic moment of studied samples (see Fig. 2): $T_{\mathrm{C-amorphouscore}} = 675$ K for FeSiB and $T_{\mathrm{C-core}} = 625$ K for CoFeSiB core of bi-phase microwires.

The typical monotonic temperature dependence of magnetic moment on temperature with two Curie temperatures was found for bi-phase microwires with CoFeSiB core and FeNi shell (see Fig. 2b) [3]. The Curie temperature of FeNi shell was found to be 840 K. The temperature of 1200 K (the maximum possible value, which is achieved by setup) is not enough to reach the Curie temperature for CoNi shell (see Fig. 2a and b for FeSiB/CoNi and CoFeSiB/CoNi microwires).

The temperature dependences of magnetic moment of bi-phase microwires with Fe-based core are nonmonotonic (see Fig. 2a). It happens because at temperatures higher than 770 K, during the recrystallization of Fe-based amorphous core its lattice constant changes and the core becomes ferromagnetic again [8]. Two Curie temperatures of the core were found to be: $T_{\mathrm{C-amorphouscore}} = 675$ K, that corresponds to the core in amorphous state, and $T_{\mathrm{C-crystallinecore}} = 950$ K, that corresponds to the core in a crystalline state. Figure 3a–d shows the hysteresis loops at $T = 700$ K, when the Curie temperatures are reached: $T_{\mathrm{c-core}}$ and $T_{\mathrm{C-amorphouscore}}$ for CoFeSiB and FeSiB cores, respectively. The loops steps disappear and the hysteresis loops become s-shaped because the metallic cores become paramagnetic.

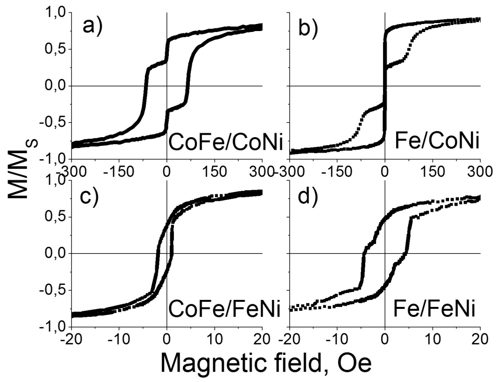

Fig. 1. Hysteresis loops for the samples at $T = 295$ K.

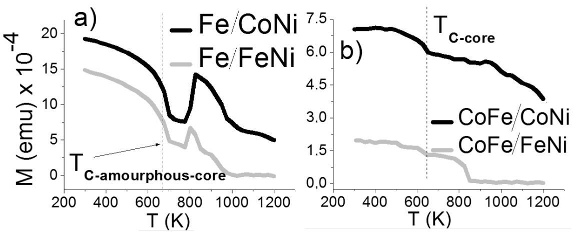

Fig. 2. Temperature dependence of the magnetic moment of bi-phase microwires: (a) with FeSiB core and (b) with CoFeSiB core.

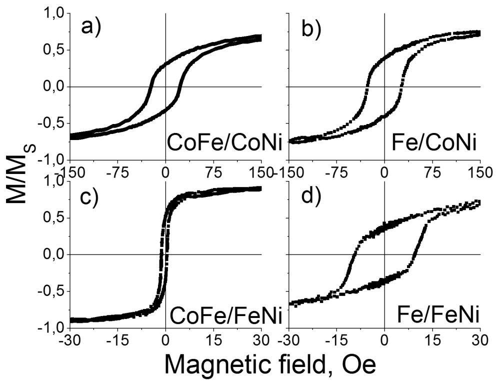

Fig. 3. Hysteresis loops for investigated samples at $T = 700$ K.

With a further increase of the temperature the properties of the bi-phase microwires change again and we can see that for each bi-phase microwire this change is quite different. At the temperature of 900 K, for example, the following behavior was found: (i) for CoFeSiB/CoNi sample the s-shaped hysteresis loop similar to Fig. 3a was observed. It means that the core is still in a paramagnetic state and shell is still in ferromagnetic state. (ii) For FeSiB/CoNi sample the hysteresis loop has two steps again — it happens because we have reached the crystallization temperature of the core, after which the lattice constant of the core was changed and we can see the magnetization process of the core again. The coercive force of the first step which corresponds to the magnetization reversal of the core becomes larger. This increase is typical for crystalline state in comparison to amorphous state.

For the microwires with a FeNi shell the situation is different because FeNi shell has reached its Curie temperature and is in paramagnetic state. (iii) The typical linear behavior for a paramagnetic state is found in CoFeSiB/FeNi sample. (iv) FeSiB/FeNi sample exhibits s-shape hysteresis loop due to the magnetization process of the crystalline core. When the temperature increases up to the maximum temperature of 1200 K there are no more contribution of the core. The magnetization versus a magnetic field curves are s-shaped hysteresis loops for bi-phase microwires with CoNi-shell (Fig. 4a,b) and linear for bi-phase microwires with FeNi-shell (Fig. 4c and d).

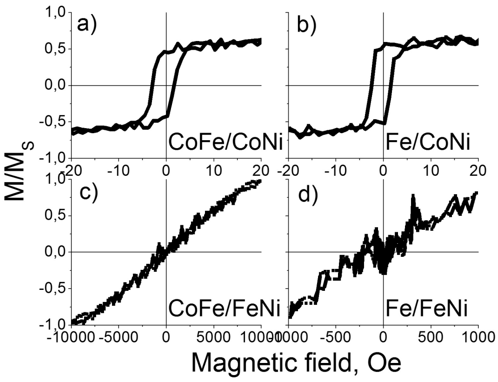

Fig. 4. Hysteresis loops for the samples at $T = 1200$ K.

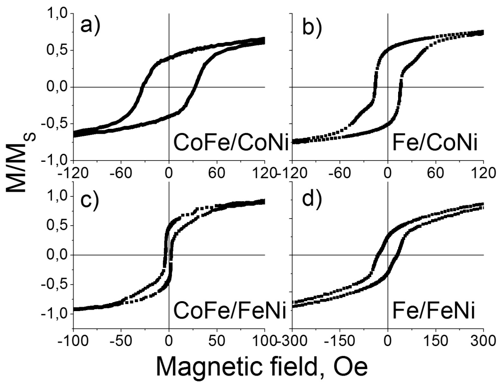

Fig. 5. Hysteresis loops for the samples at $T = 295$ K after cooling.

Summarizing all described behaviors we can conclude that the magnetization process strongly depends on temperature and the number of the "steps" in curves M vs. H depends on alternation of the Curie temperatures.

In addition, Fig. 5a–d shows the hysteresis loops at room temperature after samples cooling. The changes of the magnetic properties of the loops are irreversible because the crystallization temperatures of the cores have been reached.

4. Conclusions

In this paper, we have studied the high temperature dependence of the magnetic properties of ferromagnetic bi-phase microwires. The magnetic properties of samples varied with the composition of the core and the shell. The magnetization process strongly depends on Curie temperatures of phases. In Table the magnetic phases contribution in magnetization process are presented.

TABLE

Magnetic phases contribution in magnetization process.

Bi-phase microwire	Temperature range, [K]	Phase contribution
FeSiB/CoNi	295–675, 770–950	core + shell
	675–770, 950–1200	shell
FeSiB/FeNi	295–675, 770–840	core + shell
	675–770	shell
	840–950	core
CoFeSiB/CoNi	295–625	core + shell
	625–1200	shell
CoFeSiB/FeNi	295–625	core + shell
	625–840	shell

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References

[1] K.C. Neuman, A. Nagy, *Nature Meth.* **5**, 491 (2008).

[2] J. Torrejon, G. Badini, K. Pirota, M. Vazquez, *Acta Mater.* **55**, 4271 (2007).

[3] V. Rodionova, A. Nikoshin, J. Torrejón, G.A. Badini-Confalonieri, N. Perov, M. Vazquez, *IEEE Trans. Magn.* **47**, 3787 (2011).

[4] K. Pirota, M. Hernandez-Velez, D. Navas, A. Zhukov, M. Vazquez, *Adv. Funct. Mater.* **14**, 266 (2004).

[5] M. Vazquez, K. Pirota, J. Torrejón, G. Badini, A. Torcunov, *J. Magn. Magn. Mater.* **304**, 197 (2006).

[6] J. Torrejon, G.A. Badini Confalonieri, K.R. Pirota, M. Vazquez, *Sensor Lett.* **5**, 153 (2007).

[7] M. Vazquez, H. Chiriac, A. Zhukov, L. Panina, T. Uchiyama, *Phys. Status Solidi A* **208**, 493 (2010).

[8] Kun Peng, Fusheng Liu, Dingfa Fu, Zhigao Huang, Feng Xu, Youwei Du, *Mater. Chem. Phys.* **89**, 138 (2005).