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The stress components effect on the Fe-based microwires magnetostatic and magnetostrictive properties

V. Rodionova [a,b], I. Baraban [a,*], K. Chichay [a], A. Litvinova [a], N. Perov [a,c]

[a] Institute of Physics & Technology and STP "Fabrika" Immanuel Kant Baltic Federal University, A. Nevskogo 14, Kaliningrad 236041, Russia
[b] National University of Science and Technology "MISIS", Leninsky prospect 4, Moscow 119049, Russia
[c] Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory 1-2, Moscow 119991, Russia

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ABSTRACT

For glass-coated amorphous ferromagnetic Fe-based microwires both joint and separate effect of metallic nucleus diameter, *d*, and the ratio of metallic nucleus diameter to the total diameter of microwire in glass shell, *d/D*, on magnetic properties is investigated. Thereby the contribution of both shell-induced stresses, associated with the ratio of diameters, and internal nucleus stresses (residual, quenching), associated with the diameter of the nucleus are estimated. A strong and non-monotonic effect of the metallic nucleus diameter and metallic nucleus diameter/total microwire diameter ratio on magnetostatic and magnetostrictive properties was established. For analysis, we considered magnetically bistable microwires of "classic" $Fe_{77.5}Si_{7.5}B_{15}$ alloy with positive magnetostriction coefficient.

1. Introduction

The origin of the magnetization process in Fe-based glass-coated microwires is a fast propagation of head-to-head domain wall along the microwire axis. This high-speed magnetic switching provides a magnetical bistability of glass-coated amorphous microwires and can be widely used for different technical applications – coding, logic, and memory systems (for example, [1–3]); the results of the recent research show also that Fe-based amorphous magnetic glass-coated microwires can be used as temperature sensors for the control of biomechanical processes in the tissue-implant interface [4]. Many factors affect the speed of magnetic switching. The head-to-head domain wall's velocity and mobility are among them. These parameters of the domain wall propagation depend on microwire composition, i.e. magnetostriction coefficient of metallic nucleus material [5], and internal stresses in the metallic nucleus (for example, [6–8]). However, internal mechanical stresses affect the magnetostriction coefficient as well (for example, [9,10]).

The mechanical internal stresses consist of two components: shell-induced stresses, associated with the ratio of diameters (*d/D*, where *d* – is the diameter of the metallic nucleus, *D* – is the total diameter of the microwire with the glass), and internal nucleus stresses (residual, quenching), associated with the diameter of the metallic nucleus [6,7,11–13]. That is why we decided to consider the magnetic properties of microwires as a function of two parameters: *d* and *d/D* (not as a function of only one – *d* or *d/D* as was discussed earlier, for example, in [11–13]).

Thus, the topic of our interest is to investigate the influence of mechanical internal stress (with consideration of separate influence of *d* and *d/D*) on magnetostatic (i.e. coercivity and switching fields) and magnetostrictive properties of Fe-based magnetically bistable microwires.

2. Experimental details

We studied the magnetic properties on $Fe_{77.5}Si_{7.5}B_{15}$ microwires with the metallic nucleus diameter of 2.5–20 μm and the metallic nucleus diameter/total microwire diameter ratio, *d/D*, of 0.1-0.8. We studied 19 microwires in total with different transverse sizes. The Lake Shore vibrating sample magnetometer was used for the investigation of magnetostatic properties. Magnetostriction coefficient was measured by small angle magnetization rotation method (for example, [9]). The length of studied samples for the magnetostatic measurements was 1.5 cm, for magnetostriction – 10 cm.

Technological features of the manufacture process of glass coated microwires do not allow to produce them with the fixed thickness of the glass coating – changing even one of the production parameters (melt temperature and rate of extraction) always leads to a change in both the diameter of the metallic nucleus and the thickness of glass coating (for example, [14–16]). As a consequence, it is not possible in the experimental study to identify only the influence of stresses associated with the presence

* Corresponding author.

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of glass coating. It is always a combined influence of shell stresses (the diameters ratio) and stresses of the metallic nucleus, the distribution of which depends on the diameter of the metallic nucleus.

That is why in this work we studied the joint influence of shell and core stresses and then separated the effect of each of them by the analysis. To analyse the magnetic properties as a function of two independent variables (d and d/D) we used the *Statistica* software – solving the task with lack of data.

3. Results and discussion

3.1. Magnetostatic properties

The rectangular hysteresis loops, typical for the Fe-based microwires, were observed for all studied samples. In Fig. 1 the hysteresis loops of the samples with small and large diameters are demonstrated.

We estimated the value of the coercive force using obtained hysteresis loops and plotted all data in Fig. 2 as a function of diameter of the metallic nucleus of glass-coated microwires. The coercive force is decreasing with the metallic nucleus diameter increase. We approximated this dependence using the exponential function $H_C = y_0 + A_1 \cdot exp(-(d-d_0)/t_1)$ – a solid line in Fig. 2. The interpolation function was constructed with the following values of the coefficients: $y_0 = 0.87$, $d_0 = 1.94$, $A_1 = 9.31$, $t_1 = 4.17$.

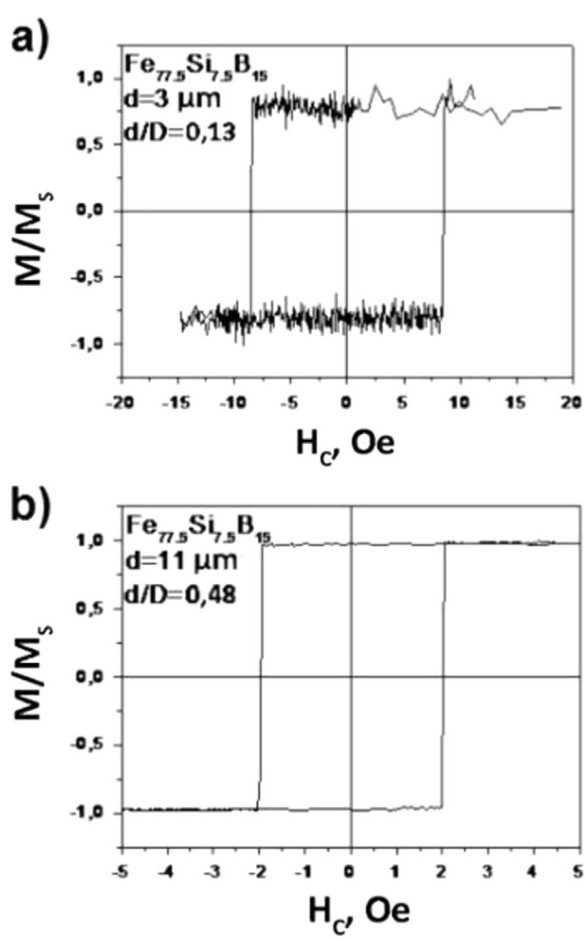

Fig. 1. The normalized hysteresis loops of the studied amorphous glass-coated microwires with different diameters of the nucleus and diameters ratio: (a) $d=3$ µm, $d/D = 0.13$ and (b) $d = 11$ µm and $d/D = 0.48$ (d – diameter of the metallic nucleus and D – total diameter of the microwire in the glass shell).

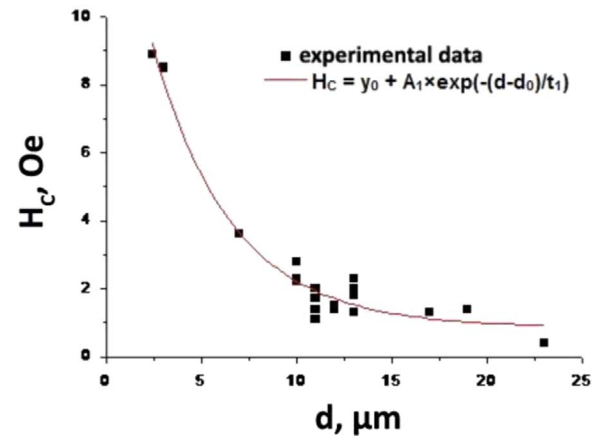

Fig. 2. The dependence of coercive force estimated from experimental data on diameter of the metallic nucleus of glass-coated microwires.

Exponential function as well as respective coefficients was selected for the best fitting of experimental data using *Origin* software.

One can see in Fig. 2 that for the same value of d there are several different values of coercivity, H_C. These values were obtained for microwires with different d/D. For example, for microwires with $d = 11$ µm the value of H_C is in the range from 1.1 Oe up to 2 Oe for d/D varying from 0.5 to 0.6 but this dependence of H_C on d/D for the same d is not monotonic. For microwires with $d = 10$ µm – H_C changes from 2.2 Oe to 2.8 Oe with non-monotonic dependence on d/D. These and other dependences of H_C on d/D for microwires with different d are presented in the Table 1.

Analyzing the data of the Table 1 we can assume the existence of the minimum in the dependence of H_C on d/D for the fixed value of d. However the measured data are not sufficient to make an unambiguous conclusion. It is not possible to assert the monotonic or clear non-monotonic dependence of H_C on d/D for all studied samples (not only for fixed value of d) – see Fig. 3.

The dependences of H_C on d and d/D (Figs. 2 and 3) characterize the influence of the properties of the nucleus and the stresses induced by the presence of glass shell, respectively, on the magnetic properties of microwires. Comparing the dependences of H_C on d and d/D, we can deduce a larger effect of the first factor than of the second one: it is possible to trace a strong dependence of H_C

Table 1
The dependence of coercive force estimated from experimental data on the d/D ratio for microwires with fixed d.

d, µm	D, µm	d/D	Hc, Oe
2.4	15	0.16	8.9
3	23	0.13	8.5
7	14	0.5	3.6
10	17	0.59	2.3
10	20	0.5	2.2
10	21	0.48	2.8
11	16	0.69	1.7
11	17	0.65	1.4
11	19	0.58	1.1
11	23	0.48	2
12	21	0.57	1.4
12	25	0.48	1.5
13	19	0.68	1.3
13	19	0.68	2
13	26	0.5	2.3
13	30	0.43	1.8
17	26	0.65	1.3
19	29	0.66	1.4
23	29	0.79	0.4

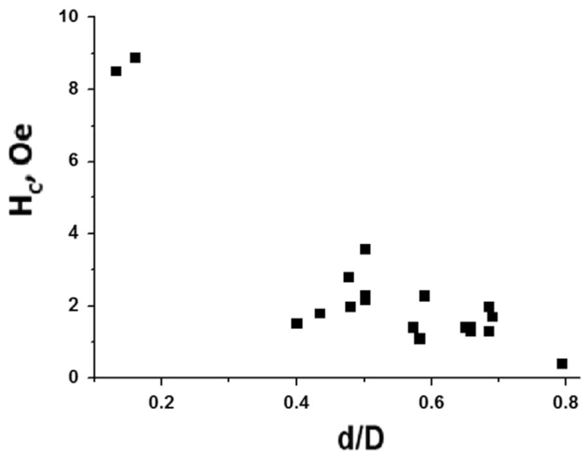

Fig. 3. The dependence of coercive force estimated from experimental data on *d/D*.

on *d* under the changing values of *d/D* in an explicit form while the dependence of H_C on *d/D* cannot be determined. Taking into account Table 1, it should be noted that the dependence of H_C on *d* for the fixed values of *d/D* must be different. We will make the appropriate correction in the mentioned dependences below, i.e. we will exclude the influence of *d/D*. The red curve in Fig. 2 represents a joint influence of both *d* and *d/D* parameters on the magnetic properties of microwires.

Summarizing the results presented in this paragraph, we can make the following conclusions. Despite the large number of the microwires under consideration with a wide range of geometrical parameters, the observed dependences of H_C on *d* and *d/D* do not allow to make an unambiguous conclusion about the separate effect of the metallic core properties and the glass shell-induced stresses, respectively.

3.2. Simulation of magnetostatic properties

As was noted above, due to the specific technological features of microwire production by Taylor-Ulitovsky technique, it is quite difficult to prepare samples with fixed values of *d* and/or *D*. That is why, in order to separate the contribution from metallic nucleus and glass shell (i.e. *d* and *d/D*, respectively) to the magnetic properties of microwires, we considered this task as a problem with the lack of data. *Statistica* software was used for data analysis. The H_C function of two arguments (*d* and *d/D)* was simulated. $H_C > 0$ and $d \le D$ are obvious boundary conditions for the H_C function imposed by the physical sense.

To derive the separate influence of *d* and *d/D* parameters on the microwires magnetic properties the dependences $H_C(d;d/D)$ for $d/D = const$ and $d = const$ were plotted. These data are presented in the Fig. 4(a) and (b), respectively.

In Fig. 4(a) one can see how the lines form changes with the *d* value. This modification as well as the non-monotonic $H_C(d/D)$ dependence can be explained taking into account the theoretical calculations of the distribution of the glass shell-induced stresses in the metallic core of glass-coated microwire along its radius [17]. The increase of the *d/D* ratio for the microwires with fixed value of *d* leads to the decrease of the glass shell-induced stresses in the metallic core, i.e. to the redistribution of the stresses along microwire radius. This, in turn, leads to the shift of the domain wall between the axially magnetized domain and the periphery domains (the Fe-based microwire has Landau-Lifshitz structure with radial magnetized periphery [18]). This shift causes drastic changes of the magnetic properties of the glass-coated microwires. Because of the nonlinearity of such shift, the non-monotonic dependences of the microwires magnetic properties are observed.

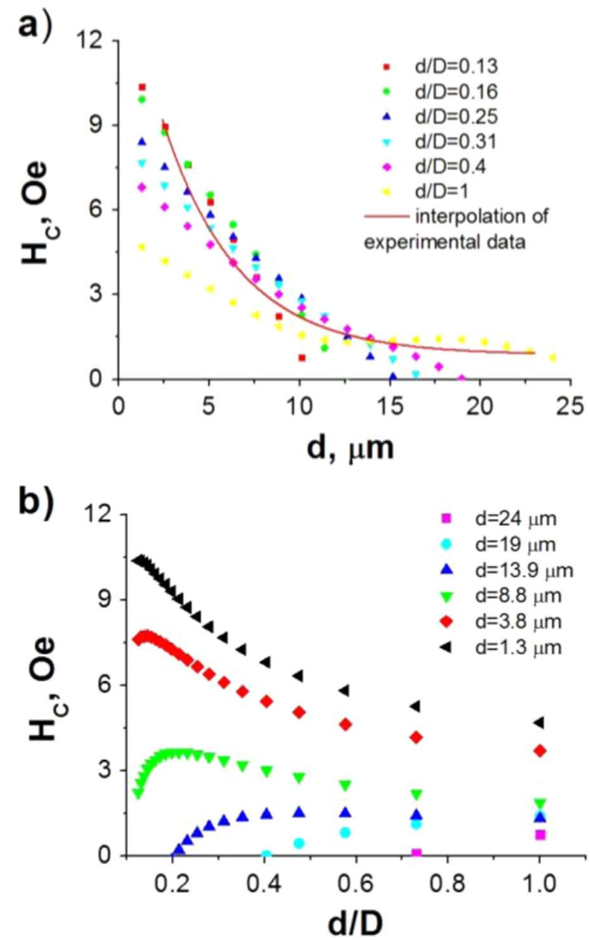

Fig. 4. The sections of the surface $H_C(d;d/D)$ by the planes (a) $d/D = const$ and (b) $d = const$.

Two obtained facts are in favor of reasoning above: (i) the changing of *d/D* in the region with the smallest *d/D* (i.e. with the highest internal stresses in metallic nucleus) provokes the largest changes of H_C for all samples and (ii) the changing of large enough *d/D* (i.e. under the consideration of the region with small internal stresses in metallic nucleus) practically does not affect the H_C for all samples. With regard to tending of coercive force to 0 for a small d/D ratio (i.e. high stresses) and large d, it can be associated with increasing of the radial domains volume in comparison with the volume of axial magnetized domain of the metallic core of the microwire.

Fig. 4(a) obviously shows the difference between the dependences of magnetic properties of microwires on the metallic core diameter with (dots) and without (solid line, the same as in Fig. 2) taking into consideration the contribution of the *d/D* parameter. The $H_C(d)$ dependences are not similar for different values of *d/D*. The tendency 'the smaller value of *d/D*, the stronger influence of *d* on the coercive force' was observed. $H_C(d)$ curve with smallest slope, i.e. the lowest influence of *d* on microwires magnetic properties, is obtained for maximum value of $d/D = 1$ (theoretically – the absence of a glass shell; in practice – the thickness of the glass shell less than 0.5 μm). Moreover, there is the value of *d*, for which the magnetic properties become independent of the *d/D*, i.e. of the stresses in the metallic nucleus. For $Fe_{77.5}Si_{7.5}B_{15}$ microwires this value is $d = 11$ μm for $d/D > 0.4$.

3.3. Magnetostriction properties

All values of the magnetostriction coefficient, λ_S, were

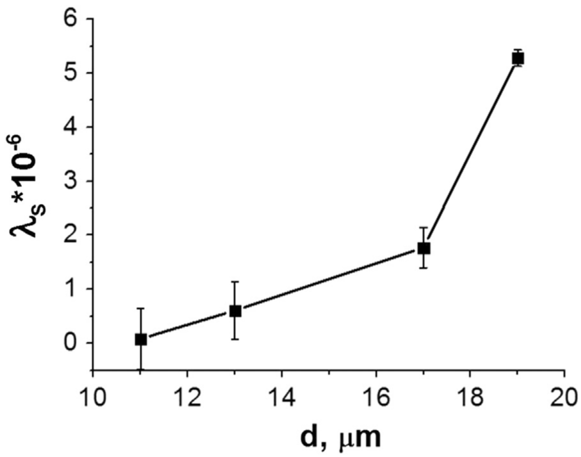

Fig. 5. Dependence of magnetostriction coefficient on the *d* for the microwires with similar values of *d/D*∼0.65–0.69.

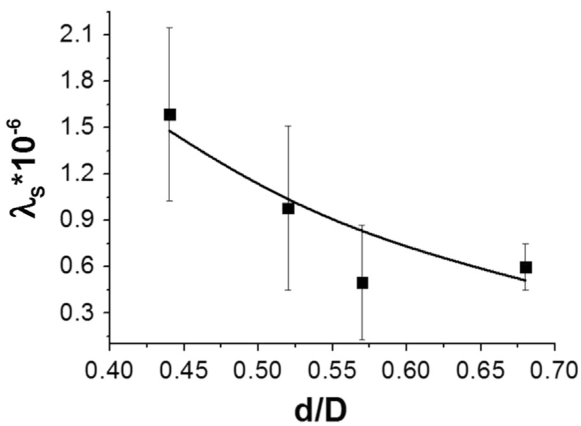

Fig. 6. Dependence of magnetostriction coefficient on the *d/D* for microwires with similar values of d∼12–13 μm.

measured by small angle magnetization rotation method and obtained by five measurements for each microwire. The number of measurements does not effect the resultant values [9]. However, there are limitations of set-up for measurements of the magnetostriction coefficient. Due to the sensitivity limit only microwires with the diameter not less than 11 μm were examined. Thus, we did not have enough data to solve the task even with data lack as we performed in the previous paragraph.

The largest value of the magnetostriction coefficient $\lambda s=1.62{*}10^{-5}$ was obtained for the microwire with following parameters: $d=23$ μm, $d/D=0.79$. This microwire has maximum diameter (see Table 1). This value is close to the magnetostriction coefficient of the bulk materials (for example, $3{*}10^{-5}$ for ribbon with the same FeSiB composition [19]).

Let us consider the effect of the microwire parameters (*d/D* and *d*) on the magnetostriction coefficient. Fig. 5 shows the dependence of λ_S on the *d* value for microwires with different core diameters (11 μm, 13 μm, 17 μm and 19 μm) and similar values of the *d/D* ratio (0.65, 0.69, 0.66 and 0.65, respectively). We observed the following dependence: the core diameter increases the magnetostriction coefficient increases.

Fig. 6 shows the dependence of the magnetostriction coefficient on the diameters ratio. In this case, we selected microwires with similar core diameter (12 μm and 13 μm) and with different *d/D* ratios. We observed the dependence on d/D, which is in contrast to behavior in the Fig. 5 the *d/D* ratio increases (the value of the internal stresses in the metallic nucleus decreases) the value of magnetostriction coefficient decreases.

Figs. 5 and 6 indicate that the influence of both *d* and *d/D* parameters on the λ_S are strong and important. The reduction of the magnetostriction coefficient is the result both of the decreasing of internal stress induced by presence of the shell (different coefficients of the glass and metal thermal expansion) and of increasing of the quenching stresses (induced my rapid solidification process) in the microwire cores.

To compare the changes in the dependences of coercive force and magnetostriction coefficient on *d* and *d/D* we considered the Figs. 4–6 For microwires with $d>11$ μm and $d/D>0.4$: (i) H_C is independent of *d* but λ_S has a strong dependence on *d* (the value of λ_S for $d=13$ μm is 6 times smaller than for $d=19$ μm); (ii) H_C slowly decreases with increasing *d/D* but λ_S increases three times in the same range of *d/D*. Thus, we can summarize that in the ranges of *d*, d/D under consideration, the magnetostriction coefficient is more sensitive than magnetostatic properties both to shell-induced, and quenching-induced mechanical stresses in the metallic nucleus of microwires. It can be explained by taking into account the dependence of coercive force on effective anisotropy, which consists of many contributions and particularly magnetoelastic one.

4. Conclusions

In this work we demonstrated that the contribution of glass shell-induced stresses (associated with the ratio of diameters – *d/D*) and the stresses originating from quenching (residual, characterized by *d*) in the metallic nucleus can be separated by the correct simulation-methods analysis of the experimental results. Dependences of the magnetic properties on *d* and *d/D* are proved to be non-monotonic and different for various shell-cased and quenching-cased stresses of $Fe_{77.5}Si_{7.5}B_{15}$ microwires. It was found that for $d/D>0.4$ and $d>3.8$ μm the dependences of the coercive field on the diameter of the metallic nucleus and diameters ratio are non-monotonic.

Magnetostriction coefficient also depends on the diameters ratio and the diameter of the nucleus. Magnetostriction coefficient is reduced due to the decreasing of the shell-induced stress (increasing of *d/D*), while increasing of the nucleus diameter (decreasing of *d*) leads to increasing of magnetostricion coefficient.

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