THE PECULIARITIES OF MAGNETOSTATIC BEHAVIOR OF AMORPHOUS WIRES.

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The average longitudinal component of the inner core magnetization as a function of the z coordinate for a short wire and for various values of external magnetic field was obtained. The remanent magnetization of the short wire was calculated as a function of a length for Co-based. Magnetostatic properties of short Co-based and Fe-based wires were investigated and experimental data correspond to theory results.

Keywords: *amorphous ferromagnetic wires, bamboo domain structure, magnetostatic properties*

Introduction. The properties of amorphous ferromagnetic wires attract considerable research interest due to its unique magnetic characteristics such as magnetic bistability and giant magneto-impedance effect. The strong dependence of magnetisation reversal process in Fe-rich amorphous wires with positive magnetostriction $\lambda>0$ on their length has been reported in [1,2]. In order to explain this significant changes of magnetostatic parameters with sample length we present the results of theoretical and experimental investigation of magnetic properties of the amorphous wires with different magnetostriction in dependence on their length.

Theory. At first we calculated the domain structure of thin amorphous wire with small and negative saturation magnetostriction constant $\lambda_s \approx -10^{-6}$. It was shown that the magnetization distribution in a core and an outer shell of amorphous wire is determined by the distribution of a residual quenching stress which arises due to cooling in rotating water [3]. But we estimated that the radius of a wire core may be smoothly reduced to zero towards its endfaces due to demagnetization field of the magnetic charge near the wire ends. This reduction leads to the dependence of the longitudinal magnetization on the coordinate along the wire axis. The characteristic length of this magnetization reduction turns out to be comparable with the wire length.

It should be noted that all derivation given for domain structure calculation, strictly speaking, only for a middle part of a sufficiently long cylindrical wire since it is easy to see that near the wire ends there are the demagnetization fields which must affect the wire magnetization substantially. Suppose for a moment that the bamboo magnetization distribution remains unchanged along the wire length up to the wire ends. Then, at the endfaces of the wire in the inner core region $\rho < R_1$ a surface magnetic charge arises with a large density $\sigma \approx M_s$. Due to relatively large value of the wire radius it is difficult to apply the method of numerical micromagnetics in order to calculate strictly the actual magnetization distribution near the wire ends. Therefore, one needs for some physically allowable assumptions. Here we suppose that in order to reduce the magnetostatic energy of the charge the wire magnetization in an inner core near the wire ends is twisted in a manner shown in Fig.1. As a result, the average longitudinal wire magnetization is a function of the coordinate z along the wire length.

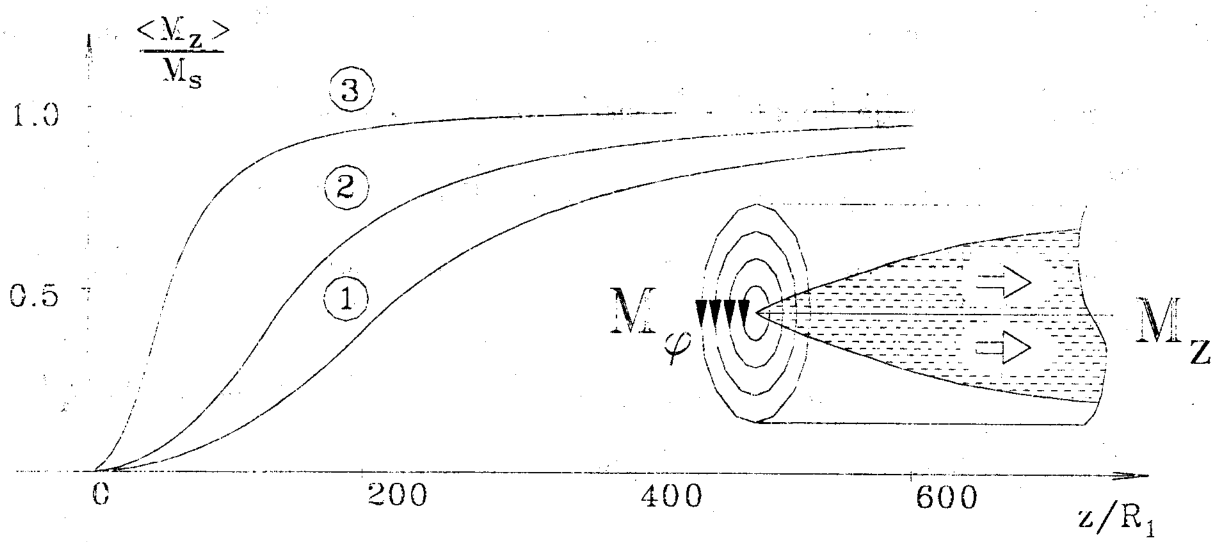


Fig.1. The average longitudinal core magnetization is a function of the coordinate z along the wire length at different magnetic field 1) $H_0 = 0$ Oe; 2) $H_0 = 0{,}01$ Oe; 3) $H_0 = 0{,}1$ Oe. Core radius $R_1 = 0.6 \div 0.8\, R$.

This fact is in accordance with the experimental data [12] where it was shown that the longitudinal magnetization of a Co-based wire increases smoothly from its endfaces within the intervals of the order of several centimetres. Besides, our model leads to the conclusion that the remanent magnetization of a short wire is a function of its length L_z. Thus, there is a critical wire length L_z^* such that for $L_z < L_z^*$ the influence of the demagnetization fields on the wire magnetization is substantial. The notion of the critical length is already discussed briefly in [?].

Minimizing the sum of the energies (the increasing of the Zeeman energy due to magnetization twisting in the core region magnetostatic energy contribution to the total core energy the magnetic anisotropy energy of the inner core) with respect to radius of inner part of wire b_0 one can obtain the equilibrium value of this parameter

$$b_0 = L_z\left[\left(\eta_1 \frac{K_e}{M_s^2} + \eta_2 \frac{H_0}{M_s}\right) \Big/ \left|\ln\left(\eta_1 \frac{K_e}{M_s^2} + \eta_2 \frac{H_0}{M_s}\right)\right|\right]^{1/2}, \qquad (3)$$

where the numerical constants are $\eta_1 = \pi\xi_a/2\xi_m \approx 0.026$, $\eta_2 = \pi\xi_H/2\xi_m \approx 0.022$, H_0 is the field amplitude, which is positive if the magnetic field points along the direction of average longitudinal magnetization component in the inner core, and K_e - the effective anisotropy energy density, M_s - saturation magnetization. We see that the core radius near the centre of the short wire is proportional to the wire length.

Let us define the critical wire length at $H_0 = 0$.by means of the equation $b_0(L_z^*) = R_1$. Then it follows from (3) that

$$L_z^* = R_1\left[\frac{M_s^2}{\eta_1 K_e} \ln \frac{M_s^2}{\eta_1 K_e}\right]^{1/2}. \qquad (4)$$

Putting $M_s = 500G$, $K_e = 250\ erg/cm^3$ we see that the ratio $M_s^2/\eta_1 K_e \approx 4\cdot 10^4$ is very large, so that we have in this case $L_z^* \approx 600R_1$. This means that the critical wire length is of the order of several centimetres for a wire with initial core radius $R_1 = (2 \div 4)\cdot 10^{-3} cm$.

The average longitudinal component of the inner core magnetization is given by the equation

$$\frac{\langle M_z \rangle}{M_s} = \frac{2}{R_1^2} \int_0^{b(z)} \rho d\rho \alpha_z = (2\ln 2 - 1)\left(\frac{b(z)}{R_1}\right)^2, \tag{5}$$

where $b(z)$ is determined by means of equation (3). For weak enough magnetic field (5) gives also the longitudinal component of the wire magnetization since in this case the outer shell with predominantly circumferential magnetization does not contribute to this quantity considerably. Fig.2 shows the reduced z-component of wire magnetization as a function of the coordinate z along the wire length as given by equation (5). It can be seen that the weak external magnetic field affects the wire magnetization considerably.

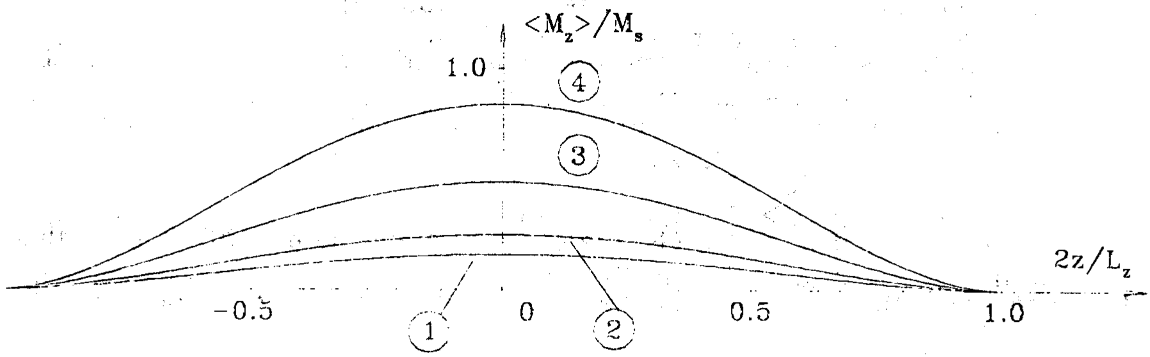


Fig. 2. The average longitudinal component of the inner core magnetization as a function of the z coordinate for a short wire with $L_z/L_z^* = 0.8$ *and for various values of external magnetic field: 1)* $H_0 = -0.2\ Oe$; *2)* $H_0 = 0\ Oe$; *3)* $H_0 = 0.5\ Oe$; *4)* $H_0 = 1.2\ Oe$. *The effective anisotropy constant and the saturation magnetization are given by* $K_e = 250\ erg/cm^3$ *and* $M_s = 500\ G$.

Using the equations (4), (5) the remanent magnetization of the short wire can be calculated as

$$\frac{M_r}{M_s} = \frac{1}{L_z M_s} \int_{z \le L_z/2} dz \langle M_z \rangle = \frac{8}{15}(2\ln 2 - 1)\left(\frac{L_z}{L_z^*}\right)^2. \tag{6}$$

Thus, in our model for $L_z < L_z^*$ the remanent wire magnetization turns out to be proportional to the square of the wire length. This fact can be easily check in experiment.

Samples and measurements. In order to prove our theoretical results we investigated magnetization reversal of amorphous ferromagnetic wires $(Fe_{.06}Co_{94})_{72.5}Si_{12.5}B_{15}$ with negative magnetostriction $\lambda<0$ and $Fe_{77.5}Si_{7.5}B_{15}$ with positive one $\lambda>0$.

Wires have diameter is 130μ, which is the same as in [1], and lengths of our sample are 8 mm and 24 mm, with ratio D/l 168 and 56 correspondingly.

The measurements were made on Vibrating Sample anisometer in fields up to 8 кOe. At longitudinal remagnetisation (magnetic field $\mathbf{H}_{||}$ is parallel to the wire axes) and at cross remagnetisation (magnetic field $H_{\perp}$ is perpendicularly to wire axis) we measured field dependence of various components of a magnetic moment: $\mathbf{M}_{||}$ - projection of the magnetic moment to the field direction, and $\mathbf{M}_{\perp}$ - projection of the magnetic moment in the perpendicular to a field direction (See fig.3A and 3B).

We define saturation magnetisation $\mathbf{I_s}$ with two methods. The first is - at cross remagnetisation the saturation appears at H equal $2\pi I_s$, so we have

$$I_S = H_S/2\pi. \qquad (7)$$

However if $\mathbf{I_s}$ >1275 Gs, the saturation will be at H>8 кOe. In this case $\mathbf{I_s}$ is defined with follows. In the field H, applied under the angle φ to the wire axis (see fig.3C),

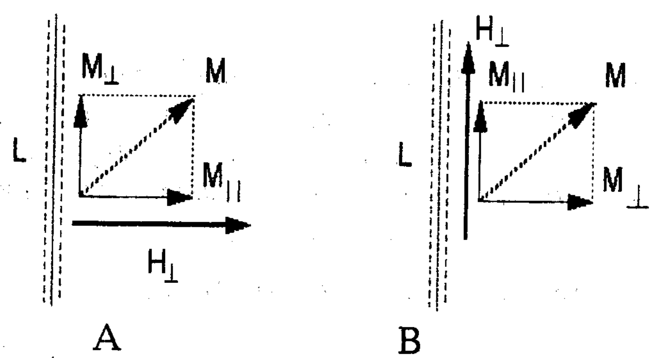
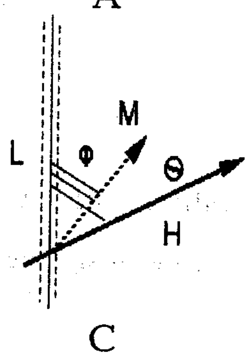


Fig 3. Measurement of hysteresis loop for different magnetic moment component at different magnetic field orientation (A, B) and definition of I_s - (C) .



A) $$I_s = \frac{H_{\perp s}}{2\pi}$$

C) $$I_s = \frac{HSin(\theta - \varphi)}{2\pi Sin2\varphi}$$

the equilibrium orientation of the magnetic moment is defined from a condition of the minimum of complete energy, which is equal to the sum of the magnetostatic energy and the anisotropy energy $2\pi I_S Sin2\phi = Sin(\theta - \phi)$, where θ is the angle between the wire axis and the magnetic moment. Then one can get a value of saturation magnetisation without value of the sample volume

$$I_S = HSin(\theta - \phi)/2\pi Sin2\phi. \quad (8)$$

Experimental results and discussion. It was founded, that influence of the samples form on the magnetostatic characteristics and the character of remagnetisation strongly depends on the sample compounds, i.e. on the sign of λ.

At *longitudinal remagnetisation* hysteresis loops all samples have a similar kind. Field dependence $M_{||}(H_{||})$ for the Fe-based wire is shown on fig.4a. For this wire coercive force is slowly decreasing from the long to the short sample H_c=0.08Oe and 0.06Oe correspondingly, but permeability sharply, almost on the order, decreases from 0.67 up to 0.06 and interval of linear remagnetisation increases from (-1 Oe ; +1 Oe) up to (-4 Oe; +4 Oe) - that corresponds to decreasing of core diameter from 0.7R to 0.55R.

Field dependence $M_{||}(H_{||})$ for the Co-based wire is shown on fig.4b. There is decreasing of permeability from 1 till 0.2 and simultaneously coercive force H_c essentially increases from 0.09 Oe up to 0.37 Oe. One can see in Table slight decreasing the core radius with length obtained from our data.

Field dependence $M_{\perp}(H_{||})$ permits to exclude coherent character of longitudinal remagnetisation for all samples because changing of $M_{\perp}$ doesn't exceed $3\%I_S$. for samples of both compounds and lengths. Hence, it is possible practically to exclude a coherent remagnetisation. The same result was obtained in [1] for Fe-rich wires with length *l*>30 mm. From our results we also can conclude that the reversal magnetization by the domain wall propagation is saving as for Co-based wires as for Fe-based ones.

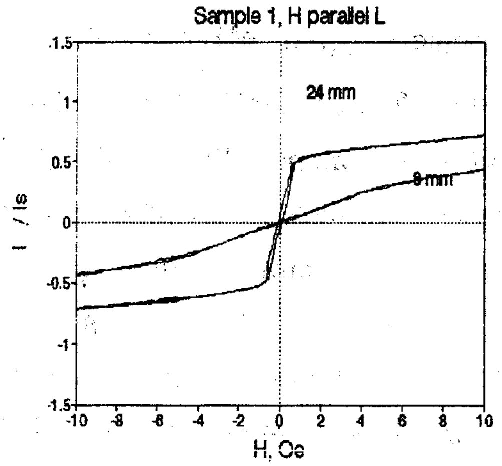


Fig.4A. The longitudinal remagnetisation of short and long samples of ($Fe_{77.5}Si7_{.5}B_{15}$.)

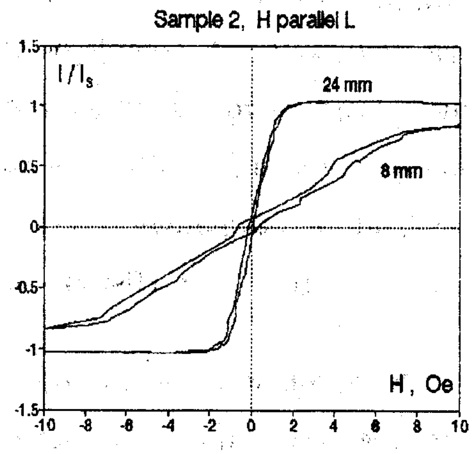


Fig. 4b. The longitudinal remagnetisation of short and long samples of $(Fe_{.06}Co_{94})_{72.5}Si_{12.5}B_{15}$

The values of the remanent magnetization obtained taking into account demagnetisation field are shown in Table 1. Their decreasing for both samples qualitatively correspond to our theory.

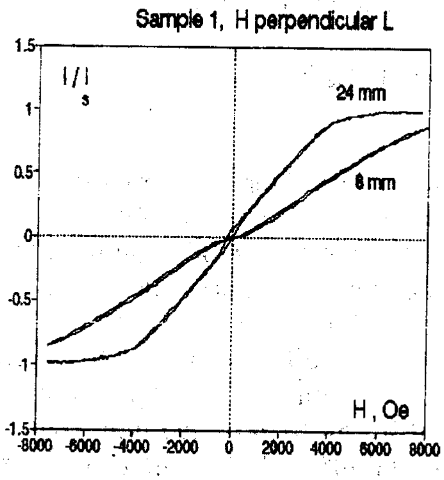
Table 1.

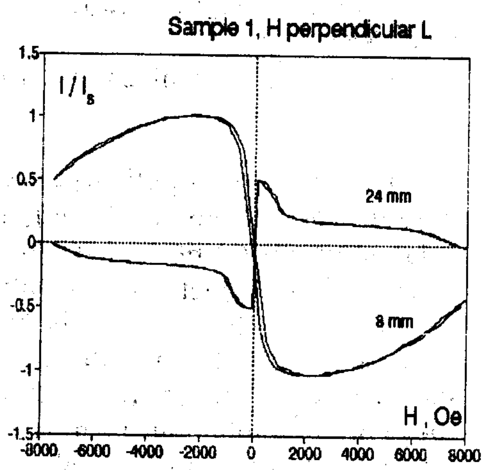
	L, mm	H_c, Oe	$H_{\perp s}$, Oe	I_r/I_s	r_{core}/R
$Fe_{77.5}Si7_{.5}B_{15}$	24	0.08	4400	$1.02*10^{-4}$	0.7
$Fe_{77.5}Si7_{.5}B_{15}$	8	0.06	-	$0.48*10^{-4}$	0.55
$(Fe_{.06}Co_{94})_{72.5}Si_{12.5}B_{15}$	24	0.09	3750	$0.16*10^{-2}$	0.99
$(Fe_{.06}Co_{94})_{72.5}Si_{12.5}B_{15}$	8	0.37	3750	$4.00*10^{-2}$	0.9

At *cross remagnetisation* of the first-type wires it was found essential increasing of saturation field H_s. So for short sample the saturation doesn't occurs in 8 kOe and we needed define I_s using the formula (8).

For long sample both methods of definition of I_s give the same significance 700 Gs, for short I_s - 1400 Gs (see fig. 3a), simultaneously there is essential changing of field dependence of $M_{\perp}$ i.e. components of a magnetic moment along the wire axis (see fig. 3b). For the long sample the maximum of

$M_\perp$ reaches $30\%I_s$ in a weak field, and then decreases up to a zero with the increasing of fields. But at wire length reduction the maximum significance $M_\perp$





Puc. 3A. The cross remagnetisation of short and long samples of ($Fe_{77.5}Si7_{.5}B_{15}$.) M // H

. 3B. The cross remagnetisation of short and long samples of ($Fe_{77.5}Si7_{.5}B_{15}$.) M // L

is quite equal to I_s in fields of the order 2 кЭ and monotonically decreasing, remains the order $45\%I_s$ in a field 8 кЭ. That corresponds to strengthening of coherent character of cross remagnetisation.

Conclusions. The average longitudinal component of the inner core magnetization as a function of the z coordinate for a short wire and for various values of external magnetic field was obtained. The remanent magnetization of the short wire was calculated as a function of a length for Co-based. Magnetostatic properties of short Co-based and Fe-based wires were investigated and experimental data correspond to theory results.

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Preface.

The Russian-Japanese joint seminar "The Physics and Modelling of Intelligent Materials and their Applications" (PMIMA) was held from 19 through 21 September 1996 at the Faculty of Physics of Moscow State University in Moscow, Russia.

The seminar aimed to discuss various subjects on fundamental and applied problems on intelligent materials and connected topics.

The seminar gathered 61 participants (13 of them were from Japan). Russian participants were from Moscow University (faculties of physics and chemistry and institute of mechanics), Chelyabinsk and Vladikaukaz Universities, Baikov Institute of Metallurgy, Moscow institute for Radioengineering Electronics and Automation, Troitsk Institute for Innovation and Fusion research and other divisions of Russian Academy of Science. 43 papers were presented that were contributed by 122 authors.

The scientific program included 6 oral sessions and a poster session. Besides there were carried out an excursion over the scientific laboratories of the faculty of physics of the Moscow University.

The seminar has demonstrated the difference between Russia and Japan in that which can be called as "fundamental" and "applied" approaches. The seminar allowed to get the best from both approaches in our countries. The following list shows possible joint research projects that can be initiated soon:

a) ferromagnetic shape memory alloy;

b) non—destructive testing;

c) biomedical applications;

d) high-T_c superconductors.

I would like to thank all of the people who contributed to the success of the seminar. Especially I appreciate the essential contribution of professors Tani J. and Takagi T. from Tohoku University (Japan).

N.S.Perov
Program Committee Chairman

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