

CAST AMORPHOUS MAGNETIC Fe-BASED MICROWIRES

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Abstract

The magnetic characteristics of Fe-based cast amorphous glass-coated microwires (with a positive magnetostriction constant) are investigated. The residual stress distributions in this type of microwires determine the domain structures and the switching field behavior.

The magnetic temperature characteristics of cast amorphous micro- and nanowires with a positive magnetostriction constant are studied. These wires are characterized by a rectangular hysteresis loop, and they can be used in measuring and identification engineering.

1. Introduction

Cast glass-coated amorphous micro- and nanowires (CGCMNWs) with positive magnetostriction are very interesting materials for theoretical study as well as for practical applications [1–10]. Having positive magnetostriction, their domain structure consists of two magnetized domains, and magnetization process runs through a large Barkhausen jump (LBJ) of a single domain wall along the entire microwire (see Fig. 1).

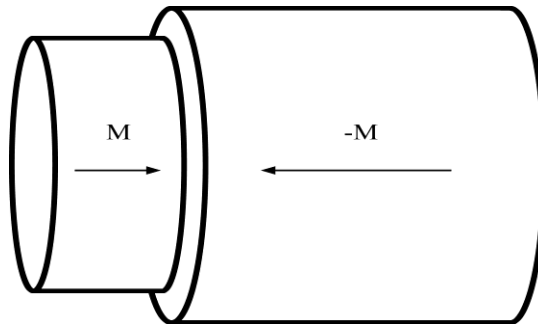


Fig. 1. Domain structure of a CGCMNW [2] proposed according to the measurements of the FMR spectra [3].

CGCMNWs are composite materials that consist of a metallic nucleus and a glass coating (see Fig. 2). The diameter of the metallic nucleus d_m is 50 nm to 70 μm , whereas the glass-coating thickness $(D_w - d_m)/2$ is 0.1–30 μm .



Fig. 2. Glass-coated magnetic microwires, where $d_m = 2 r_m$ (r_m is the radius of metallic core of the microwire) and $D_w = 2 R_w$ (R_w the total radius of the CGCMNW).

They are produced using a simple and cheap method of preparation (see Fig. 3) (up to 10 km of a microwire can be produced from 1–5 g of the alloy).

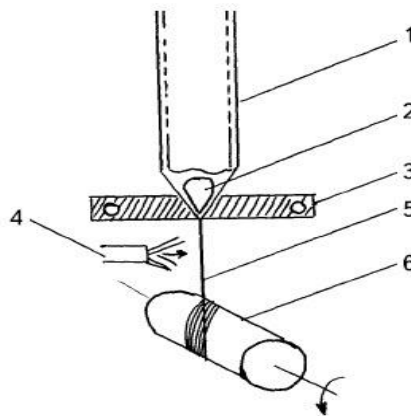


Fig. 3. Production of a CGCMNW (see [1–4]): (1) glass tube; (2) metal drop; (3) inductor; (4) water; (5) glass-coated microwire; and (6) rotating support.

The CGCMNW with positive magnetostriction is bistable in a wide range of the radii of the microwire core (30–0.5 μm) with a minimal length of the fragment on the order of 1 mm [1–5].

The value of the critical size is determined by the state of the glass coating at the flat end of the microwire [2].

The CGCMNW can be employed in construction of miniaturized sensors.

The additional coating of the glass shell with a material that has a high coefficient of thermal expansion can affect the temperature changes in the magnetic properties. For practical use, it is of interest to find the dependence of the values of coercive field H_c (or switching field H_s) and their fluctuations of σ_H on temperature and heat treatment [6–10].

2. Magnetization pulse forms

It is known that the CGCMNW with positive magnetostriction possesses a rectangular hysteresis loop and its magnetization is reversed by LBJ, the coercive force of which can be regulated by both residual and external mechanical stresses (see [1–5]).

Various wires feature properties of magnetization reversal with the use of the LBJ, and their magnetic structure can differ from the magnetic structure of the CGCMNW. In this case, the possibility of their long-term existence in certain (one of two) magnetized states and the stepwise transition from one magnetized state to another is called the magnetic bistability effect (by analogy with similar effects in other sections of physics). However, as was noted in [2], the particular domain structures of these micro- and nanowires can differ from one another. Therefore, a wider theoretical study of the bistability phenomenon in magnetic materials that will not depend on the particular magnetic structure makes some sense.

Bistable ferromagnet (BF) technology is usually reduced to its formation in materials with a strongly pronounced gradient of the magnetic potential profile, which is possible, e.g., in the CGCMNW, in the presence of quasi-mono-axial magnetic anisotropy. In this case, both bistable states can be abstractedly represented as energy levels of the system spaced by the energy barrier. BFs were previously obtained by thermal and mechanical treatment. Thus, in particular, the well-known Wiegand vicalloy wire was obtained [2]. In contrast to the Wiegand wire, since the production moment, the CGCMNW with a positive magnetostriction is a BF.

In addition to the CGCMNW manufacturing technology, there is the Unitika technology (Unitika Ltd.). The wires manufactured by the Unitika technology (this technology is also referred to as in-rotating water quenching) possess another magnetic structure and different (from CGCMNW) magnetic characteristics, although they are also referred to BF.

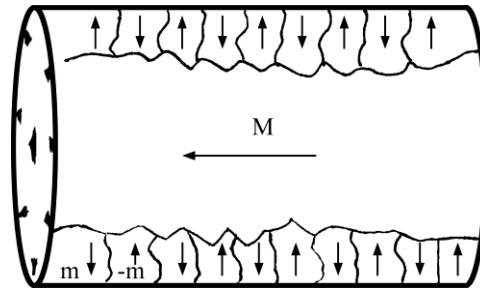


Fig. 4. Domain structure of the wires manufactured by the Unitika technology.

The properties of CGCMNW are basically discussed in this work, but many of our results can refer to any BF (see Figs. 5, 6). We will start to discuss the magnetization reversal mechanisms, which have been discovered, in particular, in studies of the magnetization reversal of materials out of the Wiegand vicalloy wire and earlier in studies of multiple jump materials and theoretically examined in detail in [2].

If the structure of single pulses in the BF, as the CGCMNW, is studied, one can find [2] that the BF magnetization reversal also occurs by two mechanisms—relaxation and accelerative. The relaxation mechanism is characterized by a pulse with a steep leading edge and a gentle falling edge, and the accelerative mechanism is characterized by a smooth increase and a sharp fall of the second leading edge of the pulse (see Fig. 7). The analysis of the studies shows that the operating characteristics of the BF in which these mechanisms show themselves are ambiguous. Therefore, it is necessary to study in detail the usefulness of the first or second type of pulses (or even their combinations).

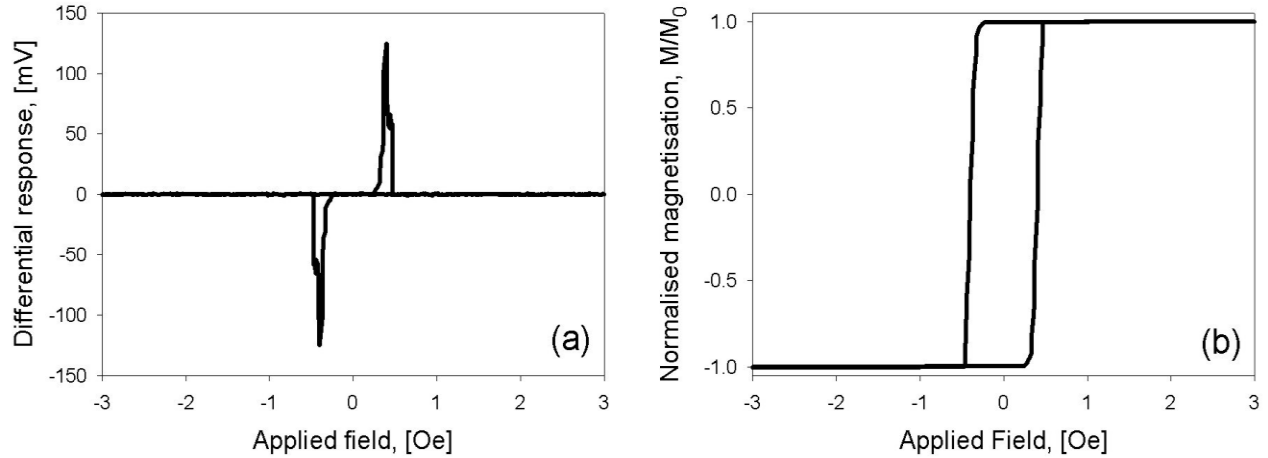


Fig. 5. Differential (a) and integral (b) hysteresis loop by LBJ.

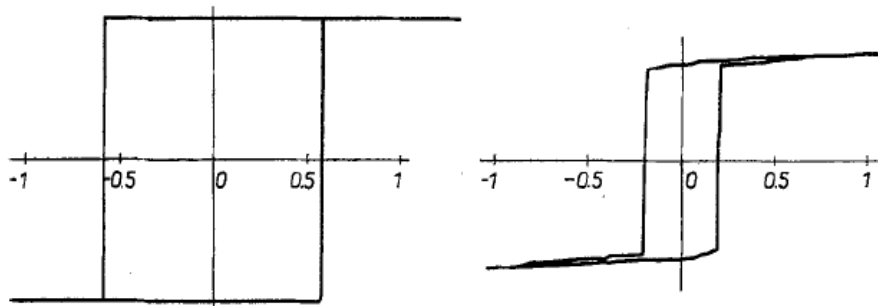


Fig. 6. Hysteresis loops of amorphous microwires with positive magnetostriction: (a) as-propagated glass coated microwire and (b) the microwire without a glass coat.

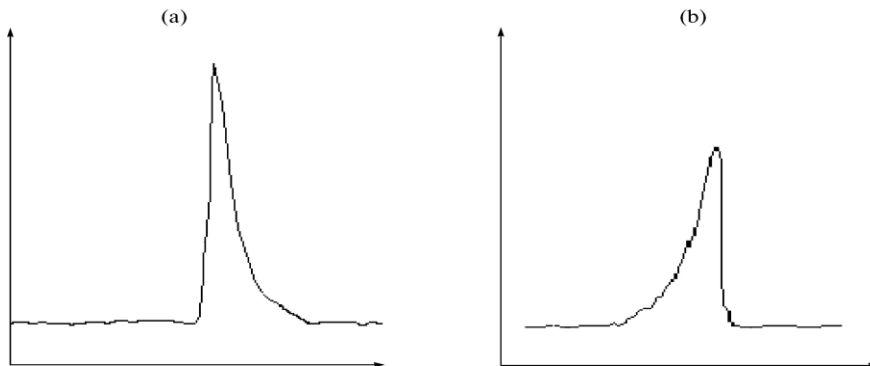


Fig. 7. (a) Relaxational and (b) accelerative pulse forms. They are plotted along the axes (in arbitrary units): X is the time at the LBJ moment (where the external field intensity slowly increases with time according to the linear law and reaches the starting field) and Y is the response of the magnetic induction arising at the BF magnetization reversal.

3. Residual stresses in CGCMNWs

The residual stresses are the result of differences in the coefficients of thermal expansion of the metal and the glass. A simple theory for the distribution of residual thermoelastic stresses was presented in [4–10]. In terms of cylindrical coordinates, the residual thermoelastic tension is characterized by axial, radial and tangential components which are independent of the radial coordinate:

$$\sigma_{0r} = \sigma_{0\phi} = P = \sigma_m k x / (1 + k/3 x + 4/3) \quad (1.a)$$

$$\sigma_{0z} = P (k + 1 x + 2) / (kx + 1) \quad (1.b)$$

Here, $x = (R_w/r_m)^2 - 1$, where r_m is the radius of the metallic core of the microwire and R_w is the radius of the microwire (see Fig. 2); also $s_m = eY_m$, where Y_m is the Young modulus of metal and $e = (\alpha_m - \alpha_g)(T - T^*)$, where α_m and α_g are the thermal expansion coefficients of the metal and the glass, respectively; T^* is the solidification temperature of the composite microwire (when both metallic nucleus and glass-coating solidify) and T is the experimental temperature; in addition, $k = Y_g/Y_m$, where Y_g is the Young modulus of the glass.

In terms of the model used for the stress formation in the microwire, the microwire strand from its axis up to the internal radius b preserves the liquid state, while from b up to in metallic core radius, R , freezes earlier and only elastic residual stresses persist. So, at $b < r < r_m$, this model gives

$$\sigma_{1r} r \approx P (1 - b/r)^2 \quad (2.a)$$

$$\sigma_{1\phi} r \approx P (1 + b/r)^2 \quad (2.b)$$

$$\sigma_{1z} r \approx \nu \sigma_{1r} r + \sigma_{1\phi} r \quad (2.c)$$

where ν is the Poisson's coefficient. In addition, at $r < b$, this model gives

$$\sigma_{2r} r \approx 2K \ln b/r + \sigma_r, \quad (3.a)$$

$$\sigma_{2\phi} r \approx 2K (1 + \ln b/r) + \sigma_\phi, \quad (3.b)$$

$$\sigma_{2z} r \approx \nu \sigma_{2r} r + \sigma_{2\phi} r, \quad (3.b)$$

where K is the thermoelastic constant [4]. Note that a rigorous solution should be obtained by solving equations (2) and (3) at $r = b$ and taking into consideration that they are unacceptable at $r = 0$; also note that $s_r < s_\phi$ for any r .

4. The effect of heat treatment on the coercive force

In the alloys with a fairly high magnetostriction, the stress relaxation occurs during annealing, which leads to a decrease in coercive field H_c . However, in the present case, we can also speak about reversible changes in the coercive force if the heating and measurement occur

rapidly until the irreversible relaxation of the amorphous material is insignificant. These reversible changes in H_c are known to be linear in a sufficiently narrow temperature range [6–10].

Annealing (with the time of heat treatment sufficient for the relaxation of the amorphous structure) up to a temperature at which the formation of microcrystals begins ($\sim 300^\circ\text{C}$) is of practical interest. At temperature above 300°C , the formation and growth of a microcrystalline phase [4–9] in CGCMNW are observed (this temperature is designated as T_{cr}). Figure 8 shows a universal dependence of change in the coercive field connected with the relaxation of the residual stresses. Previously [9], it was noted that the heat treatment up to T_{cr} can improve the magnetic properties of CGCMNW, i.e., decrease the values of σ_H and H_c .

During the recording of the universal dependence (Fig. 8), the same specimens with a rectangular hysteresis loop were studied as in the case of the low-temperature dependences (Fig. 8). Their classical composition $(\text{Fe Co Ni})_{73} \text{B}_{16} \text{Si}_{11}$ is similar to the specimens that we have examined before [4, 9]. However, the result is unified with other amorphous magnetics as well. The compositions that we have used are characterized by a high thermal stability; i.e., by a fairly high value of temperature T_{cr} . In the present study, we used specimens with a fairly high thickness of the glass coating $\sim 7\text{--}10 \mu\text{m}$ (since their magnetic properties are found to be most stable); their coercive force H_{cm} at room temperature varied in a range of $0.5\text{--}1.5 \text{ Oe}$ with respect to the positive magnetostriction value. Regardless of the fairly wide range of values of initial H_{cm} , the correlation of H_c/H_{cm} in the limits of the error is up to 20% and falls within this universal dependence (Fig. 8). The latter also results, in particular, from the theory of [9]. Let us consider its main conclusions.

For the theoretical description of the above phenomena, let us generalize formula (4) in the case of a change in the structure. On the basis of the theory of [9], we shall write with an exponential accuracy:

$$H_s/H_{sm} \sim \exp\{E_{1,2}/kT\} / [1 + \exp\{-G/kT\}], \quad (4)$$

where the first multiplier of the formula describes the low-temperature processes with activation energy $E_{1,2}$ and the second multiplier is responsible for high-temperature processes, for which G is the change in the Gibbs energy, owing to the processes of the irreversible phase transitions connected with the crystallization of the amorphous state. In the classical nucleation theory (Becker–Volmer), an inverse value is generally used, which determines the rate of the nucleation.

At low temperatures, the value of $\exp\{-G/kT\}$ is small (compared to a unity); therefore, the formula is sufficient. At high temperatures, formula (4) is represented as follows:

$$H_s/H_{sm} \sim \exp\{E_{1,2}/kT\} \exp\{G/kT\}. \quad (5)$$

The main dependence is now determined by multiplier $\exp(G/kT)$, which is the one to determine the irreversible relaxation. Note that the model proposed makes it possible to suggest that

$$G(T) \sim T(S_1 + S_2), \quad (6)$$

where S_1 is the entropy change decreasing with the relaxation of the initial amorphous state into a more stable but also amorphous state and S_2 is the entropy change increasing during the transition from the metastable amorphous state to the stable polycrystalline state [9, 10].

Since, with an increase in the entropy, the system passes into a more stable state, the fluctuations of the switching field (Fig. 8) also decrease. Thus, the universality of the presented dependence can be justified thermodynamically.

Note that the qualitatively similar dependences for H_c on the heat treatment are obtained also for the amorphous materials (with a rectangular hysteresis loop) in the form of a band (Figs. 8, 9).

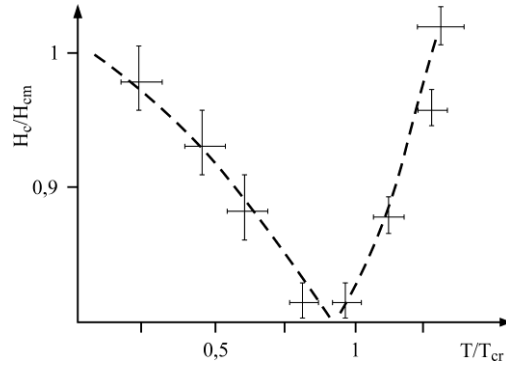


Fig. 8. Universal dependence of the relative value of coercive field H_c/H_{cm} , where H_{cm} is the initial coercive field (at room temperature), on the heat treatment at high temperatures. The errors are indicated in the measurements of the relative temperature and the relative value of H_c/H_{cm} . The latter corresponds to the relative value of σ_H .

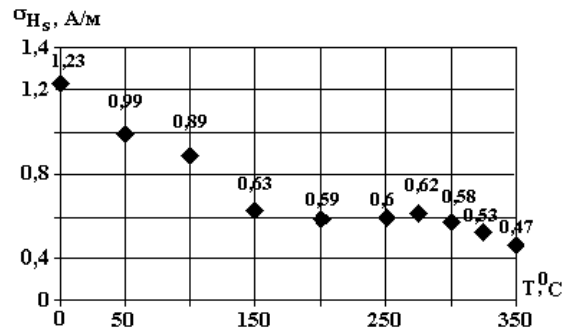


Fig. 9. Temperature dependence of the switching-field fluctuations σ_{H_s} .

The latter is interpreted here as a proof of a stronger dependence of H_c on the irreversible processes that are described by the multiplier $\exp(G/kT)$ during the high temperature treatment.

6. Domain wall of microwires

We have found that the domain structure of the Fe-based cast amorphous microwire consists of two cylindrical domains [4–6]. The domain wall (DW) can arise in the region of cylinder, where $r < b$, because the anisotropy energy in this region is smaller. One minimizes the sum of the exchange and anisotropy energies:

$$E_1 \gg AD_1^{-1} + l bK \ln(D_1/b), \tag{7}$$

where A is the exchange energy constant, λ is the magnetostriction constant and Δ is the DW thickness, which we will calculate. Hence, the energy minimization, $\delta_{\Delta} E = 0$, gives the following expression for the DW thickness Δ_1 :

$$D_1 \gg A/(l Kb). \quad (8)$$

By using the following empirical order of magnitude values $A \approx 10^{-11} J/m$, $b \sim 10^{-6} m$, $l \sim 10^{-6}$, $K \sim 10^8 Pa$, we obtain $D_1 \sim 0,1mm$.

In addition, we estimate the density energy W_1 of the DW by $W_1 \gg s l D_1$. In this approximation, W_1 is independent of the magnetostriction and it is determined by the exchange interaction and the parameter b ; also by using the given experimental values, we find

$$W_1 \sim A/b J \cdot 10^{-5} J/m^2. \quad (9)$$

On the other hand, if the DW is located in the region where $r \sim R$, we can use a method similar to the one proposed in [4].

$$E_2 \gg A D_2^{-1} + l P (D_2^2 / r_m) \quad (10)$$

Thus, the DW thickness Δ_2 is determined by

$$D_2 \gg \sqrt[3]{A r_m / (l P)} \gg (1- 0,01)mm, \quad (11)$$

and its numerical value is on the order of $0.01 \mu m$. Moreover, the energy density in this case is given by

$$W_2 \gg \sqrt[3]{A^2 l P / r_m}. \quad (12)$$

Note that it is determined by the magnetostriction, the residual thermoelastic tension, the exchange interaction and radius R of the metallic core of the microwire. In addition, using the previous experimental values, we find that

$$W_2 \sim 10^{-4} J/m^2. \quad (13)$$

Furthermore, in the formation of the domain structures, it is energetically advantageous for a large part of the DW to be in states close to metastable states.

7. Conclusions

In the fabrication of cast amorphous glass-coated microwires, the residual stresses increase from the axis attaining their maximum values on its surface. The theory of thermoplastic relaxation can be used to show that residual stresses will increase on the surface of the microwire,

which corresponds to the previously obtained experimental data. The cast glass-coated amorphous microwires exhibit residual magnetization due the specific distribution of residual stresses. This property of these microwires can be used for producing long-term magnetic storage elements and for improving the behaviour of some sensor electronic devices. We have derived a simple analytic expression for the switching field dependence on residual stresses, the radius of the metallic core of the microwire, the magnetostriction constant, and the temperature, which has been experimentally verified.

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