PREPARATION OF CAST GLASS-COATED AMORPHOUS MAGNETIC MICROWIRES

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Abstract

Technological aspects of the Ulitovsky–Taylor method for the preparation of glass-coated microwires with different structure of metallic cores are analyzed. The residual stress distributions in microwires of this type determine the domain structures. The residual stress in cast amorphous micro- and nanowires is studied.

1. Introduction

Cast glass-coated ferromagnetic amorphous microwires (CGCFMWs) are known to exhibit good magnetic properties. CGCFMWs are composite materials that consist of a metallic core and a glass coating. The glass-coating induces strong residual stress in the core. This residual (mechanical) stress affects the magnetostriction value that is determined by large magnetoelastic anisotropy.

The magnetic properties of CGCFMWs are determined by the composition, which gives the sign and magnitude of their magnetostriction, and by dimensions, i.e., metallic core diameter, glass-coating thickness, and their ratio, which are extremely relevant for the level of residual stresses induced during preparation. The magnetomechanical coupling between residual stresses and magnetostriction is mainly responsible for the distribution of anisotropy axes and domain structure formation.

2. Preparation by the Ulitovsky–Taylor method

CGCFMWs are one of the families of the amorphous materials which now are attracting growing interest due to magnetic properties and promising technological applications. A simple technology of production was first introduced in 1924 by Taylor, after whom this method is named [1–5]. Later (1950–1964), this method was significantly improved by Ulitovsky in order to produce large amounts of these microwires [3–5].

The preparation of cast glass-coated amorphous magnetic microwires by the Ulitovsky–Taylor method and the study of the magnetic properties thereof were reported in [1–14]. Amorphous microwires produced by the “in-rotating-water quenching” method have distinctive magnetic properties since they have different magnetic domain structures [7].

Technological aspects of the Ulitovsky–Taylor method for the preparation of CGCFMWs with different structure of metallic core are analyzed below (Figs. 1–3).

In the process, a few grams of the master alloy with a desired composition is placed inside a Pyrex-like glass tube placed directly within a high frequency inductor heater (Fig. 2). The alloy is heated up to the melting point to form a droplet. The portion of the glass tube adjacent to the melting metal softens and envelopes the metal droplet. After that, a glass capillary is drawn from the softened glass portion and wound on a rotating coil (Fig. 1).

Parameters of critical quenching rates for the preparation of a metastable, amorphous, or supersaturated state are 10^4–10^7 K/s.

Under suitable drawing conditions, the molten metal fills the glass capillary and a CGCFMW is thus formed where the metal core is completely coated with a glass shell (Fig. 3).

The microstructure and, hence, properties of the CGCFMW mostly depend on the cooling rate, which can be controlled by a cooling mechanism where the metal-filled capillary enters into a stream of a cooling liquid (water or oil) on its way to the receiving coil.

The properties of the microwire are largely attributed to the microstructure of the metal core. The casting analysis method offers the possibility of rapid cooling and solidification of the liquid metal in a nonequilibrium process allowing the formation and existence of metastable metallic phases. The microstructure of the rapidly cooled metal depends on the chemical composition and melting temperature of the metal and the cooling rate. Depending on the critical cooling rates, different metastable phases can be formed: a supersaturated solid solution, microcrystalline and amorphous phases.

The main advantages of this method for the preparation of CGCFMW are as follows [1–5, 10–14]:

- ✓ The preparation of continuous long pieces of a microwire of up to 10^4 m.
- ✓ Wide range of variation in parameters. (Geometrical: typical metallic core diameter *d* of 0.5–70 μm; glass coating thickness of 1–50 μm).Control and adjustment of geometrical parameters (inner metal core diameter *d* and glass thickness) during preparation.
- ✓ The presence of a vacuum machine to vary the pressure inside the Pyrex tube in order to control metallic core diameter *d*.
- ✓ Reproducibility of the microwire properties in mass production.

The main technological parameters for the preparation of glass-coated microwires are presented below.

The geometrical characteristics of the microwire depend on the physical properties of the glass and the metal, the diameter of the initial glass tube, and the parameters of the heating inductor.

According to previous analysis, the most significant effect on the geometry of a microwire comes from the glass properties. Wire radius R_g is estimated as follows:

$$R_g \sim A \frac{\eta^{2-k}}{V_d^{\,k} \sigma_s^{\,1-k}}, \quad A \sim \frac{1}{\rho}, \tag{1}$$

where k is the parameter dependent on casting rate ($0 < k < 1$); ρ is the density (wire); V_d is the casting rate; σ_s is the surface tension (glass); and η is the dynamical viscosity (glass):

$$\eta \sim \eta_o \exp\{\frac{\Delta H}{kT} + c[\exp(\frac{\varepsilon}{kT}) - 1]\}\ , \tag{2}$$

where $\varepsilon \sim 2\cdot10^2$ kJ/mol; $\Delta H \sim 10^2$ kJ/mol; and η_0, c are material constants.

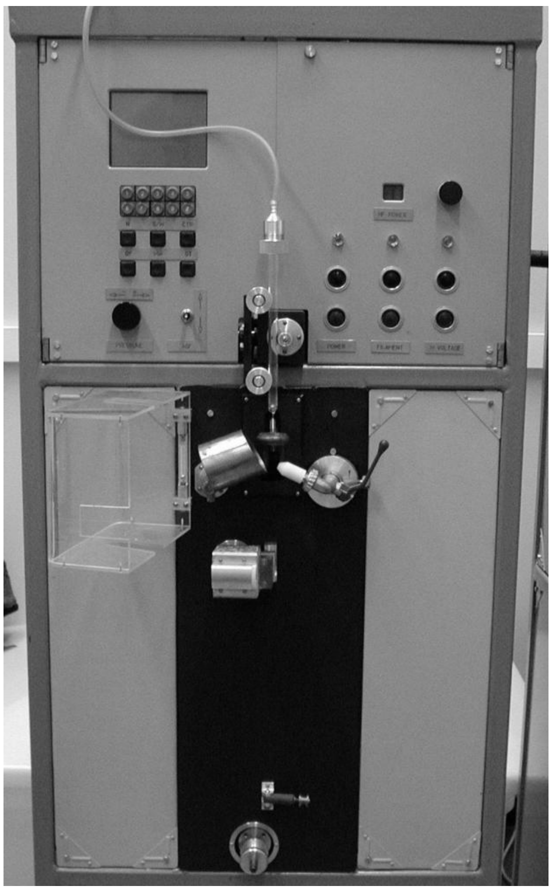

Fig. 1a. Machine for the preparation of CGCFMWs by the Ulitovsky–Taylor method (produced at AMOTEC Ltd, Moldova).

Fig. 1b. Novel machine for the preparation of CGCFMWs by the Ulitovsky–Taylor method (produced at MFTI Ltd, Moldova).

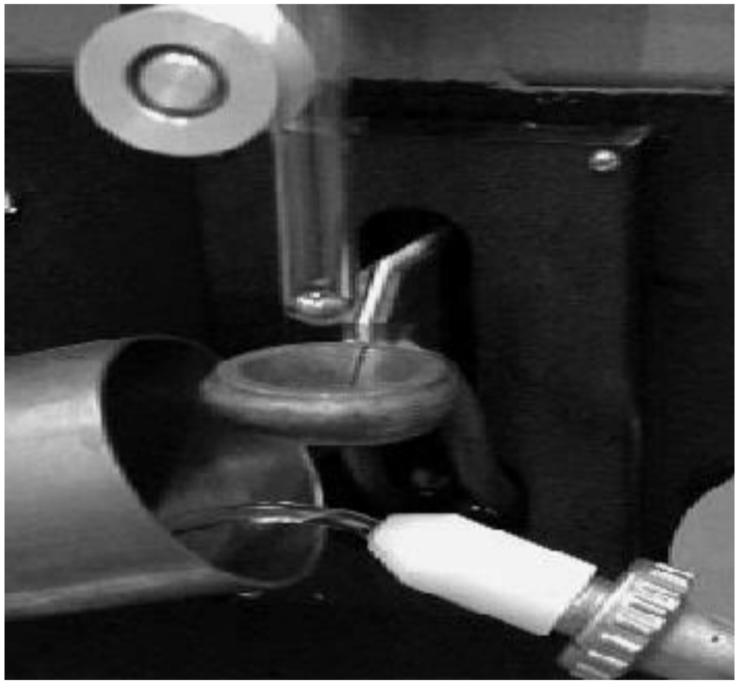

Fig. 2. Image of the microwire preparation process using the Ulitovsky–Taylor method.

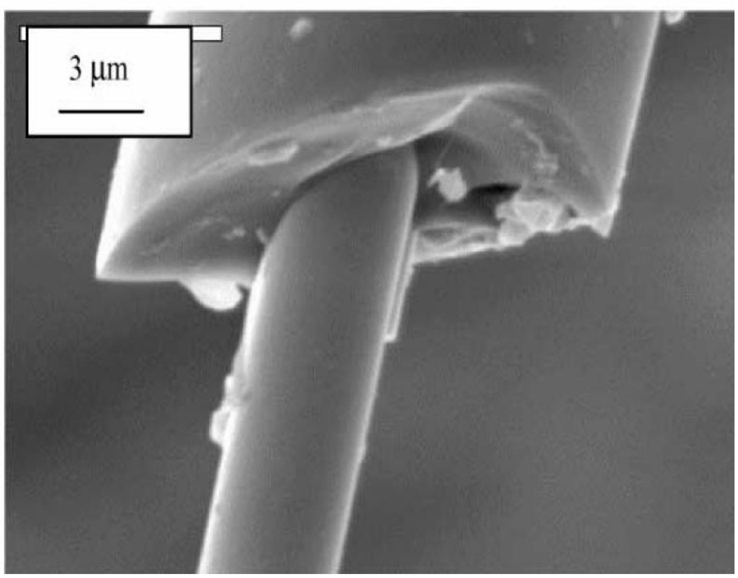

Fig. 3. Cast glass-coated ferromagnetic amorphous microwire (CGCFMW).

According to [10, 11]:

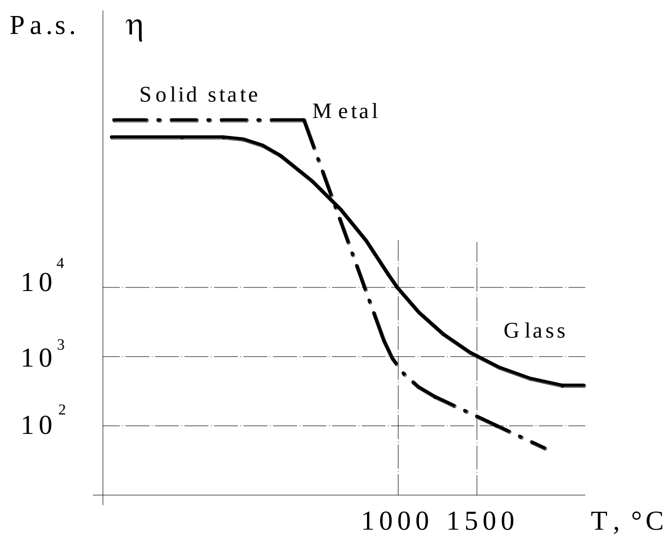

Fig. 4. Viscosity η as a function of temperature. The temperature region where the casting process can be implemented is indicated by dashed lines.

Formula (1) suggests the following. If the casting rate is extremely low, the R_g value is high. We obtain a formula similar to that in [10, 11]:

$$R_g \sim \frac{\eta^{5/3}}{\sigma^{2/3} V^{1/3} \rho} \quad , \tag{3}$$

where $k = 1/3$.
If the casting rate is sufficiently high, we obtain for R_g [10, 11]:

$$R_g \sim \frac{\eta^{4/3}}{\sigma^{1/3} V^{2/3} \rho} \tag{4}$$

where $k = 2/3$.

We obtain the theoretical limit of extremely high casting rates where $k \to 1$:

$$R_g \sim \frac{\eta}{V \rho} \tag{5}$$

Particular attention is paid to parameters determining the casting and cooling rates that are responsible for the microstructure of as-cast microwires (amorphous or microcrystalline).

3. Residual stresses

It was shown in [6–9, 12–14] that significant residual stresses occur inside the metallic core and glass coating as a consequence of the difference in thermal expansion coefficients of the metal and the glass. The value of these stresses depends on ratio x between metallic core diameter $d = 2r_m$ and total microwire diameter $D= 2R_g$:

$$x =(D^2/d^2-1) \tag{6}$$

$$\sigma_r = \sigma_\phi \equiv P_\nu ,$$

where

$$P_\nu = \sigma_0 \frac{kx}{[k[1-2\nu]+1]x + 2[1-\nu]} , \tag{7}$$

If the Poisson coefficient is $\nu = 1/3$, then

$$\sigma_r = \sigma_\phi \equiv P = \varepsilon E_1 \frac{kx}{[k/3+1]x + 4/3} , \tag{7a}$$

and

$$\sigma_z = P \frac{[k+1]x+2}{kx+1} , \tag{8}$$

where $\sigma_0 = E_1 (a_1 - a_2) (T^* - T)$, k is the ratio of Young's moduli, $k = E_2/E_1 = 0.3 - 0.6$. Numerical calculation indicates that, for small values of x, the $\sigma_z(x)$ dependence is nearly linear and exhibits saturation (up to 1 GPa) approximately at x = 10 [6–9, 12–14].

In terms of the model used for the stress formation in the microwire, the microwire strand preserves liquid status from its axis to internal radius b, while it freezes earlier from b to metallic core radius R, and only elastic residual stresses persist.
So, if

$$b < r < R ,$$

this model gives

$$\sigma_r = P_1' - \frac{c_1}{r^2}, \qquad \sigma_\varphi = P_1' + \frac{c_1}{r^2}, \tag{9}$$

The conditions of peak stresses on the strand surface, which can be estimated from (6)–(8), assume the boundary conditions. The numerical calculations suggest that the residual stresses for the CGCMNW decrease in the succeeding layers (in absolute magnitude), while remaining tensile. Analytical dependences of the residual stresses on the cylinder radius coordinate are important for calculation of the domain wall (DW) width. They are presented (according to [6–9, 12–14]) in the following form:

$$\sigma_{r(1)} \approx P\left[1-\left(\frac{b}{r}\right)^2\right], \qquad \sigma_{\varphi(1)} \approx P\left[1+\left(\frac{b}{r}\right)^2\right], \tag{10}$$

In addition, at $r < b$, this model gives

$$\sigma_{r(2)} = 2K \times \ln\left(\frac{r}{b}\right), \tag{11.a}$$

$$\sigma_{\varphi(2)} = 2K \times \left[1 + \ln\left(\frac{r}{b}\right)\right], \tag{11.b}$$

$$\sigma_z = \nu[\sigma_r + \sigma_\varphi], \tag{11.c}$$

where K is the thermoelastic constant [6–9, 12–14] and ν is the Poisson's coefficient. Note that a rigorous solution should be obtained by lacing equations (10) and (11a,b) at $r = b$ and taking into consideration the fact that they are unacceptable at $r = 0$; also note that $\sigma_r < \sigma_\varphi$ for any r.

4. Conclusions

In the preparation of cast glass-coated amorphous microwires, the residual stresses increase from the axis attaining maximum values on the surface. We have written 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 temperature; it has been experimentally verified. The macroscopic mechanism of domain wall activation qualitatively explains the main switching field dependence as an exponential form of temperature.

Theory of thermoplastic relaxation can be used to show that residual stresses will increase on the surface of a microwire, which corresponds to the previously obtained experimental data.

Cast glass-coated amorphous microwires exhibit residual magnetization due to the specific distribution of residual stresses. This property of microwires can be used for designing long-term magnetic storage elements and other electronic devices.

The main technological parameters for the preparation of glass-coated microwires have been described. Particular attention has been paid to parameters determining the casting and cooling rates that are responsible for the microstructure of as-cast microwires (amorphous or microcrystalline). The following conclusions should be outlined.

The method of continuous casting of glass-coated microwires (Ulitovski–Taylor method) has some limitations determined by the properties of the metal and the glass. The diameters of glass-coated microwires obtained by this technique are limited. In addition, there are limitations on quenching rate and metallic alloy composition.

The range of working temperatures for casting is specific for a given composition of the metallic alloy and the glass for each metallic alloy–glass pair; it depends on the viscosity of the glass and the metal and other physical properties.

The range of existence of metastable phases (amorphous, nanocrystalline, or microcrystalline) is limited to the quenching rate of the metallic core. That maximum quenching rate depends on metallic core diameter, glass coating thickness, chemical composition, and drawing rate.

The main specific feature of cast glass-coated microwires is the occurrence of residual stresses arising from the difference of thermal expansion coefficients of the metallic alloy and the glass coating. This feature is the main factor determining the physical properties of glass-coated microwires, particularly magnetic properties.

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