THE EFFECT OF GLASS INSULATION ON THE DEFORMATION OF THE MICROWIRE CORE

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The influence of the elastic deformation of the b side of the glass insulation on the state of the metal core of the microwire was studied. It was shown that the structural state of the microwire core is affected not only by the processes of nonequilibrium crystallization and heat removal conditions, but also by the application of stresses to the core from the side of the insulation in the process of drawing the microwire.

Keywords: microwires, microstructure, phase composition, melt-quenching, microhardness

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1. Introduction

The creation of new materials with high functional characteristics and methods for their production is one of the main tasks. The development of modern information, nano- and biotechnologies depends on its solution. In recent decades, researchers have paid much attention to materials with an extremely nonequilibrium amorphous structure [1-2]. Modern methods of quenching from a liquid or vapor state, such as obtaining microwires by rapid crystallization, laser processing, electrochemical deposition, three-electrode ion-plasma sputtering, extreme plastic deformation [3-7], have significantly increased the number of substances obtained in a non-crystalline state. Cast amorphous glass micro- and nanowires are very interesting materials both from the point of view of theory and from the point of view of practical application. A simple technology for obtaining cast amorphous glass micro- and nanowires was first presented in 1924 by G. E. Taylor. This method was significantly modified by A. V. Ulitovsky in the period 1950-1964. The modified Ulitovsky – Taylor method allows the production of large batches of such microwires. Interest in cast glass microwires has increased significantly over the past few years, mainly due to their technological application as sensor elements in various devices [2,3]. The production of microwires by the Ulitovsky – Taylor method and the study of their magnetic properties have been the subject of numerous publications by various research groups [2-4, 8-10]. The main feature of microwires obtained by the quenching method from the liquid state is the simultaneous rapid solidification of the glass-coated metal alloy [8-10]. Therefore, other families of amorphous magnetic wires obtained by the so-called “rotational quenching in water” or melt extraction methods have distinctive magnetic properties, since their magnetoelastic anisotropy and magnetic domain structures are different. It is very interesting to consider the possibilities of the Ulitovsky – Taylor method to produce cast glass microwires, which can have different microstructures and metal core compositions.

2. Experimental procedure

The crystal structures of the as-cast and melt-quenched (MQ) samples were characterized by X-ray diffraction (XRD) using a DRON-2.0 diffractometer with Fe K_α radiation. The XRD patterns were analyzed using the QualX2 software for qualitative phase identification [11]. The microhardness was measured using a PMT-3 microhardness tester at a load of 100 g. The microstructures of the as-cast and MQsamples were revealed by etching with a solution of hydrochloric (10 ml) and nitric (30 ml) acids for 3-10 s and observed using a NEOPHOT-21 optical microscope.

3. Results and discussion

If we conditionally accept that the microwire (MW) sample can have zero thickness, then it could be quenched without deformation at an infinite cooling rate. An increase in the thickness of the MW vein proportionally increases the hardening deformation; therefore, for a correct understanding of the processes that take place in MW, it is necessary to study in more detail the features of deformation in the place of contact between the vein and the glass, where, due to the difference in the thermal coefficients of their propagation, the highest stress level is observed. [12-14].

Calculations of stress and deformation at the interface "metal core – glass insulation" in the radial direction in MW were carried out by solving Lamé problems [12]:

$$\sigma_r = \frac{E\omega\delta}{2\nu - \varphi + \omega(\psi - 2\nu)}(1 - \frac{c^2}{a^2}) \tag{1}$$

where σ_r is the stress at the radius of the MW conductor, E and v are Young's modulus and Poisson's ratio, φ and ψ equal, respectively, $(1+b^2/a^2)$ and $(1+a^2/c^2)$ for outer layers and inner layers (Fig. 1), δ is the amount of differential compression.

In the case of MD, the coefficients in equation (1) can be written as:

$$\varphi = 1 + \frac{R^2}{r^2_c}; \qquad \psi = 1; \qquad \omega = \frac{E_S}{E_l}\left(1 - \frac{R^2}{r_c^2}\right)$$

where E_S and E_l are elastic moduli of glass and MW cores.

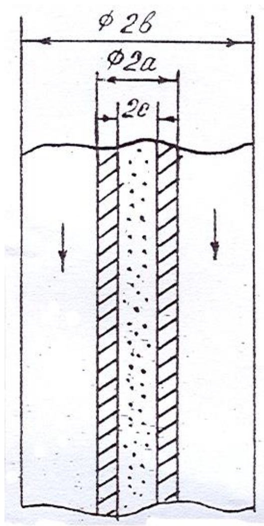

Fig. 1. To determine the coefficients *a, b, c*.

In problems of this type, important attention should be paid to the value of differential compression $\delta = \alpha\ (T_n - T_k)$ where α is temperature expansion coefficient, T_n and T_k are temperatures of the beginning and end of cooling. Since the temperature expansion coefficients (α) of glass and alloys used in practice are average coefficients in a certain temperature range, in order to determine the deformations in the MW caused by the formation of the "glass – core material" junction, it is necessary to determine this total coefficient of temperature expansion for each temperature in the interval: $T_n - T_k$. The deformation of the

MW core in the radial direction depends on its radius and, to a large extent, on the thickness of the insulation. Calculations [4] show that an increase in the thickness of the insulation by 2 microns leads to an increase in the stress on the core by 50...60%. That is, the formation of the vein structure takes place in a complex field of deformations: primarily due to the tension of the MW vein in the process of its extraction. The analysis [4] of calculations of MW deformations shows that in thin MWs, which are drawn at a high speed (> 150 m/min), the core is subjected to high stress (> $7\cdot10^{-3}$ N), and therefore the latter significantly affects the final structure of the core.

The method of determining the residual stresses in the surface layer of the material without destroying the samples used in this work is based on X-ray structural determining (jointly with Associate Professor of DNU T. I. Anishchenko) the exact period of its lattice. For this, MW segments were placed on the substrate in parallel rows. The X-ray picture was recorded in two positions of the sample: parallel and perpendicular to the beam. After measuring the interplanar distance in the crystals, the voltage was determined both in the direction and perpendicular to the axis of the MW core.

The elastic deformation in the surface layers of the sample in the direction perpendicular to the surface of the sample is determined by the formula (2) [15]

$$\varepsilon = (-\nu/E)\cdot(\sigma_1+\sigma_2) \qquad (2)$$

where σ_1, σ_2 are the tangential stresses to the surface of the sample

For further calculations, we will determine that if σ_1 and σ_2 are tensile stresses, then ε is a compression strain (Fig. 2).

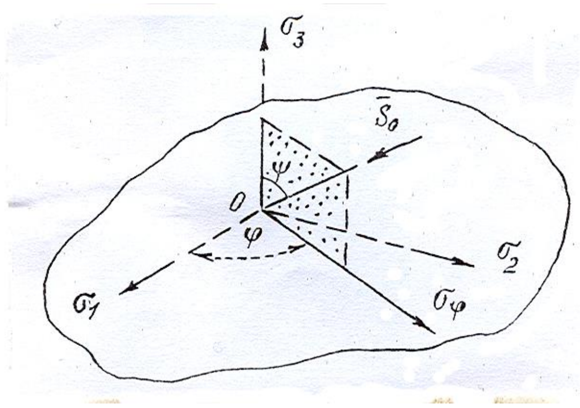

Fig. 2. Angular relations between the principal stresses, the measured stress σ_φ and the coordinate axes *x* , *y* , *z* [15].

To determine the deformation, it is necessary to find the value of the change in the interplanar distances *d* in the atomic planes parallel to the surface of the sample, since $\varepsilon = \Delta d/d$, then [15]

$$\sigma_1+\sigma_2 = (-E/\nu)(\Delta d/d) \qquad (3)$$

Experimentally, the task was reduced to the radiographic determination of relative deformation magnitude at different angles between the surface of the MW and the direction of the original beam. To determine the effect of insulation on the stress that occurs in the core, samples were taken with and without glass insulation. In Fig. 3. the profiles of the line (311) from the MW (core diameter d_c= 8 μm , insulation thickness Δ = 4 μm) from a single-phase alloy $Ni_{94}Si_6$ (wt.%) are shown for the mentioned cases, from which it can be concluded that the interaction of the core and insulation during the cooling of the MW causes dynamic stresses in the core, which disappear after the insulation removing (Table 1). Calculations show that the insulation causes additional stress in the MW core of approximately $\varepsilon = -0.0036$, which disappear after annealing for 10 min. at 500 °C.

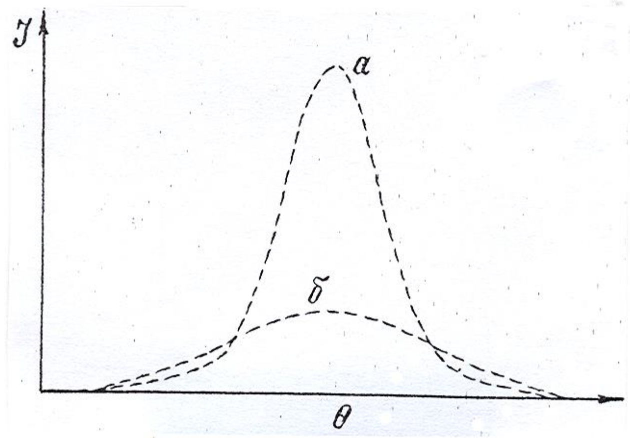

Fig. 3. X-ray line profiles (311) of MW alloy (wt.%) $Ni_{94}Si_6$: a) for a sample without insulation; b) for a sample with insulation.

Table 1

The position of the line (311) of the MW alloy depending on the shooting conditions (Fe radiation)

State	θ_{11}	$\theta_{\perp}$	$\theta_{11},\varphi=45^o$	$\theta_{\perp},\varphi=45^o$
output with insulation	66.18	66.20	66.29	66.10
output without insulation	66.10	66.19	66.18	66.17
annealed with insulation	66.16	66.18	66.16	66.14
annealed without insulation	66.11	66.19	66.21	66.42

In order to establish the influence of the structure on the stresses that arise in the MW, X-ray structural studies were also carried out on samples of copper alloys (wt.%): 1st group – Cu -30 Ni - 4.5 Si - 4.5 Mn ; 2nd group – Cu - 30 Ni - 2.5 Si - 2.5 Mn .

The influence of insulation and heat treatment on stress was determined by stress components σ_ψ when the original beam was deflected by an angle $\psi = 30°$ in the normal plane.

Stresses of the 1st kind were determined by the formula [15]:

$$\sigma_\psi = \frac{(d_\psi - d)E}{d(1+\nu)} \sin^{-2}\psi \qquad (4)$$

where d, d_ψ are, respectively, interplane distances at angles 90°, 30°.

The annealing mode was chosen so that no structural and phase transformations occurred during the heat treatment in the MW vein, which structurally consisted only of a supersaturated copper-based solid solution. The analysis of the data on the 1st kind of stresses shows that the chemical composition has a significant effect on the stress in the MW vein: for example, an increase in silicon to 4.5% increases it by almost 2.7 times (Table 2).

Table 2

Dependence of stresses of the 1st kind on heat treatment in MW of Cu-Ni-Si-Mn alloys

Microwire	Stress, MPa			
	initial state		after heat treatment	
	with insulation	without insulation	with insulation	without insulation
1 group	393	267	– 144	– 133
2 group	145	8	122	0

Note: d_c = 10 μm , Δ = 5 μm.

Removing the insulation reduces stress, but the residual stresses in the first group continue to be greater than in the second, which can only be explained by the increased content of silicon. After heat treatment, the pattern of stress distribution in the listed groups of alloys is opposite, if in the 2nd group the stresses decrease, and after removing the insulation, the latter disappears, then in the first group, they change sign and remain significant even after the insulation is removed.

X-ray structural studies of the samples after high-temperature annealing made it possible to establish in the MW of the 1st group the release of complex silicide at the first stage $(Cu,Ni)_X Si_Y$ with a yet undetermined lattice. A similar behavior of stresses in the first group of MW can naturally be explained by the presence of regions with a close arrangement of atoms, characteristic of this silicide, in the solid solution matrix.

During the MW study, it was also established that in the samples with 4.5% Si, the radiographs show a weakening of the interference lines with large indices associated with the influence of second-order stresses. In the work, this type of defectiveness is evaluated by the ratio ($W = I_{311} / I_{111}$) intensity of the lines. Our experiments showed that it practically does not depend on the composition of the alloys but increases significantly (by 1.4 – 1.5 times) with an increase in the cooling rate, which proportionally affects the magnitude of the stresses of the second kind (microstresses, $\Delta a / a$).

Conclusions

1. The structural state of the MW vein is influenced not only by non-equilibrium crystallization processes and heat removal conditions, but also by the application of stresses of the first and second kind to it in the process of drawing the MW.

2. An increase in the amount of deformation helps to obtain a more uniform structure in the core of the microwire.

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