

# Magnetic domains structure of dc Joule-heated amorphous glass-covered magnetic wires

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In this paper, we have analyzed the influence of dc Joule heating on the magnetic domains structures of amorphous glass-covered wires. We have calculated the thermal stresses owing to the successive heating, crystallization and cooling of the metal as well as to contractions generated by the glass cover in the metal during the thermal treatment due to difference between the thermal expansion coefficients of metal and glass. We have found that: (i) the resultant stresses strongly depend on the dimensions of the metallic part and the glass cover of amorphous glass-covered wires; (ii) the dimensions of the cylindrical inner core (CIC) increase with the increase of the metal's part radius; (iii) the increase of CIC's radius after the thermal annealing leads to the values of the reduced remanence from 0.90 to 0.98.

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## 1. Introduction

The amorphous glass-covered wires (AGCW) are receiving a considerable attention, because of their superior mechanical, magnetic and electrical properties in comparison with the similar counterparts. The dc Joule heating considerably influences the internal stresses in the AGCW, leading to an improvement of their magnetic properties. It is well known that AGCWs with a Fe-B-Si composition exhibit a positive magnetostriction, while the induced stresses in the metallic core by the radial temperature gradients and also by the glass insulation lead to the formation of a cylindrical inner core (CIC) with a uniaxial longitudinal anisotropy [3,5]. This leads to the appearance of a large Barkhausen jump (LBE) in low axially applied magnetic fields. Considering at least a linear dependence of the resistivity on the temperature, the conduction and radiative losses, as well as the structural changes during the crystallization process, will be analyzed the radial and temporal temperature distribution, both in the metallic core and the glass cover of an AGCW. The temperature distribution corresponding to a given value of the annealing electrical dc passing through the sample allows the calculation of the internal stresses as a function of  $I(A)$ . In this paper we analyze the influence of dc Joule heating on the magnetic domains structures of the "Fe - B - Si" AGCWs having the different dimensional parameters. In this aim, we firstly calculate the internal total stresses that appear in both the preparation process [4, 5] and the dc Joule heating of these wires and then we analyze the variation of CIC's radius after the thermal annealing in comparison with that obtained after the preparation process, for seven AGCWs, considered as being representative. The results obtained in this paper show that by changing the dimensional parameters of the AGCWs one can obtain a better control of the magnetic structure in a sample.

## 2. Internal stresses induced during dc joule heating

In this section we calculate the internal stresses induced in AGCWs due to the Joule-heating of the sample during the thermal treatment, taking into account the difference between the thermal expansion coefficients of the two materials in contact (metallic core and glass cover). Let us consider an AGCW, placed in vacuum, submitted to a dc Joule heating thermal treatment. We assume that the cylindrical metallic core has a radius  $R_m$  and the glass insulation has the thickness  $d_g = R_w - R_m$ , where  $R_w$  is the total radius of the wire (metal + glass). We associate a cylindrical system of coordinates  $(r, \theta, z)$  with the sample, having the  $Oz$ -axis along the wire's axis. Using the Hooke's law [2, 5] and taking into account the radial temperature gradient in AGCW, we obtain the diagonal components of the stress tensor in the metallic core:

$$\sigma_{rr}^m = \frac{E_m(C_1^m + 2\mu b_m)}{2(1+\mu)(1-2\mu)} - \frac{E_m\alpha_m}{r^2(1-\mu)} \int_0^r T(r)dr \quad (1)$$

$$\sigma_{\theta\theta}^m = \frac{E_m(C_1^m + 2\mu b_m)}{2(1+\mu)(1-2\mu)} + \frac{E_m\alpha_m}{r^2(1-\mu)} \int_0^r rT(r)dr - \frac{\alpha_m E_m T(r)}{1-\mu} \quad (2)$$

$$\sigma_{zz}^m = \frac{E_m(C_1^m + 2\mu b_m)}{(1+\mu)(1-2\mu)} - \frac{\alpha_m E_m T(r)}{1-\mu} \quad (3)$$

as well as in the glass cover:

$$\sigma_{rr}^g = \frac{E_g(C_1^g + 2\mu b_g)}{2(1+\mu)(1-2\mu)} - \frac{E_g\alpha_g}{r^2(1-\mu)} \int_{R_m}^r rT(r)dr - \frac{E_g C_2^g}{(1+\mu)r^2}$$

$$\begin{aligned}\sigma_{\theta\theta}^g &= \frac{E_g(C_1^g + 2\mu b_g)}{2(1+\mu)(1-2\mu)} + \frac{E_g\alpha_g}{r^2(1+\mu)} \int_{R_m}^r rt(r)dr + \\ &+ \frac{E_g C_2^g}{(1+\mu)r^2} - \frac{\alpha_g E_g t(r)}{1-\mu} \\ \sigma_{zz}^g &= \frac{E_g(C_1^g + 2\mu b_g)}{(1+\mu)(1-2\mu)} - \frac{\alpha_g E_g t(r)}{1-\mu},\end{aligned}\quad (4)$$

where,  $T(r)$  is the radial temperature in the metallic core,  $t(r)$  is radial temperature in the glass cover, while  $E_m$  and  $E_g$  are the Young's modulus for the metal and for the glass, respectively. In order to find the resultant stresses both in the metallic core and the glass insulation, we must calculate the constants  $C_1^m, C_1^g, C_2^g, b_m$  and  $b_g$ , taking into account the different values of the thermal expansion coefficients of the two materials (metal and glass). This can be done using the equilibrium conditions that must be satisfied by the stresses which appear both at the metal-glass interface:

$$\sigma_{rr}^m(r=R_m) - \sigma_{rr}^g(r=R_m) = 0, \quad (5)$$

$$\sigma_{zz}^m(r=R_m) + S\sigma_{zz}^g(r=R_m) = 0 \quad (6)$$

and at the exterior surface of the wire:

$$\sigma_{rr}^g(r=R_w) = 0 \quad (7)$$

First of all, the following conditions have to be imposed, so that all the strains appearing in this process are due only to the difference between the thermal expansion coefficients of the metal and glass:

$$u_z^m(r=R_m) - u_z^g(r=R_m) = \varepsilon z \quad (8)$$

and

$$u_r^m(r=R_m) - u_r^g(r=R_m) = \varepsilon R_m. \quad (9)$$

$S = \frac{S_{rr}^g}{S_{rr}^m} = \frac{R_w^2}{R_m^2} - 1$ ,  $S_{rr}^g$  and  $S_{rr}^m$  are the cross section areas of the glass cover and of the metallic core, respectively,  $u_r^m$  and  $u_z^m$  are the radial and axial displacements in the metallic core,  $u_r^g$  and  $u_z^g$  are radial and axial displacements in the glass cover,  $\varepsilon = \varepsilon_m - \varepsilon_g = (\alpha_m - \alpha_g)\Delta T$  is the resultant strain due to the thermal contraction in the metal and glass respectively, while  $\alpha_m$  and  $\alpha_g$  are the corresponding thermal expansion coefficients. As we can see from (1)÷(9), the calculation of the internal stresses corresponding to three successive stages of the dc Joule heating: heating-crystallization-cooling demands the knowledge of the radial temperature,  $T_m(r)$  (in the metallic core) and  $t(r)$  (for the glass insulation).

#### Stresses at the onset of the crystallization process

In this subsection, we calculate the internal stresses that appear during first stage of the annealing, starting

from the radial temperature of an AGCW, through which an electrical dc passes. We assume the ends of the sample thermally isolated and take into account the linear dependence of the electrical resistivity on temperature. At the thermal equilibrium, for a value of electrical dc applied to the sample, the Fourier equation of the heat transport [2] has the solution:

$$T_m(r) = T_0 - \alpha^{-1} + C(I)J_0\left(r\sqrt{\alpha\rho_0 I^2 k_m^{-1} S_1^{-2}}\right) \quad (12)$$

as well as the temperature  $T_g(r)$  in the glass cover,

$$T_g(r) = A_1(I) \ln r + A_2(I). \quad (13)$$

The constants  $C(I)$ ,  $A_1(I)$  and  $A_2(I)$  are obtained from the boundary conditions at the metal-glass interface ( $r = R_m$ ), (as a result of the continuity of the thermal flux from the adjacent regions):

$$k_m(dT_m/dr) = k_g(dT_g/dr), \quad (14)$$

$$T_m(R_m) = T_g(R_m), \quad (15)$$

and the thermal equilibrium between the sample and the environmental medium (as a result of the radiative heat loss):

$$-dT_g/dr|_{r=R_w} = P k_g^{-1} [T^4(R_w) - T_0^4]. \quad (16)$$

$k_m$  and  $k_g$  are the coefficients of thermal conductivity for the metallic core and glass insulation, respectively, while  $P$  is the *wire's loss parameter*. Using the relations (12) and (13) in (1)÷(9), we calculate the internal stresses corresponding to this stage of the thermal annealing. Thus, for the same  $R_m$ , the higher the  $d_g$ , the higher the stresses' values are, while for the same value of the  $d_g$ , the higher  $R_m$ , the smaller the stresses' values are.

#### Stresses induced during the crystallization process

The internal stresses induced in the AGCW's metallic core during the crystallization process are given by the relations:

$$\begin{aligned}\sigma_{rr}^m = \sigma_{\theta\theta}^m &= \frac{3E_g E_m S [(\alpha_{amorph} - \alpha_g) + (\alpha_{cryst} - \alpha_{amorph})x(t)](T(t) - T_M)}{(E_g + 3E_m)S + 4E_m} \\ \sigma_{zz}^m &= \sigma_{rr}^m \frac{(E_g + E_m)S + 2E_m}{E_g S + E_m}.\end{aligned}\quad (17)$$

#### Stresses induced during the cooling

The determination of these stresses implies the knowledge of the thermal behavior of the metal-glass

system during the cooling. Using the Fourier equation of the heat transport [4], we obtain  $T_m(r)$  and  $t(r)$  and then from the relations (1-9) we find that the smaller the metallic core's radius is, the bigger the internal stresses induced in this core are.

### 3. Domains structure: Results and discussion

The thermal stresses induced in the radial, azimuthal and axial directions during dc Joule heating of the magnetic AGCWs (owing to the successive heating, crystallization and cooling of the metal as well as to contractions generated by the glass cover in the metal during the thermal treatment due to difference between the thermal expansion coefficients of metal and glass) strongly depend on the radius of the metallic part of AGCWs and on the thickness' of the glass cover. In the Fig. 1 we represented the resultant stresses calculated by adding to the internal stresses induced in the preparation process [4,5], the different stress components induced in the three considered stages of the thermal treatment (heating – crystallization – cooling) for a wire with  $R_m = 3.65 \mu\text{m}$ ,  $d_g = 7.50 \mu\text{m}$ . The following magnetic domains structure results: between  $r = 0$  and  $r = R_c^i$  a zone I with a uniaxial magnetic anisotropy; between  $r = R_c^i$  and  $r = R_{Oz}$  a zone II with a radial magnetic anisotropy; finally, between  $r = R_{Oz}$  and  $r = R_m$  we have a zone III.

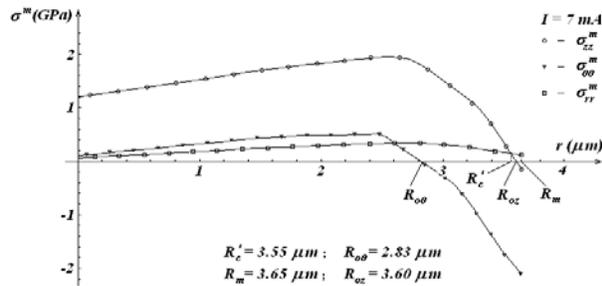


Fig. 1. The internal total stresses induced in AGCW after the preparation process and thermal treatment (heating – crystallization – cooling) for an wire with  $R_m = 3.65 \mu\text{m}$ ;  $d_g = 7.50 \mu\text{m}$ .

Zone I lead to formation of CIC having a radius ( $R_c^i$  ( $i = 1 \div 7$ )) for each sample) while the zone II and III form the outer shell (OS). Fig. 2 presents the schematic diagram of the magnetic domains structure corresponding to the seven samples.

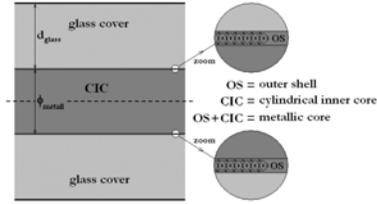


Fig. 2. The schematic diagram of the estimated domain structure after dc Joule heating.

The intersection point between  $\sigma_{zz}^m(r)$  and  $\sigma_{rr}^m(r)$  (which before the thermal treatment is at  $R_c^i$ ) moved away to  $R_c^i$  after dc Joule heating, for each sample. The radius of CIC after the thermal treatment ( $R_c^i$ ) increases in comparison with that obtained after the preparation process. This means that CIC enlarges significantly after the thermal treatment. In Table 1 is represented the radius of CIC for the seven samples before and after dc Joule heating. In the case of wires nos 1 and 2, the increase of the  $R_c^i$  is bigger than for the case of wires nos 3, 4 and 5. An AGCW with the smaller  $R_m$  and bigger  $d_g$  (wire no 7) presents an increase of  $R_c^i$  bigger in comparison with a wire having the bigger  $R_m$  and smaller  $d_g$ . Magnetic measurements were performed at a maximum value of the axially applied field of 150 Oe, at a frequency of 400 Hz. The values of  $M_s$  are measured by the fluxmeter method. From the ratio  $M_r / M_s$  determined experimentally it follows that the radius' of the CIC range between  $\cong 92\%$  of  $R_m$  and  $\cong 99\% R_m$ , i.e., its are very close to the determined values from theoretical considerations. The increase of the CIC's radius after the thermal annealing leads to the values of the reduced remanence from 0.90 to 0.98.

Table 1. Evolution of the CIC after dc Joule heating.

Wire	Dimensional characteristics	$R_c^i$ ( $i = 1 \div 7$ )	$R_c^i - R_c^i$ ( $i = 1 \div 7$ )
1.	$R_m = 3 \mu\text{m}; d_g = 10 \mu\text{m}$	$81.2\% R_m$	$10.8\% R_m$
2.	$R_m = 3 \mu\text{m}; d_g = 15 \mu\text{m}$	$81.9\% R_m$	$11.1\% R_m$
3.	$R_m = 2 \mu\text{m}; d_g = 7.50 \mu\text{m}$	$92\% R_m$	$4.1\% R_m$
4.	$R_m = 3.65 \mu\text{m}; d_g = 7.50 \mu\text{m}$	$93\% R_m$	$4\% R_m$
5.	$R_m = 5 \mu\text{m}; d_g = 7.50 \mu\text{m}$	$94.9\% R_m$	$3.6\% R_m$
6.	$R_m = 9 \mu\text{m}; d_g = 3 \mu\text{m}$	$89.3\% R_m$	$8.7\% R_m$
7.	$R_m = 2 \mu\text{m}; d_g = 4.50 \mu\text{m}$	$82\% R_m$	$14.5\% R_m$

#### 4. Conclusion

By the calculation of induced thermal stresses that appear in AGCW during both the preparation process and dc Joule-heating thermal treatment (heating–crystallization–cooling), information about evolution of the magnetic structure with annealing can be obtained directly. The results presented in this paper show that by changing the values of dimensional parameters of AGCW, after the solidification and dc Joule annealing one can obtain the internal stresses that lead to the control of the magnetic domains. The higher obtained values of the reduced remanence in highly magnetostrictive AGCW opens up a larger field of sensing applications for these wires.

#### References

- [1] I. Astefanoaei, D. Radu, H. Chiriac, J. Optoelectron. Adv. Mater. **8**(3), 978 (2006).
- [2] I. Astefanoaei, D. Radu, H. Chiriac, J. Optoelectron. Adv. Mater. **8**(5), 1731 (2006).
- [3] H. Chiriac, T. A. Óvári, Prog. Mater. Sci. **40**, 333-336 (1996).
- [4] I. Aștefănoaei, D. Radu, H. Chiriac, IEEE 3-rd Magnetism Society Romanian Chapter Conference 2005.
- [5] H. Chiriac, T.A. Óvári, Gh. Pop, Phys. Rev B., "Internal stress distribution in glass-covered amorphous wires" **52**, 10104-10113 (1995).

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