Intermetallics 44 (2014) 88–93

Contents lists available at ScienceDirect

Intermetallics

journal homepage: www.elsevier.com/locate/intermet

Effect of composite origin on magnetic properties of glass-coated microwires

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ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form
21 August 2013
Accepted 25 August 2013
Available online 21 September 2013

Keywords:
A. Composites
B. Magnetic properties
B. Glasses, metallic
F. Metallographic techniques

ABSTRACT

We observed that magnetic properties (Giant magneto.-impedance effect and domain wall dynamic) of glass-coated microwires are closely related with the peculiarities of the fabrication technique involving rapid solidification of metallic alloy surrounded by glass coating from the melt.

We present studies of the interfacial layer between the metallic nucleus and glass coating and studies of the inhomogeneities related with fabrication process of thin ferromagnetic microwires.

We observed gas bubbles within the glass coating with volume content of about 8–12%. The sizes of the bubbles were between 1 and 15 μm. The existence of such bubbles might be the origin of the inhomogeneities in the internal stresses distribution.

Using scanning electron microscope JEOL JSM-6610 we obtained the image of the interfacial layer and the elements distribution within the glass coating and metallic nucleus. This allowed us to estimate the thickness of the interfacial layer.

Understanding of the origins of the interfacial layer and defects may help for improvement of the existing technology for thin composite wires fabrication and enhance their magnetic properties.

1. Introduction

Studies of magnetically soft composite microwires consisting of metallic nucleus covered by glass coating attracted great attention owing to a number of outstanding magnetic properties such as magnetic bistability and giant magneto-impedance, GMI, effect [1,2]. As a rule, better soft magnetic properties and GMI effect are observed for nearly-zero magnetostrictive Co-rich compositions. On the other hand microwires with Fe-rich metallic nucleus composition present hysteresis loops related with large and single Barkhausen jump. The remagnetization of this family of microwires is determined by the fast magnetization switching within single domain axially magnetized inner core [3]. From the point of view of applications most interest attracted amorphous wires and microwires exhibiting with low magnetostriction constant exhibiting best soft magnetic properties owing to the absence of defects typical for crystalline materials and low magnetoelastic contribution [2,4].

Generally magnetic properties of amorphous ferromagnetic microwires depend on the composition of the metallic nucleus as well as on the composition and thickness of the glass coating. The character of hysteresis loops changes from rectangular, typical for amorphous Fe-rich compositions, to inclined, typical for Co-rich compositions [1,2]. Such strong dependence of the hysteresis loops on these parameters has been attributed to the magnetoelastic energy given by:

$$K_{me} \approx 3/2\lambda_s\sigma_i, \tag{1}$$

where λ_s is the saturation magnetostriction and σ_i is the internal stress. The magnetostriction constant depends mostly on the chemical composition and is vanishing in amorphous Fe–Co based alloys with Co/Fe ≈ 70/5 [1,5,6]. For conventional amorphous materials main compositional dependence is related with stresses arising from the rapid solidification process, when the metallic alloy solidifying from the surface. Stronger dependence of magnetic properties of glass-coated microwires on metallic nucleus composition is originated to the additional internal stresses arising from the glass coating. Main feature of the fabrication technique of glass-coated microwires is that it involves the simultaneous solidification

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http://dx.doi.org/10.1016/j.intermet.2013.08.014

of composite microwire consisting of ferromagnetic nucleus surrounded by glass coating. Quite different thermal expansion coefficients of the glass and the metallic alloys introduce considerable internal stresses inside the ferromagnetic nucleus during simultaneous fast solidification of the composite microwire [1,2,5]. Strength of these internal stresses depends on ρ-ratio defined as the $\rho = d/D$, where d is the metallic nucleus diameter and D-total microwire diameter. The estimated values of the internal stresses in these glass-coated microwires arising from the difference in the thermal expansion coefficients of metallic nucleus and glass coating are of the order of 100–1000 MPa, depending strongly on the ratio between the glass coating thickness and metallic core diameter [7–11], increasing with the glass coating thickness.

Consequently, tailoring of the magnetoelastic energy, K_{me}, is essentially important for optimization of magnetic properties of glass-coated microwires [1,2]. Considerable attention has been paid to studies of correlation between the magnetoelastic energy, K_{me}, induced by the stresses and magnetic properties.

On the other hand, the glass coating technique involves complex metallurgical processes, such as the effect of electromagnetic field of inductor on alloy ingot and the interaction between the alloy and the glass coating at elevated temperatures. These problems are less studied [11]. Additionally the technology has been initially developed for the non-magnetic alloys [11,12]. The character of interaction depends on chemical composition of the ingot as well as on type of glass used for the casting [11].

Generally, small particles of the glass can be involved by the molten metal ingot moving under the effect of the high-frequency magnetic field of the inductor. Therefore the chemical composition of the ingot at the beginning of the casting process can be different from the alloy composition from that at the end of casting process.

Additionally, for the case of non-magnetic alloys the interfacial layer between the metallic nucleus and glass coating has been observed and studied [11,12]. As regarding the origin and the properties of the interfacial layer, there are few possibilities described for the non-magnetic alloys. Thus, among the origins of the interfacial layer the following considerations have been discussed:

1. Formation of the series of solid solutions. In this case the thickness of the interfacial layer is about few μm.
2. Uncompensated molecular forces on the interface between the glass and the metallic nucleus. In this case the thickness of the interfacial layer should be less than 0,1 μm.
3. Formation of stable chemical compounds with the structure different (from crystallographic point of view) from that of the interacting materials. The thickness of the interfacial layer is of the same order (few μm) as in the case of formation of solid state solutions, but the interface layer is more visible, like it was observed by microscopy in few cases [11,12].

Taking into existence of the interfacial layer we must consider, that glass-coated microwire consist of metallic nucleus, glass insulating shell and interfacial layer.

From the point of view of high-frequency magnetic properties (like the GMI effect) the interfacial layer between the metallic nucleus and glass coating is especially relevant [1,2,13]. Recently we observed, that the frequency, f, dependence of a maximum GMI ratio, $\Delta Z/Z_m$, usually presents an optimum frequency (at which $\Delta Z/Z_m$ versus f exhibits the maximum). One of a possible explanation for this is that the magnetic structure and the anisotropy canbe different inside the microwire and near the surface. At higher frequencies the current flows closer to the surface, then the effective anisotropy field and permeability dispersion can change with frequency [14].

The other source of instability of properties of cast microwire is related with gas content inside the microwire. The sources of the gas are: the atmosphere, the gas impurities in the alloy and the glass. Some content of oxygen and/or hydrogen (about 5 cm^3/100 g each other) and even nitrogen has been detected. Gaseous precipitations can cause the metallic nucleus deformation, cracks and even discontinuities. Chemical reactions of hydrogen with the oxides of the metals can result in appearance of water bubbles inside the metallic nucleus as well as in the glass coating.

Recently we showed that the microwires's inhomogeneities sufficiently affect the remagnetization process of magnetically bistable microwires limiting single domain wall, DW, propagation regime as well as the domain wall propagation velocity, v [15].

We observed the correlation of the domain wall dynamics with the distribution of the nucleation fields.

On the other hand, we observed that there is a correlation between the distribution of the local nucleation field along the length and the domain wall, DW, dynamics. Thus if external magnetic field, H, is below some critical value we observed single DW propagation along the wire axis, manifested as linear $v(H)$ dependence. Measuring the local nucleation fields, H_n, along the microwire length, L, we observed considerable oscillations and even dip holes on the $H_n(L)$ dependences identified as the positions of localized defects existing within the microwire [16]. The minimum value of local nucleation field, H_{nmin}, determines the threshold between single and multiple DW propagation regimes. Thus, we observed the spontaneous DW nucleation on local defects, which limits the single DW propagation regime in magnetically bistable microwires [15,16]. Below H_{nmin} there is a linear dependence of DW velocity, v, on the applied magnetic field, H, for all microwires with positive sign of the magnetostriction constant. Above H_{nmin} we observed abrupt jumps on the $v(H)$ dependences associated with multiple DW propagation regime.

Consequently, the microwires inhomogeneities sufficiently affect the remagnetization process [3,15,16]. The origin of the defects is unclear, and might be related to stress inhomogeneities, shape irregularities, oxides etc. It is assumed, that at least some of these defects might have a magnetoelastic origin and, therefore, might be affected by heat treatment.

In this paper we present our last results on studies of the metallurgical processes during the microwires fabrication on structure and magnetic properties (DW dynamics and GMI effect) of glass-coated microwires. We are paying special attention to studies of the interfacial layer between the metallic nucleus and glass coating and studies of the inhomogeneities related with fabrication process of thin ferromagnetic microwires.

2. Experimental

We studied amorphous Co-rich and Fe-rich glass-coated microwires with different metallic nucleus diameter, d, and total microwire diameter, D, were produced by modified Taylor–Ulitovsky method [1–3]. It is worth mentioning, that the strength of internal stresses is determined by ratio ρ [7–11]. Therefore, controllable change of the ρ-ratio allowed us to control the residual stresses.

Hysteresis loops have been determined by fluxmetric method, as described elsewhere [2,3].

We have measured dependences of the diagonal Z_{zz} and off-diagonal $Z_{\phi z}$ impedance components and GMI ratio, $\Delta Z/Z$, on external axial magnetic field H in microwires, as described elsewhere [2,12,14].

The magneto-impedance ratio, $\Delta Z/Z$, has been defined as:

$$\Delta Z/Z = [Z(H) - Z(H_{max})]/Z(H_{max}), \quad (2)$$