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Magnetic Migration Delays in Fe-Based Amorphous Alloys

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The amorphous state is characterized by metastability, which results in structural relaxation even at low temperatures. These relaxations contribute to the magnetic properties of amorphous alloys, such as the value of the coercive field, losses from hysteresis or magnetic susceptibility. In amorphous materials, as opposed to crystalline ones, the description of relaxation phenomena is difficult due to the fact that these processes are described by the activation energy spectrum and occur in a wide temperature range. The paper presents the results of the analysis of migration processes based on the adopted H. Kronmüller model, in which the reorientation of atoms takes place in areas of reduced volume called free volumes.

topics: magnetic susceptibility disaccommodation, activation energy of elementary processes, bulk amorphous alloys, structural relaxation

1. Introduction

The constantly growing consumption of electricity is the factor driving the boom for newer and newer materials, which are to meet higher and higher standards. The group of modern materials includes bulk amorphous alloys, which are considered as a separate group of amorphous materials [1, 2]. We divide amorphous alloys into classic and bulk ones. Classic alloys are those produced in the form of tapes, the thickness of which does not exceed 100 μm. Bulk amorphous alloys, on the other hand, include alloys with a thickness greater than the limit for ribbons. Electrotechnical materials, especially those used in transformers, should be characterized by a low coercive field, high saturation magnetization, low core losses, and a relatively high Curie temperature [3, 4]. During operating electric or electronic devices, good stability of parameters is expected.

An important factor influencing the quality of an electrotechnical material is the stability of its magnetic susceptibility over time from the moment of demagnetization. The theory describing this phenomenon for amorphous materials was also developed by H. Kronmüller based on the assumptions of Allen's theory for magnetic delays occurring in crystalline materials [5]. The study of the phenomenon of magnetic susceptibility disaccomodation gives a full description of the susceptibility temporal stability of the examined amorphous material. Disaccomodation of magnetic susceptibility is studied in the Reley range and is related to skipping of pairs of atoms within free volumes.

The paper presents the results of the analysis of magnetic susceptibility deaccomodation curves for the spectrum of continuous relaxation times obtained for bulk amorphous samples after solidification in the form of rods with a diameter of 1 mm and chemical compositions $(Fe_{74}B_{20}Nb_2Hf_2Si_2)_{100-x}Y_x$ ($x = 1, 2$).

2. Theoretical details

Data obtained from measurements of magnetic susceptibility as a function of temperature were used for the numerical analysis. A continuous spectrum of relaxation times was assumed for amorphous alloys. The change in magnetic susceptibility over time, describing its decrease, is related to the change in the stabilization potential of the domain wall. Such a relationship is described by [6, 7]

$$\Delta\frac{1}{\chi} = \Delta\frac{1}{\chi(t)}\Delta\frac{1}{\chi(0)} = \frac{1}{2M_s^2 S_{\acute{S}}}\frac{\mathrm{d}^2 E_{\acute{S}}(U,t)}{\mathrm{d}U^2}\Big|_{U=0}, \tag{1}$$

where $S_{\acute{S}}$ is the area of the domain wall per unit volume, χ is the initial susceptibility and M_S is the saturation magnetization. The stabilization potential of the domain wall described according to [8]

$$E_{\acute{S}}(U,t) = -c_0(t)\left\langle \frac{1}{\cosh^2\left(\frac{\Delta_s}{k_B T}\right)}\right\rangle \times \left(1-\mathrm{e}^{t/\tau_R}\right)\int_{-\infty}^{+\infty}\mathrm{d}z\left\langle \Delta_m(z-U)\,\Delta_m(z)\right\rangle, \tag{2}$$

where

$$c_0(t) = n_0(t) = n_\infty + \left(n_0(0)-n_\infty\right)\mathrm{e}^{-t/\tau_A} \tag{3}$$

is the average number of pairs of atoms per unit volume. The relaxation times, $\tau_A = \tau_{0A}\,\mathrm{e}^{Q_A/(k_B T)}$ and $\tau_R = \tau_{0R}\,\mathrm{e}^{Q_R/(k_B T)}$ are related to the defect density change and the reorientation of the axis of pairs of thermally activated atoms, respectively (Q_A, Q_R — activation energies). In the case of Δ_m and Δ_s, these are respectively the magnetic and structural fission energies between two orientations of pairs of atoms, defined as [8]

$$2\Delta = 2\Delta_s + 2\Delta_m. \tag{4}$$

Whereas, the energy of magnetic fission of the i-th pair of atoms is defined as the differences between the energies of magnetic interactions [8]

$$2\Delta_{mi} = \varepsilon_{i,2} - \varepsilon_{i,1}, \tag{5}$$

where $\varepsilon_{i,j}$ — energy of the magnetic interaction.

In the vicinity of the free volume at temperature T, the reorientation of the axis of pairs of atoms occurs by a thermally activated jump above the potential barrier. For numerical calculations, an isochronous magnetic susceptibility disaccomodation curve was presented for several relaxation processes in the form of the relationship [9]

$$\Delta\left(\frac{1}{\chi}\right) = \sum_{i=1}^{1}\int_{-3\beta_i}^{+3\beta_i}\mathrm{d}z\,\frac{1}{\beta\sqrt{\pi}}\frac{I_{pi}T_{pi}}{T} \times \left(\mathrm{e}^{-\mathrm{e}^z\,t_1/\tau_{mi}} - \mathrm{e}^{-\mathrm{e}^z\,t_2/\tau_{mi}}\right)\mathrm{e}^{-(z/\beta_i)^2}, \tag{6}$$

where $z = \ln(\frac{\tau}{\tau_m})$, I_{pi} — the intensity of the i-th process at peak temperature T_{pi}, and β — width of distribution.

In this study, these changes were investigated in an alternating magnetic field using the transformer method.

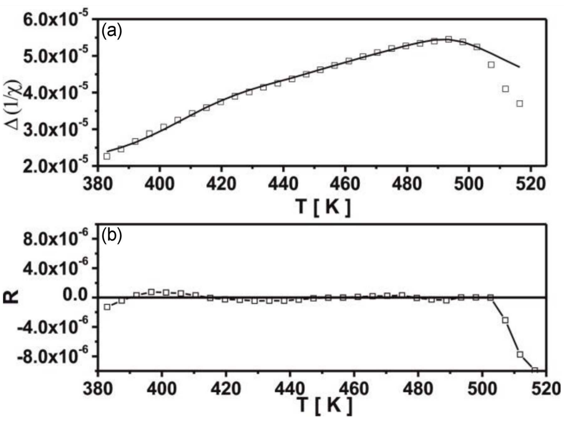

Fig. 1. (a) Theoretical isochronous magnetic susceptibility disaccomodation curves and (b) distribution of deviations between the theoretical curve and the experimental points for the $(Fe_{74}B_{20}Nb_2Hf_2Si_2)_{99}Y_1$ alloy.

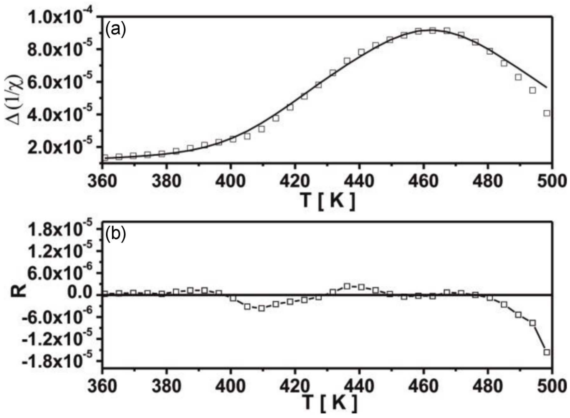

Fig. 2. (a) Theoretical isochronous magnetic susceptibility disaccomodation curves and (b) distribution of deviations between the theoretical curve and the experimental points for the $(Fe_{74}B_{20}Nb_2Hf_2Si_2)_{98}Y_2$ alloy.

3. Results and discussion

Figures 1 and 2 show the theoretical isochronous magnetic susceptibility disaccomodation curves calculated according to (6) and the experimental points obtained for the alloy samples

TABLE I

Data from the analysis of disaccommodation of magnetic susceptibility curves as a function of temperature for Fe alloy; $\beta_{\tau i}$ is the width of the Gaussian distribution.

Process	T_{pi} [K]	I_{pi} ($\times 10^{-5}$)	Q_{mi} [eV]	τ_{mi} ($\times 10^{-15}$) [s]	$\beta_{\tau i}$
I	410	1.76	1.21	6.40	2.17
II	454	1.67	1.41	1.09	1.58
III	482	1.37	1.47	2.85	0.03

TABLE II

Data from the analysis of disaccommodation of magnetic susceptibility curves as a function of temperature for Fe alloy.

Process	T_{pi} [K]	I_{pi} ($\times 10^{-6}$)	Q_{mi} [eV]	τ_{mi} ($\times 10^{-15}$) [s]	$\beta_{\tau i}$
I	436	3.93	1.29	5.37	2.10
II	444	44.5	1.30	6.63	1.45
III	472	4.56	1.44	1.99	1.39

$(Fe_{74}B_{20}Nb_2Hf_2Si_2)_{100-x}Y_x$, where $x = 1, 2$, in the solidified state and the distribution of deviations between the theoretical curve and experience points.

Curves are a superposition of three elementary processes. The times of elementary processes are described by the Gaussian distribution. The parameters characterizing these processes are presented in Tables I and II.

The average activation energies for the tested samples are similar. The pre-exponential factor of Arrhenius law τ_{mi} is on the order of 10^{-15} s. This means that the observed phenomenon of disaccomodation is related to the migration of point relaxators [10].

4. Conclusions

Based on the research and numerical analysis of the theoretical isochronous magnetic susceptibility disaccomodation curves, it was found that:

1. For the two examined alloys, the theoretical isochronous disaccomodation curves of magnetic susceptibility were a superposition of three elementary processes.
2. The width of the distribution is smaller in an alloy with 2 at.% of Y. The reduction of the parameter β is related to the reduction of relaxators, which introduces changes in the short range ordering in amorphous alloys. Sample Y_2 achieved a better glass forming ability.
3. The coefficient τ in the Arrhenius law is of the order of 10^{-15} s, which, means that in the studied alloys the atoms within the free volumes change the orientation of the atom pairs axis. Such reorientation corresponds to two energy levels [7].

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