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Changes in the Initial Magnetic Susceptibility in Amorphous Alloys Exhibiting Soft Magnetic Properties

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In weak magnetic fields, there are changes in the arrangement of atoms, which are otherwise called magnetic relaxations. The exact phenomenon that will be investigated in this paper concerns the disaccomodation of magnetic susceptibility, which is one of the most frequently observed effects of magnetic lag. During this magnetic delay, there is a reorientation of the axes of pairs of atoms corresponding to two different energy levels. This energy is related to the energies of exchange and spin–orbit coupling. The paper presents the results of magnetic susceptibility disaccomodation and describes its influence on the relaxation time matching spectrum.

topics: initial magnetic susceptibility, amorphous alloy, X-ray diffraction

1. Introduction

A very important utility parameter of soft-magnetic ferromagnetic alloys is the temperature stability of magnetic susceptibility. This applies not only to materials with a crystalline structure but to all consumer materials with soft magnetic properties [1–3]. In amorphous materials, the initial magnetic susceptibility shows a slightly different behavior than that observed in crystalline materials. Many papers have presented and described the results of measurements of the initial magnetic susceptibility as a function of temperature for amorphous and nanocrystalline materials [4–6]. When measuring the susceptibility at time t after demagnetizing the sample, a random distribution of the orientation of the axis of atom pairs occurs. Atom pairs tend to align their axes according to the spontaneous magnetization of the domain wall, thus introducing a distribution of local anisotropy and deepening the potential well. As a result, the domain wall stabilizes, which in turn results in a reduction in compliance over time (Fig. 1) [4, 5].

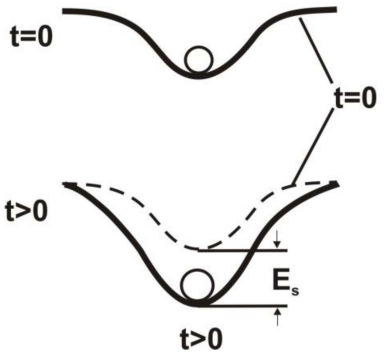

Fig. 1. Development of the domain wall stabilization potential over time [5].

The decrease in magnetic susceptibility over time is related to the temporary stabilization of the domain wall potential ($E_ś$). After demagnetizing the sample, the position of the domain wall is determined by the anchoring potential of this wall, E_0, which is the result of the presence of structural defects and surface irregularities.

In this case, for $t > 0$, the total potential associated with the movement of the domain wall is determined by the relationship [6]

$$E(U,t) = E_0(U) + E(U,t). \tag{1}$$

The total process of relaxation of magnetic susceptibility between time t_0 and t is presented by the relationship [3]

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

where $S_{ś}$ it is the area of the domain wall per unit volume; U — a distance of displacement of the domain wall after time t from its initial position; $E_{ś}(U,t)$ — domain wall stabilization potential described according to the formula [7]

$$E_{ś}(U,t) = -c_0(t)\left\langle \frac{1}{\cosh^2\left(\frac{\Delta_s}{k_\mathrm{B}T}\right)}\right\rangle \left(1 - \mathrm{e}^{t/\tau_R}\right) \times \int\limits_{-\infty}^{+\infty} \mathrm{d}z \left\langle \Delta_m(z-U)\Delta_m(z)\right\rangle. \tag{3}$$

Here, $c_0(t) = n_0(t) = n_\infty + (n_0(0) - n_\infty)\,\mathrm{e}^{-t\tau_A}$ is the average number of pairs of atoms per unit volume; $\tau_A = \tau_{0A}\,\mathrm{e}^{Q_A/(k_\mathrm{B}T)}$ and $\tau_R = \tau_{0R}\,\mathrm{e}^{Q_R/(k_\mathrm{B}T)}$ — relaxation times related, respectively, to the change in defect density and the reorientation of the axes of thermally activated atom pairs (Q_A, Q_R — activation energies); Δ_m and Δ_s are the energies of magnetic and structural fission between two orientations of atom pairs.

The paper presents the results of initial magnetic susceptibility tests performed for the $Fe_{63}Co_9Y_8B_{20}$ bulk amorphous alloys in the form of a plate, made using two production methods: injection method or suction casting method.

2. Experimental procedure

The test material in the form of amorphous samples was made of high-purity ingredients: Fe — 99.99 at.%, Co — 99.999 at.%, Y — 99.99 at.%, Zr — 99.99 at.%. Boron was added in the form of a previously prepared alloy with the chemical composition of $Fe_{45.6}B_{54.4}$. Adding boron in the form of an alloy ensures that the nominal boron values in the alloy are achieved. An attempt to introduce boron as a pure component did not make it possible to maintain the assumed chemical composition. Boron is a material that can spray in the furnace chamber during remelting, which changes the chemical composition of the alloy and makes it difficult to obtain the intended research material. The prepared batches of alloying elements are mixed and placed in a cavity on a copper plate in an arc furnace. The weighed samples have a mass of 10 g. The alloy components are melted in a protective atmosphere of argon, which promotes amorphization. The material is melted several times on each side (at least 3 times), which ensures good mixing. After cooling in the furnace, the ingots prepared in this way are cleaned mechanically and using an ultrasonic bath. Then, as a result of crushing, they are divided into smaller portions of a few grams each. The samples were produced using two methods: the injection method and the method of sucking the liquid alloy into a water-cooled copper mold. In these methods, the liquid alloy is placed in a copper mold in a protective atmosphere of argon. In the case of the suction method, the alloy is melted using an electric arc, and in the injection method — using eddy currents. The samples thus obtained were tested for structure and magnetic properties. Structure tests were performed using a Bruker X-ray diffractometer, model ADVANCE 8. The tests were performed for low-energy powders, which made it possible to test the material in volume. The X-ray measurement was performed in the range of the 2θ angle from 30 to 100° with a measurement step of 0.02° and a measurement time per step of 3 s. Tests of magnetic properties in low magnetic fields were performed using an automated system for measuring magnetic susceptibility. Measurements were made in the temperature range from room temperature (20°C) to the temperature of the ferromagnetic–paramagnetic magnetic transition. The samples produced were so-called open ones, in which the magnetic circuit had to be closed. The magnetic circuit was closed using a yoke made of superpermalloy. Two windings of 30 turns each are wound. One winding was secondary, the other primary.

3. Results

Figure 2 shows the X-ray diffraction patterns obtained for the samples prepared after solidification using injection and suction methods.

Both X-ray diffractograms are similar. Only a broad halo with a maximum near angle of 50° is visible. This shape of X-ray diffractograms is typical for materials with an amorphous structure.

Figure 3 shows the initial magnetic susceptibility curves measured for the tested samples produced by two methods. The measurement was performed in the magnetic field range of $0.4H_C$, the so-called Rayleigh's area.

The initial magnetic susceptibility curves obtained for the tested alloys are similar. Generally, in the temperature range from 300 to about 500 K, a weakly temperature-dependent background is visible, which increases with increasing temperature. The sudden drop in the initial magnetic susceptibility is associated with the magnetic transition from the ferromagnetic state to the paramagnetic state. However, the influence of the production method is visible.

Relaxation processes of magnetic susceptibility are directly related to the time dependence of potential stabilization (1). After demagnetizing the

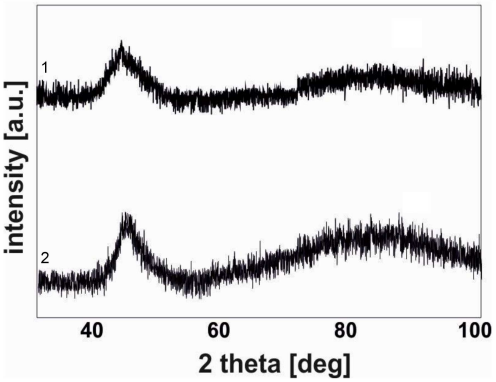

Fig. 2. X-ray diffractograms obtained for the tested samples of the $Fe_{63}Co_9Y_8B_{20}$alloy made by: line 1 — injection, line 2 — suction.

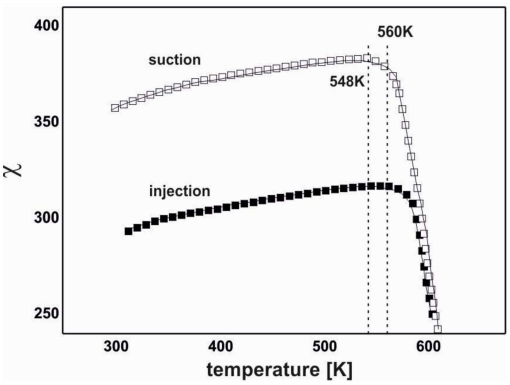

Fig. 3. Initial magnetic susceptibility curves measured for the tested samples of the $Fe_{63}Co_9Y_8B_{20}$ alloy made by: injection (full symbols), suction (empty symbols).

sample with a current with amplitude decreasing to zero, the position of the domain walls is determined by the static anchoring potential of the domain wall $E_0(U)$ (1), which is the result of the presence of structural defects and surface irregularities. Due to the magnetic interactions between spontaneous magnetization and mobile defect configurations within domain walls, defect rearrangement provides the opportunity to reduce the total magnetic interaction energy of domain walls with structural defects. As a result, it leads to a time-dependent so-called "stabilization potential" (3), within which domain walls move. It should follow from the above that for production methods with the same cooling rate, the obtained samples should have a very similar value of initial magnetic susceptibility and maintain a similar course as a function of temperature.

4. Conclusions

The value of the initial magnetic susceptibility is related to the presence of free volumes in the melt after solidification. The two production methods used, i.e., the method of forcing and the method of sucking liquid alloy into a water-cooled copper mold, have a similar cooling speed ranging from 10^{-1} to 10^3 K/s. One would expect very similar curves obtained for the same alloy. However, as the research results show, it is different. X-ray diffraction patterns clearly indicate that the samples have an amorphous structure. Also, the curves from the measurements of the initial magnetic susceptibility are similar to those for amorphous materials. It is clearly visible that in both tested samples there is a different number of structure defects in the form of free volumes. The Curie temperature determined on the basis of the analysis of the initial magnetic susceptibility curves is different. This indicates that amorphous materials are thermodynamically unstable materials in which atoms are constantly rearranged in their volume. Atoms try to create configurations with lower and lower internal energy. This means that despite repeated melting of alloys, areas with different concentrations of alloy components are formed during solidification, which explains the small change in the Curie temperature. In crystalline materials, where the structure is the same throughout the volume, the Curie temperature has a constant value. Please remember that the production process is a very important factor. In this case, production methods with the same liquid melt cooling rates were used. However, the method of placing the material in the mold was different, and, most importantly, the melt temperature was different. The liquid material obtained by injection had a lower temperature than that melted by the arc method. From these considerations, it can be concluded that the key factor is the determination of all parameters of the manufacturing process, which is often omitted in scientific studies.

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