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The Influence of Heat Treatment on Irreversible Structural Relaxation in Bulk Amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ Alloy

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Amorphous materials contain structural defects, which play a key role in the magnetization process within the condition known as the "approach to ferromagnetic saturation". This paper presents the results of magnetization studies, carried out on bulk $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy when under the influence of a strong magnetic field. The alloy samples were obtained in the form of a rod 1 mm in diameter, and tested in the as-quenched state and after an isothermal annealing process, at a temperature below the crystallization temperature. It was observed that the heat treatment, carried out below crystallization temperature T_x, leads to irreversible structural relaxations, specifically reorganizing the atomic configuration within the volume of the alloy into an amorphous structure.

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1. Introduction

As a result of their structure, amorphous alloys exhibit unique magnetic and mechanical properties. Themain feature of amorphous materials is a lack of long-range atomic order. However, short-range order (SRO) does exist in this atomic arrangement. The amorphous state is thermodynamically unstable and changes in short-range order occur during thermal treatment, even at well-below the crystallization temperature. In the amorphous alloys, there is a lack of structural defects, normally existing in crystalline materials, such as: vacancies, or dislocations (linear or screw); however, other kinds of structural defects may be found. So-called "free volumes" and quasidislocational dipoles, found in the amorphous alloys, are the source of the internal stresses and, due to magnetoelastic internal exchange, they cause inhomogeneous distribution of magnetization. Free volumes promote atomic diffusion processes and lead to thermal and time instability of the physical properties of the amorphous alloys. One of the methods for investigation into the microstructure of the alloys involves the measurement of the magnetization process under the influence of strong magnetic fields. According to the theory of Kronmüller, the magnetization of an amorphous alloy within a strong magnetic field could be described by the so-called "approach to magnetic saturation" equation

$$\mu_0 M(H) = \mu_0 M_s \left(1 - \sum_{n=1}^{4} a_{n/2}/\mu_0 H^{n/2}\right) + b\left(\mu_0 H\right)^{1/2},$$

where M_s — spontaneous magnetization, μ_0 — magnetic permeability of a vacuum, H — magnetic field, $a_{1/2}$, a_1, a_2 — gradient coefficients of the linear fit related with the type of defect, b — gradient coefficient of the linear fit related to thermal dumping of the spin-waves by the strong magnetic field.

The coefficient b is related with the stiffness parameter of the spin waves D_{sp} by the following relationship:

$$b = 3.54 g\mu_0\mu_B \left(1/4\pi D_{sp}\right)^{3/2} kT \left(g\mu_B\right)^{1/2},$$

where g — Landé split coefficient, μ_B — Bohr magneton [1].

2. Experimental procedure

The samples were prepared by the injection-casting method. The molten alloy was injected into a copper die, which facilitated the formation of rod-shaped samples of diameter of approximate dimensions: diameter 1 mm and length 1 cm. The structure of the resulting alloy was investigated by means of an X-ray diffractometer, using samples both in the as-quenched state and after thermal treatment (at a temperature of 720 K for 15 min). The 'BRUKER' X-ray diffractometer was equipped with a lamp with a Cu K_α source. Investigations were carried out over the 2Θ range from 30° to 120°, with a measurement step of 0.02° and time per step of 7 s. The investigations of the structure were performed on samples which had been powdered in a low energy process. The aim of the thermal treatment was only to relax the structure, and not to crystallize the sample. The measurements of magnetization were performed over a magnetic field range from 0 T to 2 T using a vibrating sample magnetometer (VSM).

3. Results and discussion

Figure 1 shows the X-ray diffraction patterns for the samples in the as-quenched state and after thermal treatment. The presented diffraction patterns consist only of one, broad, maximum at the 2θ angle equal to 50°, which confirms the amorphicity of the investigated alloys.

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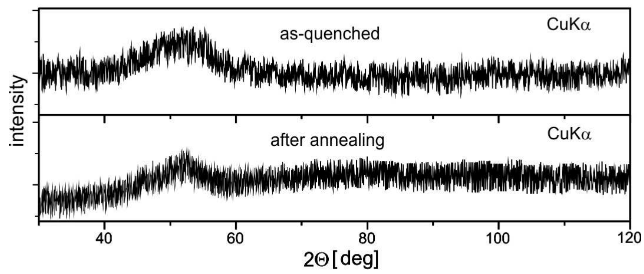

Fig. 1. X-ray diffraction patterns for powdered $Fe_{61}Co_{10}Ti_3Y_6B_{20}$.

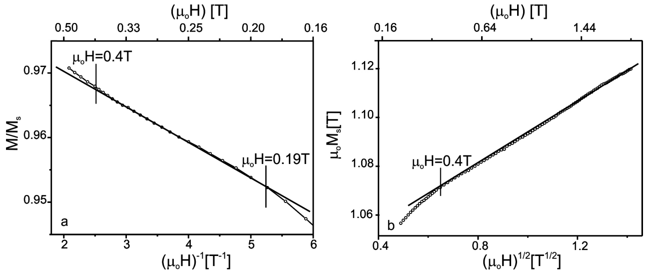

Fig. 2. High-field magnetization curves $M/M_s((\mu_0 H)^{-1})$ (a) and $M_s((\mu_0 H))^{1/2}$ (b) for the bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy in the as-quenched state.

Figure 2 shows high-field magnetization curves, as a function of the magnetizing field, for the investigated alloy, in the as-quenched state (Fig. 2a,b), and after annealing at a temperature of 720 K for 15 min (Fig. 3a,b).

In amorphous materials, the structural defects are in the form of so-called "free volumes" (point defects) or linear defects: so-called quasidislocational dipoles. These defects are the source of the short- and medium-range stresses and influence magnetization behaviour in strong magnetic fields. According to the Kronmüller theorem, a linear relationship of reduced magnetization as a function of $\mu_0 H^{-1/2}$ indicates the presence of point defects in a sample, whereas a linear relationship of reduced magnetization as a function of $\mu_0 H^{-1}$ indicates the presence of quasidislocational dipoles.

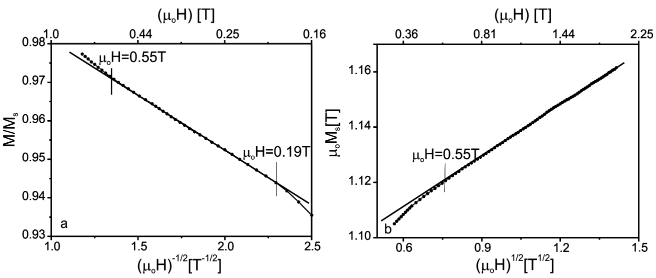

Fig. 3. High-field magnetization curves $M/M_s((\mu_0 H)^{-1/2})$ (a) and $M_s((\mu_0 H))^{1/2}$ (b) for the bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy after annealing.

For the as-quenched sample, a linear fit to the first law could not be obtained; however it was possible to obtain a better fit for $(M/M_s((\mu_0 H)^{-1})$. The linear relationship of the reduced magnetization from $(\mu_0 H)^{-1}$ (Fig. 2a) confirms that, within the magnetizing field range of 0.19 T to 0.4 T, the magnetization process is influenced by quasidislocational dipoles. In the case of the thermally-treated sample, a linear fit was possible only for the first law of the approach to magnetic saturation $(M/M_s((\mu_0 H)^{-1/2}))$. This is related to the presence of point defects, which, within the magnetic field range of 0.19 T to 0.55 T are instrumental in the magnetization process in the sample.

In stronger magnetic fields, of greater than 0.4 T and 0.55 T for the samples in the as-quenched and annealed states, respectively, the slight increase in the magnetization is caused by the dumping of thermally-induced spin waves (Figs. 2b, 3b).

The results obtained from analysis of the high-field magnetization curves are presented in Table.

TABLE

Experimental values of the parameters $a_{1/2}$, b and the spin wave stiffness parameter D_{sp}.

Parameters / State	$a_{1/2}$ $[T^{1/2}]$	a_1 $[T^1]$	b $[T^{1/2}]$	D_{sp} $[10^{-2}$ eV nm$^2]$
as-quenched	–	0.0055	0.0451	52.45
after annealing	0.0287	–	0.0365	60.40

4. Discussion and conclusions

In the as-quenched sample, the second law of the approach to ferromagnetic saturation has been fulfilled. After the isothermal annealing process, conducted at a temperature well below the crystallization temperature of the alloy, the collective re-grouping of the free atoms in the sample volume caused disintegration of the thermally unstable two-dimensional defects into point defects; also, for this sample the high-field magnetization process performs according to the first law of the approach to ferromagnetic saturation. In the cases of both of the samples, within higher magnetic fields the magnetization process is connected with the Holstein–Primakoff paraprocess. This was confirmed by the linear relationship of $(\mu_0 M_s((\mu_0 H)^{1/2})$. According to [2], it was expected that the value of the D_{sp} parameter would increase after thermal treatment; this is connected with the change of the internal parameter of the sample. After annealing, the distances between the magnetic atoms in the nearest neighbourhood changes. Kaul [3] and Corb [4] state that in the relaxed amorphous structure each of the magnetic atoms possess ≈12 nearest neighbours, compared with only 9–10 for the stressed structure. An increase in the value of D_{sp} may be explained by an increase in the number of magnetic atoms in the nearest neighbourhood, and an improvement in the chemical (SRO).

The annealing of the alloy was performed at a temperature much lower than (T_x), which for the investigated alloy was about 950 K. The aim of the thermal treatment was only to relax the structure, and not to crystallize the sample. The aim of the paper was to show the effect of the thermal treatment on the structural changes occurring in the amorphous state; that is why the annealing was performed at a temperature which was more than 200 K lower than the crystallisation temperature of the alloy. The results of investigations performed in the papers [5–7] have indicated that structural relaxations in the amorphous state lead to changes in magnetic properties. Investigations have been performed on these same samples, first in the as-quenched state and then after thermal treatment, therefore the observed changes in the magnetic properties are the result of the annealing process.

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