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The Influence of Structural Relaxation on the Holstein–Primakoff Paraprocess

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Structural relaxations play a large role in forming the properties of magnetic materials. In amorphous alloys, which are metastable materials, obtaining a relatively stable structure requires a properly designed thermal treatment process. Samples should be annealed above the Curie temperature and below the crystallization temperature. With the process designed in such a way, the domain structure is not interfered with and the formation of crystal grains does not occur. By analyzing the so-called Holstein–Primakoff paraprocess, it is possible to determine the influence of magnetic atoms on the magnetization process in strong magnetic fields above the field of effective anisotropy.

topics: bulk amorphous alloys, magnetization process, Holstein–Primakoff paraprocess

1. Introduction

Magnetic materials play a crucial role in various technologies, including data storage media, magnetic sensors, and commonly available components such as transformers. Amorphous materials are metastable substances that exhibit unique magnetic properties [1–3].

Amorphous alloys, due to the absence of a well-defined crystalline lattice, exhibit properties that can be modified through controlled thermal treatment. A key stage of this process involves annealing the material at temperatures above the Curie temperature but below the crystallization temperature [4, 5]. This technique enables the formation of a relaxed structure without the risk of crystallization, which could significantly alter the material's properties. Importantly, this process does not interfere with the magnetic domain structure, which is crucial for preserving the material's magnetic characteristics.

One of the methods for studying the structure of amorphous alloys is the analysis of their magnetization process in strong magnetic fields. In the region of the so-called approach to ferromagnetic saturation [6, 7], magnetization is not a linear function of the external magnetic field intensity. The magnetization process of the sample is hindered by structural inhomogeneities. In the case of amorphous alloys, two types of defects are distinguished: point defects (free volumes) and line defects (pseudo-dislocation dipoles).

This study presents the results of research on the structure and magnetic properties of bulk amorphous alloys subjected to annealing at temperatures below the crystallization temperature.

2. Experimental procedure

The ingot for the production of rapidly cooled alloys was prepared in an arc furnace. The elements were weighed with an accuracy of 0.0001 g. The ingot was placed in a cavity on a water-cooled copper plate. The melting process was conducted in a protective argon atmosphere using a tungsten electrode. The ingot was remelted five times, flipping it over each time to ensure a thorough mixing of the components.

The rapidly cooled bulk alloy was produced using the injection casting method. The process was carried out in a protective argon atmosphere after

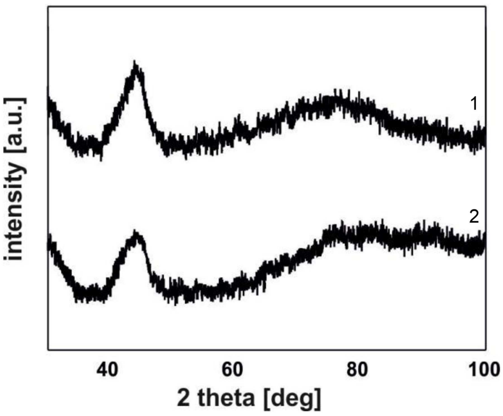

Fig. 1. X-ray diffraction patterns for the rod-form samples of $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloys: line no. 1 — after solidification, line no. 2 — after annealing at 700 K/30 min.

reaching a vacuum of approximately 10^{-5} mBa in the working chamber. The ingot was placed in a quartz crucible with a 1 mm diameter opening, and melting was performed using eddy currents. The molten alloy was injected into a copper mold under argon pressure, resulting in rod-shaped samples with a thickness of 0.5 mm and a length of 20 mm.

The heat treatment of the samples was conducted in a tube furnace under vacuum. The alloy samples were annealed at 700 K for 30 min and subsequently cooled by gravity. The structure of the produced alloys was analyzed using X-ray diffraction. A Bruker D8 ADVANCE X-ray diffractometer was used for the measurements, which were performed over a specified 2θ angular range of 30–100°, with a measurement step size of 0.02° and an exposure time of 7 s per step. The analysis was carried out on powdered material.

3. Results

Figure 1 shows X-ray diffraction for tested alloys. The X-ray diffraction patterns measured for the investigated samples are characteristic of amorphous materials. Only broad maxima are observed in the 40–50° range of the 2θ angle.

The alloy samples underwent magnetic property analysis. Figures 2 and 3 present the magnetization process analysis in the approach to ferromagnetic saturation. The analysis indicates that in the as-solidified state, the magnetization process of the alloy sample within the external magnetic field intensity range of 0.031–0.06 T is associated with the rotation of the magnetization vector around point defects.

Above this range, in the interval from 0.06 to 0.46 T, the alloy's magnetization is associated with the presence of line defects. The magnetization

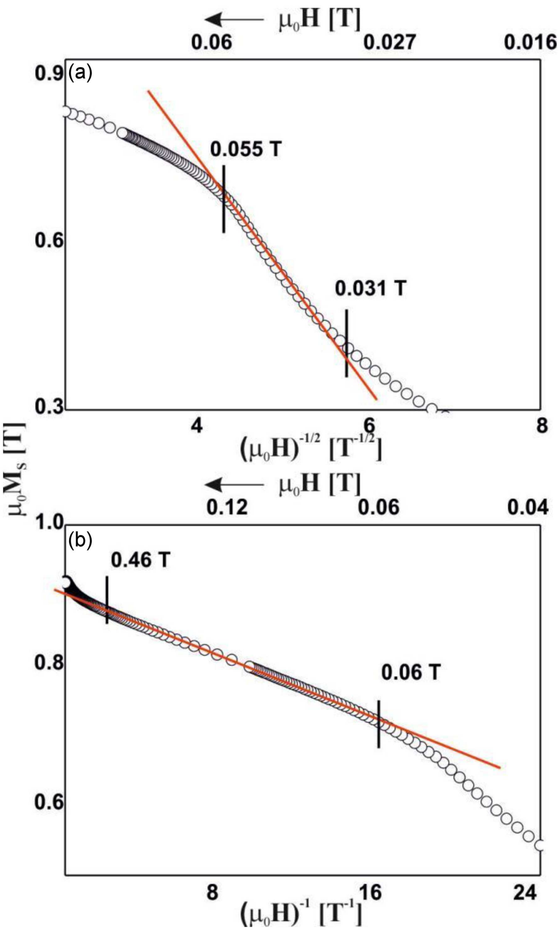

Fig. 2. Magnetization of $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloy after solidification as a function of: (a) $(\mu_0 H)^{-1/2}$, (b) $(\mu_0 H)^{-1}$.

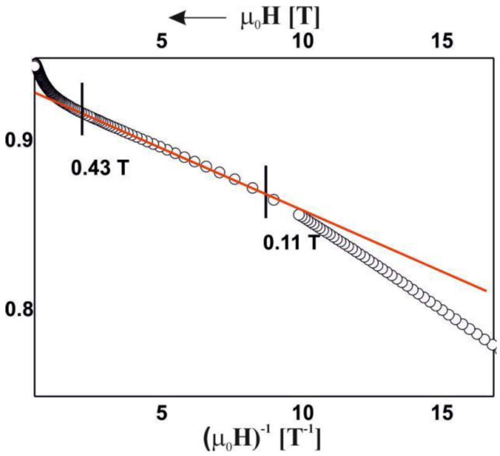

Fig. 3. Magnetization of $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloy after annealing as a function of $(\mu_0 H)^{-1}$.

process of the annealed sample exhibits a slightly different behavior. The analysis of the magnetization process did not reveal the presence of point defects. In this case, magnetization in the approach to ferromagnetic saturation is related to the rotation of

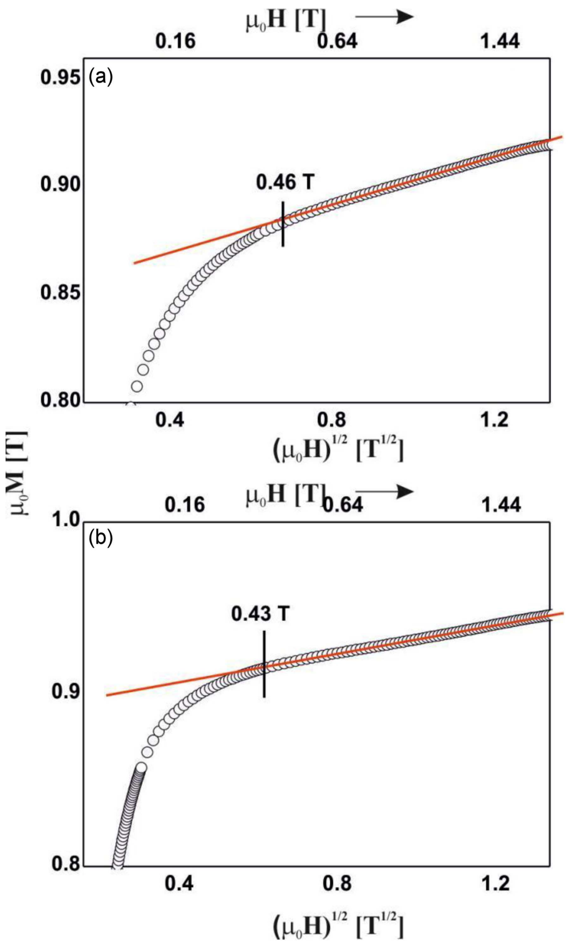

Fig. 4. Magnetization, as a function of $(\mu_0 H)^{1/2}$ for the $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloy samples: (a) after solidification, (b) after annealing at 700 K/30 min.

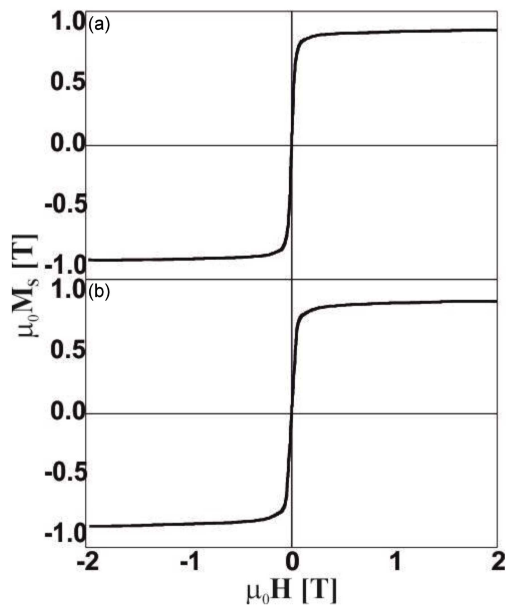

Fig. 5. Static hysteresis magnetic loops for the $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloy samples: (a) after solidification, (b) after annealing at 700 K/30 min.

TABLE I

Values of $\mu_0 M_S$ — saturation magnetization [T], H_C — coercive field [A/m], and D_{spf} — spin-wave stiffness parameter [meV nm^2] of the investigated samples.

$Fe_{45}Co_{25}B_{20}Cu_1Nb_9$	$\mu_0 M_S$	H_C	D_{spf}
after solidification	0.92	30	45
after annealing	0.95	35	53

the magnetization vector around pseudo-dislocation dipoles in the external magnetic field intensity range of 0.11 to 0.43 T.

Figure 4 presents the analysis of the magnetization process beyond the region of effective anisotropy.

Above the approach-to-ferromagnetic-saturation region, further magnetization of the alloy is associated with the damping of thermally excited spin waves (the so-called Holstein–Primakoff paraprocess) [8]. Based on linear fitting of the magnetization dependence as a function of the external magnetic field intensity, the spin wave stiffness parameter D_{spf} was determined, with the values presented in Table I.

Figure 5 shows the static magnetic hysteresis loops for the investigated samples.

The measured hysteresis loops are characteristic of materials exhibiting soft magnetic properties. By zooming in on the origin of the coordinate system, the coercive field values for the investigated samples were determined. The results are presented in Table I.

The annealing process influenced the relaxation of the $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ alloy's structure without inducing crystallization of the amorphous matrix. The energy supplied to the sample promoted the consolidation of point defects into larger linear defects. This process also led to changes in the interatomic distances between magnetic atom pairs: Fe–Fe, Fe–Co, and Co–Co. This is reflected in the increase in the spin wave stiffness parameter D_{spf}, accompanied by a corresponding rise in saturation magnetization (M_S).

4. Conclusions

The paper presents the results of structural and magnetic property investigations of the amorphous alloy $Fe_{45}Co_{25}B_{20}Cu_1Nb_9$ subjected to thermal treatment at temperatures below the crystallization temperature. The magnetization process analysis showed that supplying an appropriate amount of energy to the sample allows for structural relaxation.

The annealing process influenced the conglomeration of free volumes into linear defects and the change in the distance between magnetic atoms. This leads to an increase in the saturation magnetization and the spin wave stiffness parameter. The annealing process did not lead to a significant change in the coercive field value.

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