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Process of Magnetization in Strong Magnetic Fields of Amorphous Fe-Based Alloys

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Amorphous alloys exhibit a similar course of the magnetization process as crystalline materials. This means that there is also a domain structure in their volume, the changes of which describe the magnetization process well. These defects are a kind of inhomogeneity of the material structure and become an area where there are disturbances in the alignment of spins in relation to the intensity of the external magnetic field. These disturbances are the reason for the change in the course of the M–H curve. Using the theory developed by H. Kronmüller, it is possible to study the process of magnetization of amorphous ferromagnetic alloys in strong magnetic fields. The work analyzes the change in the process of magnetization of amorphous iron alloys along with the change in their chemical composition.

topics: bulk amorphous alloys, soft magnetic properties, magnetization process

1. Introduction

Fe-based amorphous alloys are modern functional materials and an interesting research subject. A characteristic feature of amorphous materials is their disordered structure — a structure typical for liquids. Despite the same chemical composition, amorphous alloys differ significantly from their crystalline counterparts. First of all, these materials are characterized by good mechanical properties. However, this is not their most important feature — the most important are good magnetic and soft magnetic properties, which are the result of the fact that such alloys are characterized by a high content of ferromagnetic elements [1–3]. Due to the lack of an ordered structure, free rotations of domain walls are possible, which results in an easy magnetization process of these materials. In crystalline materials, the magnetic structure is related to the orientation of crystals. In the case of amorphous alloys, despite the disordered structure, one can distinguish the directions of magnetization, namely "easy" and "difficult" [4]. However, it should be noted that the differences in the anisotropy values for these directions are insignificant. This is related to the process of producing such alloys. So far, such a phenomenon has not been fully explained.

The magnetization process of amorphous alloys is very similar to that of their crystalline counterparts. The primary magnetization curve is divided into 4 areas [5]. In the first area, the magnetization process is associated with reversible shifts of domain walls and is described by Rayleigh's law. In the second area, in the range of 0.4–10H_C, the 180-degree shifts of domain walls are irreversible. In the third area, called the Ewing knee, the closing domains are magnetized. In the case of amorphous materials, magnetization in this area is associated with the presence of structural defects occurring in the form of free volumes and pseudodislocation dipoles. In the fourth area, the further magnetization of the alloy is associated with the suppression of thermally excited spin waves, i.e., the so-called Holstein–Primakoff paraprocess.

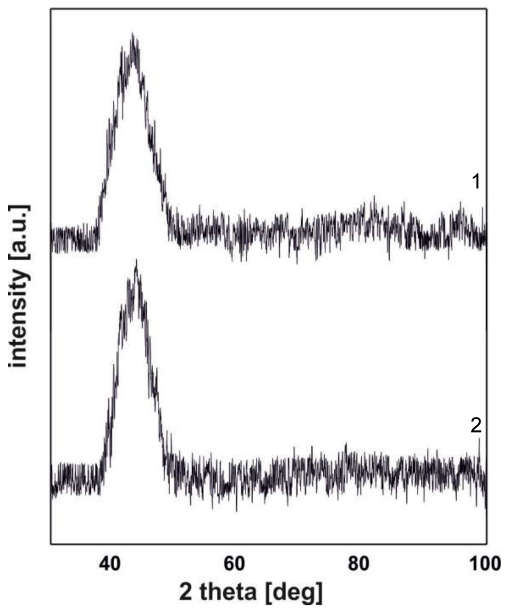

Fig. 1. X-ray diffraction patterns for the rod-form samples of the investigated alloys: line 1 — $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79.5}B_{19.5}$, line 2 — $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79}B_{19}$.

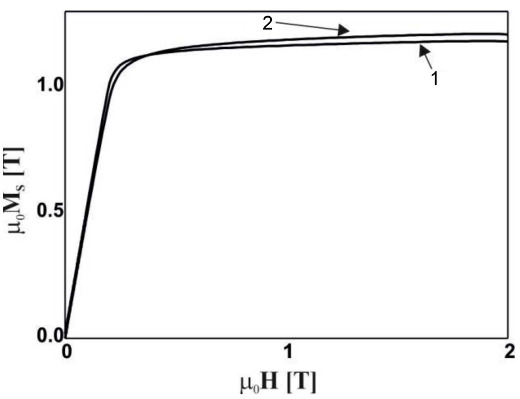

Fig. 2. Primary magnetization curves for the alloy samples in the form of 0.5 mm thick plates: line 1 — $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79.5}B_{19.5}$, line 2 — $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79}B_{19}$.

This paper presents the results of research on the magnetization process of bulk amorphous alloys with a high Fe content in high magnetic fields.

2. Experimental procedure

The batch for the production of fast-cooling alloys was produced in an arc furnace. Two 10-gram ingots were melted from the following components, each with a purity of 99.9%: Fe, Si, Hf, Nb, and B.

The elements were weighed to the nearest 0.0001 g. The batch was placed in a cavity on a water-cooled copper plate. The melting process was carried out in an argon protective atmosphere using a tungsten electrode. Bulk amorphous alloys in the form of plates with dimensions of $10 \times 10 \times 5$ mm^3 were produced by the pressing method.

The structure of the produced alloys was examined using X-ray diffraction. A Bruker D8 ADVANCE X-ray diffractometer was used. Measurements were taken in the range of 30–100° of the 2θ angle, with a measuring step of 0.02° for powdered material.

The primary magnetization curves were measured using a Lake Shore 7307 vibrating sample magnetometer at an external magnetic field strength of up to 2 T. The curves were analyzed according to the theory of the ferromagnetic saturation approach [6–8].

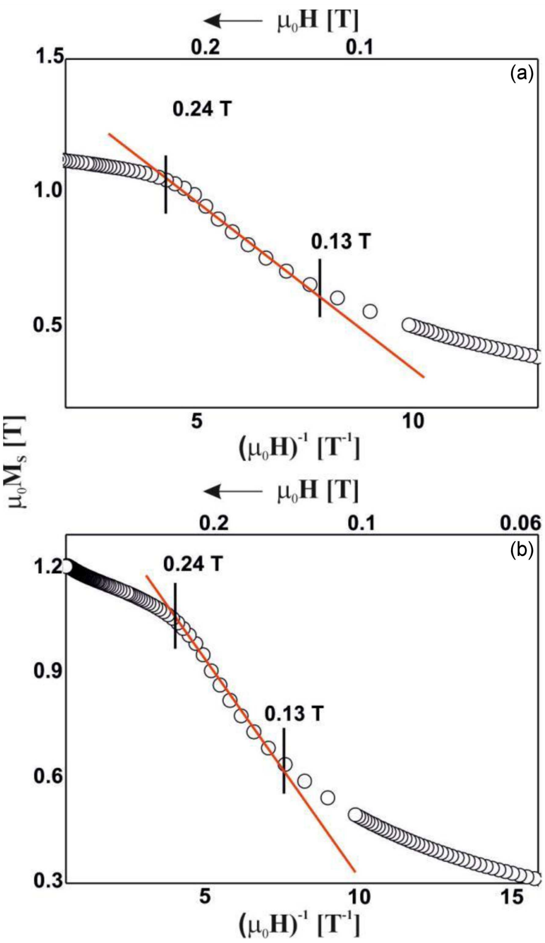

Fig. 3. Magnetization, as a function of $(\mu_0 H)^{-1}$, for the alloy samples in the form of 0.5 mm thick plates: (a) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79.5}B_{19.5}$, (b) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79}B_{19}$.

3. Results

Figure 1 shows the X-ray diffraction patterns measured for the produced alloy samples.

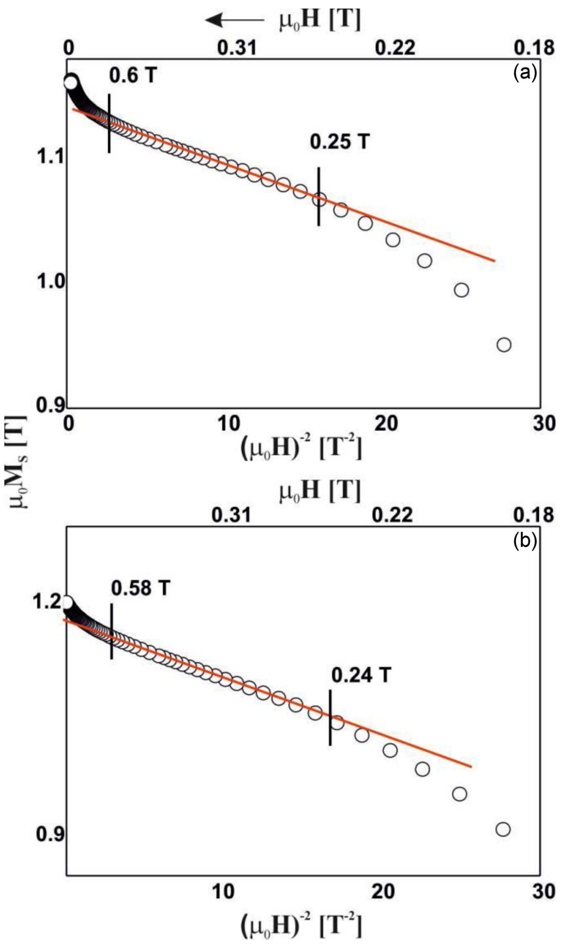

Fig. 4. Magnetization, as a function of $(\mu_0\mathrm{H})^{-2}$, for the alloy samples in the form of 0.5 mm thick plates: (a) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79.5}B_{19.5}$, (b) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79}B_{19}$.

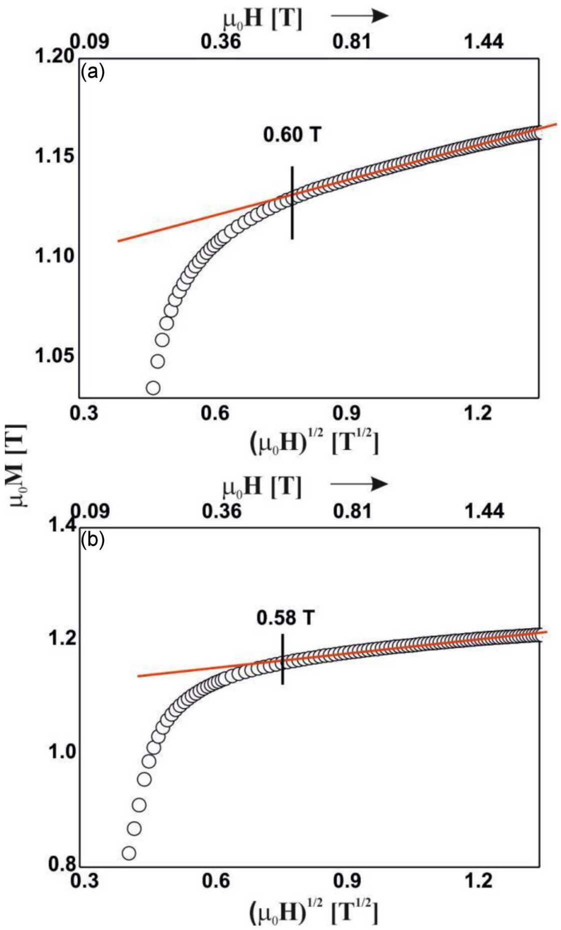

Fig. 5. Magnetization, as a function of $(\mu_0\mathrm{H})^{1/2}$, for the alloy samples in the form of 0.5 mm thick plates: (a) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79.5}B_{19.5}$, (b) $(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{79}B_{19}$.

The samples of the alloys produced are characterized by an amorphous structure. This is indicated by broad maxima in the range of 40–50° of the 2θ angle. Figure 2 shows the primary magnetization curves for the alloys tested.

The primary magnetization curves for both samples are almost identical. Based on them, the saturation magnetization value MS was determined (Table I). Figure 3 presents the analysis of the primary magnetization curves in the region approaching ferromagnetic saturation.

Analysis of the magnetization process in high magnetic fields has shown that in the range of external magnetic field strength from 0.13 to 0.24 T, the alloy magnetization process is related to the rotation of the magnetization vector around linear defects of dimensions not exceeding the exchange distance. Figure 4 presents the analysis of the primary magnetization curves as a function of $(\mu_0 H)^{-2}$.

The analysis showed that the further magnetization process of the tested alloys is associated with the presence of linear defects with dimensions exceeding the exchange distance. It is worth noting that the presence of these defects affects the magnetization process of the alloys in almost the same range of the external magnetic field intensity. Figure 5 presents the analysis of the primary magnetization curves above the area of approach to ferromagnetic saturation.

The magnetization process of amorphous alloys in the region above the effective anisotropy is related to the suppression of thermally excited spin waves. In this region, the sample is single-domain, and a small increase in the magnetization value is related to the ordering of spins under the influence of an external magnetic field. This phenomenon is called the Holstein–Primakoff paraprocess [9]. Based on a linear fit to the magnetization curve as a function of $(\mu_0\mathrm{H})^{1/2}$, the spin wave stiffness parameter D_{spf} was determined. The results are given in Table I.

A slightly higher value of the M_S saturation magnetization can be observed for the alloy sample $(Fe_{92.5}Si_{2.5}Hf_{2.5}Nb_{2.5})_{79}B_{19}$, which is of course related to a slightly higher Fe content in the alloy. An interesting phenomenon is the significantly lower stiffness parameter of the spongy wave D_{spf} for this

TABLE I

Values of $\mu_0 M_S$ — saturation magnetization [T] and D_{spf} — spin-wave stiffness parameter [meV nm^2] of the alloy samples.

Alloy	$\mu_0 M_S$	D_{spf}
$(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{80.5}B_{19.5}$	1.16	43
$(Fe_{92,5}Si_{2,5}Hf_{2,5}Nb_{2,5})_{81}B_{19}$	1.20	34

sample. Theoretically, a higher Fe content should result in an increase in both the saturation magnetization and the D_{spf} parameter. A slight increase in the Fe content should result in a decrease in the distance between the Fe–Fe magnetic atoms and, as a result, cause an increase in the D_{spf} parameter — in the case of the tested alloys, this relationship does not occur.

4. Conclusions

The magnetization process of bulk amorphous alloys based on Fe produced by the extrusion method was investigated in this work. The alloy samples produced differed in the content of boron (and proportionally in the remaining alloying elements). Both alloys are characterized by an amorphous structure and a similar course of the magnetization process. In both cases, in the area of approach to ferromagnetic saturation, the magnetization process is associated with the rotation of the magnetization vector around linear defects with dimensions smaller than the exchange distance (dependence $\mu_0 M_S(\mu_0 H)^{-1}$) and larger than the exchange distance (dependence $\mu_0 M_S(\mu_0 H)^{-2}$). Linear defects affect the magnetization process of these samples in almost identical ranges of the external magnetic field intensity. The shape of the primary magnetization curves is also almost identical. This indicates good repeatability of the production of alloy samples from this group. Interestingly, despite these similarities, the magnetization process of the alloys tested above the area of approach to ferromagnetic saturation is diverse. For the sample with a higher Fe content, the expected result is to achieve a higher saturation magnetization value and a higher D_{spf} parameter value. In the case of the latter value, a different result was obtained. Therefore, it should be stated that the obtained amorphous structure for both samples has a slightly different form. It is possible that the reduction of the B content led to a reorganization of the structure in the immediate vicinity of Fe atoms. Future studies, using, among others, Mössbauer spectroscopy or magnetic susceptibility disaccommodation measurements, can explain this phenomenon in more detail. In addition, these alloys are characterized by good soft magnetic properties. For the above reasons, these alloys are an interesting object for further research.

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