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Total Core Losses of $Fe_{70}Y_5Nb_xMo_{5-x}B_{20}$ Bulk Amorphous Fe-Based Alloys

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Remagnetisation losses are one of the most important performance parameters of materials designed for the production of low-loss transformer cores. Classical Fe–Si alloys are characterised by losses of a few W/kg. However, the crystal structure makes these materials unsuitable for use at high frequencies. The ferromagnetic Fe-based alloys constitute an interesting group of alloys with magnetic soft properties. This group includes alloys from the Fe–Me–B system (where Me is one of the range of transition metals). This study investigates the structure, and losses due to remagnetisation, of bulk amorphous FeYMoNbB-based alloys. It was found that the addition of a small quantity of Nb changes the structure, and the magnitude of the losses. The addition of Nb significantly reduces additional losses; this effect is associated with the changing melt viscosity.

topics: bulk amorphous alloys, injection casting, total core losses, additional losses

1. Introduction

Fe-based amorphous alloys have great application potential. Depending on the content of Fe, transition metals and non-metals, these alloys may show good mechanical properties [1–3] or high corrosion resistance [4, 5]. Alloys with a correspondingly high content of Fe and the addition of other ferromagnetic components exhibit 'soft magnetic' properties. Alloys in the form of thin strips exhibit particularly good properties, often having a coercive field value of less than 5 A/m [6–8]. Alloys with a low value of coercive field are characterised by a very low level of losses. The disorder of the component atoms facilitates the process of magnetisation, meaning that these materials can be used to build low-loss transformer cores. Unfortunately, due to their limited dimensions, it is necessary to package the alloy strips, or tapes, into groups for greater thickness. This results in the entrapment of air between the alloy surfaces, leading to unnecessary heating of the core during high frequency operation. Therefore, the so-called bulk amorphous alloys can be an alternative. Bulk amorphous alloys show low magnetisation losses of the order of a dozen W/kg [9, 10]. The total losses (P_t) in amorphous alloys are related to the hysteresis loop surface (P_{his}), the losses for eddy currents (P_{cl}) and the so-called additional losses (P_{exc}) [11, 12].

$$P_t = P_{\mathrm{his}} + P_{\mathrm{cl}} + P_{\mathrm{exc}}. \quad (1)$$

As an approximation, additional losses could be represented in the following way:

$$P_{\mathrm{exc}} = 8.76\sqrt{\sigma G S V_0}\,(f B_{\mathrm{peak}})^{3/2}, \quad (2)$$

where B_{peak} — the maximum value of the induced field, f — frequency, σ — electrical conductivity, G — dimensionless factor, S — the cross-section area of the sample and V_0 — the constant associated with the impact of breaking centres of the domain walls.

This study investigated the effect of Nb on the generation of magnetisation losses and additional losses in Fe-based bulk amorphous alloys.

2. Materials and methods

$Fe_{70}Y_5Nb_xMo_{5-x}B_{20}$ alloy ingots were produced in an arc furnace. High purity components were used to prepare the polycrystalline alloys: Fe — 99.99%, Mo — 99.99%, Nb — 99.99%, Y — 99.95%, B — 99.95%. The batch was measured to an accuracy of 0.0001 g (i.e., 5 gram sample). The melting

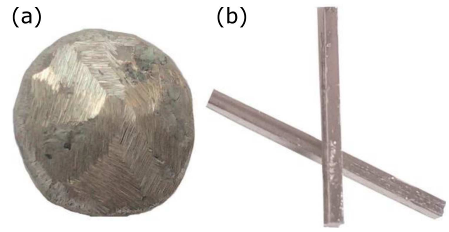

Fig. 1. Produced alloys: (a) polycrystalline ingot, (b) amorphous rod.

process was carried out under an argon atmosphere, at 700 hPa. Cleanliness of the working chamber was ensured by the use of a set of rotary and vacuum pumps as well as by melting a titanium getter. Ingots were smelted using a tungsten electrode, through which a current of 180–300 A was passed. The process was repeated 6 times to obtain a homogeneous structure. The resulting ingots were mechanically cleaned, crushed into smaller pieces, and subjected to further cleaning in an ultrasonic bath. The required rapidly cooled alloys were produced using an injection-casting method. The production process was carried out under a protective argon atmosphere, at a pressure of 700 hPa, after obtaining a high vacuum. The charge was melted using induction heating, the liquid alloy then being injected under argon pressure into a water-cooled copper mould. Rods with a diameter of 1 mm and a length of 20 mm were produced. The produced alloy samples are shown in Fig. 1.

The structure of each alloy was investigated using X-ray diffraction. A BRUKER D8 Advance diffractometer with a CuK_α lamp and a semiconductor counter was used for this process. Measurements were performed over a two theta angle range of 30–100° with an exposure time of 5 s per measurement step (0.02°).

The loss curves as a function of maximum induction field were measured using a FERROMETER measurement system. Alloy samples were placed in a yoke made of superpermalloy. Loss measurements were made at room temperature over the frequency range of 50–1000 Hz.

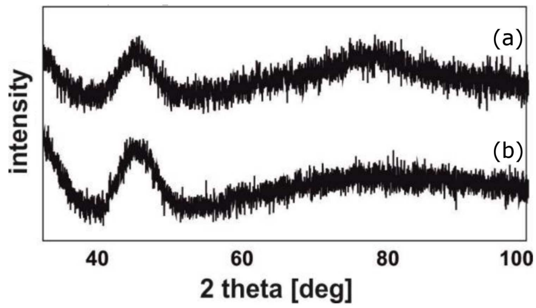

Fig. 2. X-ray diffractograms for the tested alloys: (a) $Fe_{70}Y_5Mo_5B_{20}$, (b) $Fe_{70}Y_5Nb_1Mo_4B_{20}$.

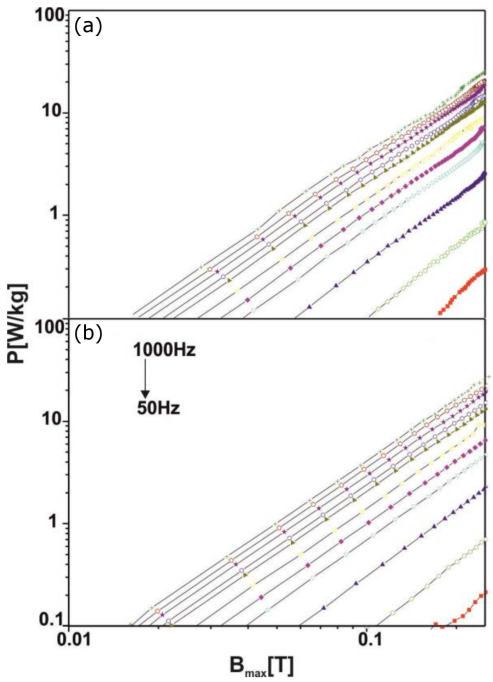

Fig. 3. Remagnetisation losses for the produced alloys, as a function of maximum induction field (the frequency range of the magnetising field was 50–1000 Hz): (a) $Fe_{70}Y_5Mo_5B_{20}$, (b) $Fe_{70}Y_5Nb_1Mo_4B_{20}$.

3. Results

Figure 2 shows the X-ray diffraction images for the produced alloy samples. On the recorded diffractograms, a single wide maximum is visible in the range of 2θ angle of 40–50°. This maximum is related to the absence of atomic order within the volume of the alloys and proves their amorphous structure. Figure 3 shows the remagnetisation losses for the produced alloy samples.

In amorphous materials, the remagnetisation losses are the sum of the losses related to eddy currents, the area of the dynamic magnetic hysteresis loop and additional losses. During the magnetisation process of a sample, eddy currents are produced that generate a magnetic field in opposition to the applied field. Alloys with an amorphous structure are characterised by relatively low losses due to eddy currents. This is due to the relatively low electrical conductivity of these materials [13]. In these alloys, the main component of the losses is related to the area of the magnetic hysteresis loop — occurring as a result of irreversible magnetisation processes. These processes are the result of the presence of centres that inhibit the movement of domain walls. "Additional losses" make up an often-neglected component of the total losses. Additional losses are related to so-called fluctuating viscosity and migratory relaxation processes. The alloys, tested in this study, are characterised by low losses — comparable to those of Fe-Si sheets [13–15]. The addition of Nb was not found to exert any effect on the magnitude of the losses of the tested alloys. Analysis was

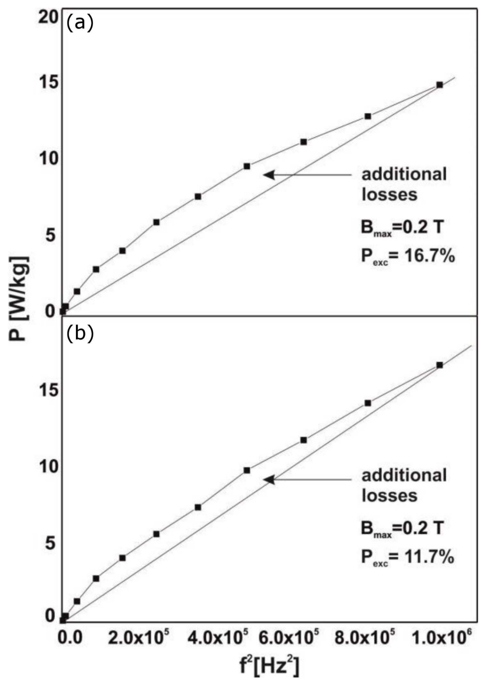

Fig. 4. Additional losses, determined for $B_{\max} = 0.2$ T, for the tested alloys: (a) $Fe_{70}Y_5Mo_5B_{20}$, (b) $Fe_{70}Y_5Nb_1Mo_4B_{20}$.

conducted on the curves, measured for the maximum induction value of $B_{\max} = 0.2$ T. This analysis is presented in Fig. 4.

In theory, the losses are a linear function of the square of the frequency. As can be seen from the shapes of the curves in Fig. 4, this is not the case. Differences between the linear waveform and the actual relationship of the losses, with the square of the frequency, constitute additional losses. The surface area characterising P_{exc} was determined for the tested alloy samples. It was found that, for the $Fe_{70}Y_5Mo_5B_{20}$ alloy, additional losses amount to 16.7%; whereas for the $Fe_{70}Y_5Nb_1Mo_4B_{20}$ alloy, additional losses amount to 11.7%. The addition of Nb reduced the proportion of P_{exc}, and this may be associated with the more homogeneous structure of the $Fe_{70}Y_5Nb_1Mo_4B_{20}$ alloy. This conclusion can be drawn on the basis of the more stable shape of the curves for higher values of the maximum induction and the very fact that the alloy is a five-component alloy, which should be characterised by a higher glass transition ability. Interestingly, the addition of Nb practically did not affect the level of losses.

4. Conclusions

This study investigated the effect of the addition of Nb on the structure and losses of FeYMoB-based amorphous alloys. The tested alloys have an amorphous structure, as indicated by the X-ray diffraction studies. The remagnetisation losses, recorded for the tested alloys, show low values; no effect on their level was observed for the addition of Nb. On the other hand, the effect of the addition of Nb on the "proportional breakdown of the losses" is visible: for a five-component alloy, additional losses constitute a smaller share than for a four-component alloy. This fact should be related to the more homogeneous structure of the $Fe_{70}Y_5Nb_1Mo_4B_{20}$ alloy, and its higher degree of relaxation.

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