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# The Influence of Nb and Mo Content on the Magnetisation Process of Bulk Amorphous Alloys Based on Fe

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The defects, present in ferromagnetic alloys with amorphous structure, have a major impact on the magnetic properties of these alloys. These defects are present in the forms of point and linear defects. There is no direct method allowing for their observation. However, the sensitivity of the magnetisation vector to the presence of all inhomogeneities gives the opportunity for indirect estimation of the type of defects and their volume, based on analysis of the initial magnetisation curve. The alloys studied within this work were produced by injection of each respective liquid alloy into a copper die. For the alloys obtained in this way, investigations into the structural and magnetic properties were performed. The structural analysis of the Fe-based bulk amorphous alloys was performed according to the Kronmüller theorem. Based on the results of the investigations, it was found that an increase in the Mo contribution (at the expense of Nb) effected decreases in the values of the saturation magnetisation and the stiffness parameter $D_{\mathrm{spf}}$. In the region known as the "approach to the ferromagnetic saturation", the magnetisation process of the investigated alloys is connected with the rotation of the magnetisation vector in the vicinity of quasi-dislocational dipoles. For the alloys with Mo content of 4 and 5 at.%, the presence of linear defects meeting the condition $D_{\mathrm{dip}} > l_H$ was identified.

topics: approach to ferromagnetic saturation, injection-casting method, bulk amorphous alloys

## 1. Introduction

The bulk amorphous alloys based on iron are very interesting subjects for research [1, 2]. Alloys exhibiting so-called soft magnetic properties, i.e. a low value of coercivity and a high value of saturation magnetisation, are especially interesting [3, 4]. Despite numerous studies, the amorphous structure has not been fully explained and described. One of the remaining problematic subjects is the description of the structural defects in amorphous materials. In the case of alloys with the ferromagnetic properties, there is an indirect method allowing for the observation of the structural defects. This method employs the fact that the magnetisation vector is highly sensitive to all inhomogeneities existing within the structure of the material. Analysis of the magnetisation process, according to the Kronmüller theorem [5–8], allows the determination of the type(s) and number of structural defects within the sample. In amorphous materials, point defects called "free volumes" and linear defects called "quasi-dislocational dipoles" can be present [9]. The presence of these defects affects the magnetisation process in the so-called "approach to saturation magnetic region".

The aim of this work was to investigate the influence of Mo and Nb content on the structure (i.e. structural defects) and magnetic properties of rapidly-quenched alloys with the compositions $Fe_{70}B_{20}Y_5Nb_{2-x}Mo_{3+x}$ (where $x = 0$, 1, 2).

## 2. Methods and materials

Samples of polycrystalline alloys with the chemical compositions $Fe_{70}B_{20}Y_5Nb_{2-x}Mo_{3+x}$ were produced in an arc furnace, under a protective argon atmosphere. The chemical compositions of the alloys were designed in accordance with the criteria formulated by Inoue [10, 11] related to the main components of an alloy. Ingots were made, each weighing 10 g. The melting process was repeated seven times, and after each time the ingot was physically inverted. In addition, a titanium getter was melted, in order to intercept and trap contaminants remaining in the working chamber. The ingots were divided into smaller pieces and cleaned using an ultrasonic cleaner. The rapidly-quenched alloys were produced by a method involving the injection of liquid alloy into a copper die. The production process was carried out under a protective argon atmosphere. The alloy samples were cast as 0.5 mm thick plates. The injection-casting method allows cooling rates of up to $10^3$ K/s to be achieved.

The structure of the investigated samples was investigated by means of X-ray diffractometry; a BRUKER D8 Advance system, equipped with a Cu $K_\alpha$ radiation source was used. The samples were exposed for 7 s per measurement step of 0.02°. The initial magnetisation curves and the static magnetic hysteresis curves were recorded using a Lake Shore vibrating sample magnetometer. The measurements were taken in an external magnetic field of up to 2 T.

According to the Kronmüller theorem, magnetisation near the region known as the approach to ferromagnetic saturation can be defined as:

$$\mu_0 M(H) = \mu_0 M_s \left[1 - \frac{a_{1/2}}{(\mu_0 H)^{\frac{1}{2}}} - \frac{a_1}{(\mu_0 H)^1} - \frac{a_2}{(\mu_0 H)^2}\right] + b(\mu_0 H)^{\frac{1}{2}}, \quad (1)$$

where $M_s$ — spontaneous magnetisation, $\mu_0$ — magnetic permeability of a vacuum, $H$ — magnetic field, $a_i$ ($i = \frac{1}{2}$, 1, 2) — angular coefficients of the linear fit corresponding to the free volume and linear defects, $b$ — slope of the linear fit corresponding to the thermally-induced suppression of spin-waves by a magnetic field of high intensity.

In strong magnetic fields above the anisotropy field, where the magnetizing process is not related to the stresses of the near- and middle-range structure, thermally-suppressed spin-waves play a dominant role. Using the relationship given in Eq. (2), the parameter $D_{\rm spf}$ was calculated

$$b = 3.54 g \mu_0 \mu_{\rm B} \left(\frac{1}{4\pi D_{\rm spf}}\right)^{3/2} kT (g\mu_{\rm B})^{1/2}. \quad (2)$$

## 3. Results

Figure 1 shows the X-ray diffraction (XRD) patterns recorded for the $Fe_{70}B_{20}Y_5Nb_{3-x}Mo_{2+x}$ alloys in the as-quenched state.

The recorded XRD patterns are typical of those of amorphous alloys. For all of the investigated samples, a wide maximum in the $2\theta$ range of 40–50° is visible. This confirms the random atomic distribution within the samples — which is typical for amorphous materials.

Figures 2 to 4 present the results of analysis of the initial magnetisation curves for the investigated alloys.

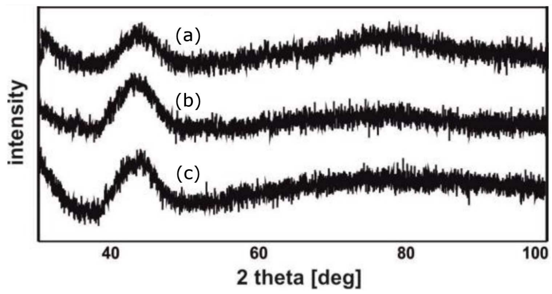


Fig. 1. X-ray diffraction patterns for the alloys: (a) $Fe_{70}B_{20}Y_5Nb_2Mo_3$, (b) $Fe_{70}B_{20}Y_5Nb_1Mo_4$, (c) $Fe_{70}B_{20}Y_5Mo_5$.

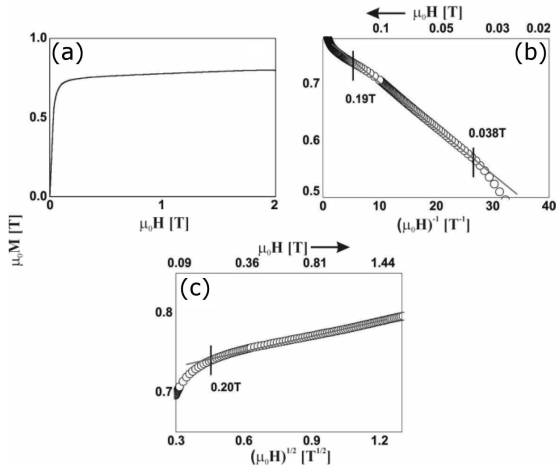


Fig. 2. Magnetisation curves obtained for the $Fe_{70}B_{20}Y_5Nb_2Mo_3$ alloy: (a) initial magnetisation curve, magnetisation as a function of: (b) $(\mu_0 H)^{-1}$ and (c) $(\mu_0 H)^{1/2}$.

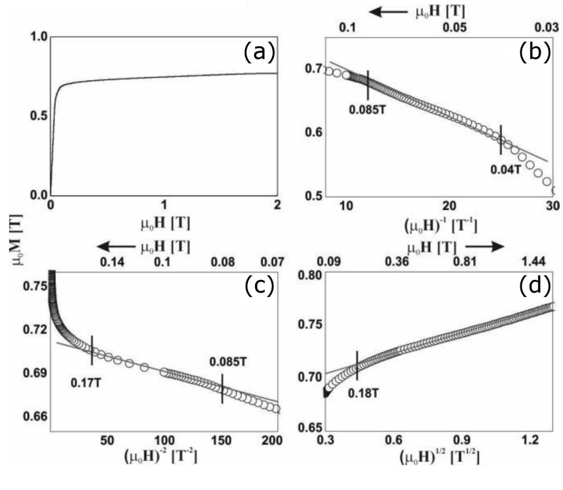


Fig. 3. Magnetisation curves obtained for the $Fe_{70}B_{20}Y_5Nb_1Mo_4$ alloy: (a) initial magnetisation curve, magnetisation as a function of: (b) $(\mu_0 H)^{-1}$, (c) $(\mu_0 H)^{-2}$ and (d) $(\mu_0 H)^{1/2}$.

Analysis based on the initial magnetisation curves allowed the determination of the saturation magnetisation, and the identification of the type of the defects present in the investigated alloys. It was found that the magnetisation process in

TABLE I

Magnetic properties of the alloys: $Fe_{70}B_{20}Y_5Nb_{2-x}Mo_{3+x}$: $H_c$ [A/m]; $M_s$ [T]; $D_{spf}$ [meV nm$^2$]. $D_{dip}$ — dipole width, $l_H$ — exchange length.

| Alloy | $H_c$ | $M_s$ | Structural defects | | $D_{spf}$ |
|---|---|---|---|---|---|
| | | | $D_{dip} < l_H$ | $D_{dip} > l_H$ | |
| $Fe_{70}B_{20}Y_5Nb_2Mo_3$ | 22 | 0.80 | + | | 43.8 |
| $Fe_{70}B_{20}Y_5Nb_1Mo_4$ | 16 | 0.77 | + | + | 43.4 |
| $Fe_{70}B_{20}Y_5Mo_5$ | 10 | 0.75 | | + | 42.9 |

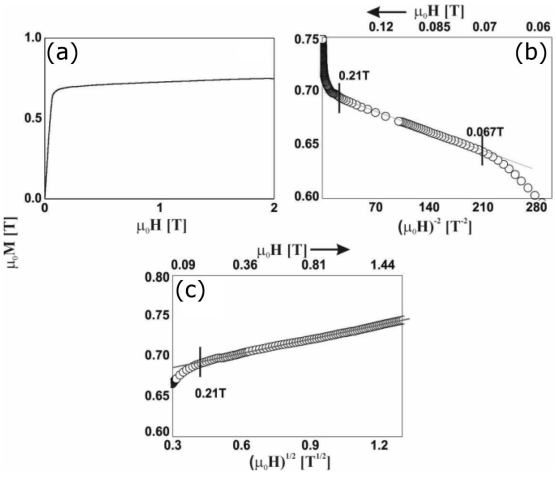


Fig. 4. Magnetisation curves obtained for the $Fe_{70}B_{20}Y_5Mo_5$ alloy: (a) initial magnetisation curve, magnetisation as a function of: (b) $(\mu_0 H)^{-2}$ and (c) $(\mu_0 H)^{1/2}$.

the approach to ferromagnetic saturation region is connected with the rotation of the magnetisation vector in the vicinity of linear defects. Moreover, on the basis of the fit-coefficient for the Holstein–Primakoff paraprocess, the stiffness parameter of the spin-wave was determined. The obtained results formed the basis of the analysis are assembled in Table I. In the investigated alloys, an increase in the content of Mo — at the expense of Nb — was found to result in a decrease in the value of the saturation magnetisation (for every 1 at.%, the magnetisation decreased by 0.03 T). Together with the decrease in the magnetisation, the value of the spin-wave stiffness parameter $D_{spf}$ was found to decrease.

This is connected with changes in the distances between pairs of ferromagnetic atoms, i.e. Fe–Fe. The change in the distance results in weakening of the exchange interactions, which can explain the decrease in the value of the saturation magnetisation. For the $Fe_{70}B_{20}Y_5Nb_2Mo_3$ alloys, the presence of linear defects fulfilling the condition $D_{dip} < l_H$ was identified. In the volume of the $Fe_{70}B_{20}Y_5Nb_1Mo_4$ sample, defects fulfilling both the $D_{dip} < l_H$ and $D_{dip} > l_H$ conditions were detected. In the case of the $Fe_{70}B_{20}Y_5Mo_5$ alloy, the only defects present had dimensions greater than the exchange length. These results suggest that the presence of Mo influences the degree of structural deformation. The dimensions of the defects influence the magnetisation process of the alloys and the maximum value of saturation magnetisation attained.

## 4. Conclusions

The alloys made and studied within this work were characterised by an amorphous structure. The investigated materials exhibited good soft magnetic properties, i.e. low value of coercivity and relatively high value of saturation magnetisation. Analysis of the initial magnetisation curves allowed for identification of the type of structural defects present in the materials and the determination of the value of the spin-wave stiffness parameter $D_{spf}$.

Based on the results of the investigations, it can be stated that:

1. Addition of Mo decreases the value of the spin-wave stiffness parameter, which means an increase in the distances between the iron atoms and a decrease in the value of the saturation magnetisation.

2. The presence of Mo influences the dimensions of the defects within the amorphous structure; for the $Fe_{70}B_{20}Y_5Mo_5$ alloy, the only defects present fulfilled the condition $D_{dip} > l_H$.

3. The degree of structural deformation has no significant influence on the value of the coercive field in the case of the investigated alloys.

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