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journal homepage: www.elsevier.com/locate/jalcomInfluence of the cooling speed on the soft magnetic and mechanical properties of $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ amorphous alloyMarcin Nabiałek^{a,*}, Paweł Pietrusiewicz^a, Marcin Dośpiał^a, Michał Szota^b, Joanna Gondro^a, Konrad Gruszka^a, Anna Dobrzańska-Danikiewicz^c, Simon Walters^d, Anna Bukowska^b^a Czestochowa University of Technology, Faculty of Materials Processing Technology and Applied Physics, Institute of Physics, 19 Armii Krajowej Av., 42-200 Czestochowa, Poland^b Czestochowa University of Technology, Faculty of Materials Processing Technology and Applied Physics, Materials Engineering Institute, 19 Armii Krajowej Av., 42-200 Czestochowa, Poland^c Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems, 18a Konarskiego Av., 44-100 Gliwice, Poland^d University of Brighton, School of Computing, Engineering and Mathematics, Cockcroft Building, Lewes Road, Moulsecoomb, Brighton BN2 4GJ, UK

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ABSTRACT

The properties of metallic amorphous materials depend mainly on their chemical composition and the degree of relaxation of the structure. The relaxed amorphous structure is usually obtained by annealing below the crystallization temperature (T_x). However, this process can be forced during the production process. In this paper, the results are presented of investigations into the: microstructure, magnetic and mechanical properties of $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ alloy. The samples, fabricated in the forms of ribbons and plates, were produced using cooling speeds of 10^4 – 10^6 K/s and 10^1 – 10^3 K/s, respectively. In the course of the investigations, it has been found that varying the quenching speed of the liquid alloy has a major influence on the properties of the $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ amorphous alloys.

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1. Introduction

The constant development of civilization requires new electronic and electrical devices, which in turn drives the manufacturers of these devices to conduct investigations into new component materials. Modern electrotechnical materials, used in the production of energy-efficient transformer cores, should exhibit exceptional magnetic and mechanical properties. Every year, thousands of samples of new electrotechnical materials are being tested in industrial research laboratories. The research and development teams are looking for materials exhibiting: low coercivity, high saturation magnetization, excellent thermal and time stability of the magnetic susceptibility, and high values of hardness and wear resistance. All of the aforementioned properties, depending of the chemical composition, could be achieved in the iron-based amorphous alloys, exhibiting so-called 'soft magnetic properties' [1–7]. In addition, further improvement of these properties in the amorphous alloys could be obtained by thermal treatment [8–10]. Annealing of the alloys is usually performed below the crystallization temperature, and should lead to the creation of fine grains of the crystalline phase (less than 100 nm in each direction)

embedded in the amorphous matrix [11]. These materials are called 'nanocrystalline'. Change in type of production process, from melt-spinning onto suction or injection-casting, results in a significant reduction of solidification speed, what in turn results in lesser anisotropy as well as changes in the quantity and type of structural defects in the amorphous material. Comparison of mechanical and magnetic properties of materials, produced at different cooling rates were presented, respectively in [12,13] and [13–15].

Certain conditions maintained during the production process could lead to a relaxation process in the amorphous alloys and better soft magnetic properties. The main condition is a change in the cooling rate during the production process of the amorphous materials. The most popular manufacturing method for these materials involves unidirectional cooling of the molten alloy on a copper wheel which is rotating with high linear velocity; the resulting cooling speed ranges from 10^3 K/s to 10^6 K/s. This gives a much more rapid cooling rate than is possible for samples made using methods involving radial cooling using copper moulds [16,17]. Using the latter techniques, cooling speed ranging from 10^{-1} K/s to 10^3 K/s may be achieved [18,19]. Increasing the solidification time of the molten alloy to the amorphous state leads to noticeable re-grouping of the mobile atom pairs, which could create structural defects in the form of quasidislocational dipoles [20,21]. These defects are two-dimensional, rather unstable, creations and

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they release additional energy during their synthesis into point defects. During the energetic process, point defects could be freed towards the surface of the sample [19]. Observation of the structural changes in the volume of such materials, and knowledge of their real structure, is very interesting. Investigation into the disaccommodation of the magnetic susceptibility and the analysis of the initial magnetization curve in the so-called ‘approach to ferromagnetic saturation’ area facilitate the evaluation of the effect of structural defects on the magnetic properties of the amorphous alloys [22].

In this paper, results are presented from investigations into the microstructure and the magnetic and mechanical properties of classical and bulk amorphous alloys with the chemical composition $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$.

2. Material research

The initial ingots of $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ alloy were made by arc-melting the following high purity components: Fe-99.99 at.%; Co-99.99 at.%; Y-99.99 at.%; and W-99.9999 at.%. Boron was added to the initial ingot as an alloy with known composition – $\text{Fe}_{45.4}\text{B}_{44.6}$. The final samples were made in the forms of ribbons and plates, by melt-spinning and injection-casting methods, respectively. Ribbon-shaped samples have thickness and width measurements of approximately 30 μm and 4 mm, respectively; the corresponding measurements for the plate-shaped samples are approximately 0.5 mm and 10 mm, respectively. All samples of the $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ alloy have been subjected to microstructural investigations using a “BRUKER ADVANCE D8” X-ray diffractometer (XRD) and a “S/TEM TYTAN 80-300 FEI” transmission microscope. The initial magnetic susceptibility and its disaccommodation were measured by means of an automated set-up, using the transformer method. The initial magnetization curves and static hysteresis loops were measured using a ‘LakeShore’ vibrating sample magnetometer (VSM). Saturation magnetization, as a function of temperature, was measured using a Faraday magnetic balance. All magnetic, X-ray and Mössbauer investigations were performed on low-energy powdered samples; this yielded the following two benefits. Firstly, in the case of the magnetic measurements, the shape-associated factor of the sample could be neglected. Secondly, in the case of the microstructure investigations, information could be gained from the entire volume of the samples. The microhardness of the samples was obtained using a “FutureTech 740” micro-hardness system with 100 G load (in the form of a pyramid with the apex angle between the planes of 136°) and over a 6 s period.

3. Theoretical background

The theorem allowing for description of the influence of structural defects on the magnetization process in strong and weak magnetic fields was proposed by Kronmüller and Fahnle [20], Kronmüller et al. [21].

Above the anisotropy field ($H > \frac{2K_{\text{eff}}}{\mu_0 M_s}$) the magnetization could be described by the equation [23]:

$$\Delta M = \Delta M_{\text{wew}} + \Delta M_{\text{para}} + \Delta M_{\text{def}}, \quad (1)$$

where (ΔM_{para}) – is related to the dumping of thermally-induced spin waves by an external magnetic field, (ΔM_{wew}) – represents internal fluctuations, such as anisotropy or change in density and (ΔM_{def}) – is the result of the structural defects.

In this paper, the factor ΔM_{wew} will be omitted due to its very minor influence on the magnetization process. Without this factor magnetization could be described by the relation [15,23]:

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

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.

Expressions in Eq. (2), related to ΔM_{def} , are described by relationships (3)–(5) [23].

$$\frac{a_{1/2}}{(\mu_0 H)^{1/2}} = \mu_0 \frac{3}{20A_{\text{ex}}} \left(\frac{1+r}{1-r} \right)^2 G^2 \lambda_s^2 (\Delta V)^2 N \left(\frac{2A_{\text{ex}}}{\mu_0 M_s} \right)^{1/2} \frac{1}{(\mu_0 H)^{1/2}}, \quad (3)$$

$$\frac{a_1}{\mu_0 H} = 1.1 \mu_0 \frac{G^2 \lambda_s^2}{(1-v)^2} \frac{Nb_{\text{eff}}}{M_s A_{\text{ex}}} D_{\text{dip}}^2 \frac{1}{\mu_0 H}, \quad (4)$$

$$\frac{a_2}{\mu_0 H^2} = 0.456 \mu_0 \frac{G^2 \lambda_s^2}{(1-v)^2} \frac{Nb_{\text{eff}}}{M_s^2} D_{\text{dip}}^2 \frac{1}{(\mu_0 H)^2}, \quad (5)$$

where ΔV – is the change of volume caused by the presence of the point defects described by volume density N , A_{ex} – exchange constant, G – shear modulus, r – Poisson ratio and λ_s – magnetostriction constant.

While term ΔM_{para} is described by Eq. (6) [22].

$$b = 3,54 g \mu_0 \mu_B \left(\frac{1}{4\pi D_{\text{spf}}} \right)^{3/2} kT (g \mu_B)^{1/2}, \quad (6)$$

where k – Boltzman constant, μ_B – Bohr magneton, g – gyromagnetic coefficient and D_{spf} – the stiffness parameter of the spin wave.

The term A_{ex} present in relationships (3) and (4) is called the exchange constant [24]:

$$A_{\text{ex}} = \frac{M_s D_{\text{spf}}}{2g \mu_B}, \quad (7)$$

Analysis of the initial magnetization curves facilitates determination of whether or not the magnetization process in the vicinity of the magnetic saturation is connected to the presence of structural defects [15,24,25]. If the main role in the magnetization process is played by free-volumes, the associated volume density can be calculated (8). Conversely, if the magnetization process is

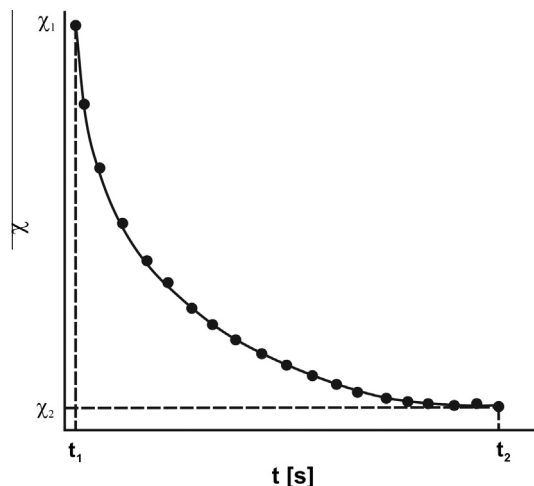


Fig. 1. Disaccommodation of the magnetic susceptibility.

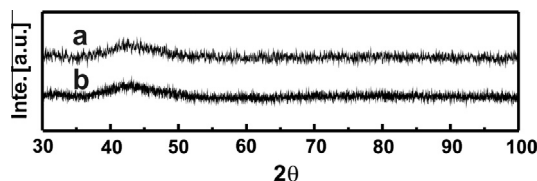


Fig. 2. X-ray diffraction patterns for the $\text{Fe}_{61}\text{Co}_{10}\text{Y}_8\text{W}_1\text{B}_{20}$ alloy in the as-quenched state; sample in the shape of: ribbon (a) and plate (b).

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