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Effect of manufacturing method on the magnetic properties and formation of structural defects in $Fe_{61}Co_{10}Y_8Zr_1B_{20}$ amorphous alloy

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A B S T R A C T

Soft magnetic properties of amorphous alloys are determined by their structure, which strongly depends on their manufacturing method. Alloys obtained in the form of conventional amorphous alloys (tapes) are cooled with a much higher rate than the material obtained in the form of tiles by the injection casting method. The cooling rate and production method determines the type and number of structural defects created in the volume of produced samples. The paper presents an indirect method for the analysis of structural defects and their effect on the magnetic properties of studied alloys. Basing on initial magnetization curve analysis in the area of so-called approach to ferromagnetic saturation was found that point defects were forming in the samples in the form of tapes. The magnetization process of tiles were influenced by the presence of conglomerates of point defects called quasidislocation dipoles.

1. Introduction

Amorphous alloys are materials very interesting both from a cognitive and application matter [1,2]. The first amorphous tape was produced more than half a century ago. As a date of birth of bulk amorphous materials (BMG) is treated 1989, when A. Inoue of the University of Tohoku formulated three criteria that allowed for their regular production [3]. The interest in amorphous materials has been and is still very large, what is resulting from their outstanding properties [1,4–9]. From the moment when the mass production of amorphous ferromagnetic materials began, many industrial companies and research laboratories started to intensely study their structure. The main reason was to understand the influence of the structure on the properties of amorphous alloys and an attempt to perform its accurate description [6,10]. With the current technical advancement, characterization of crystalline materials and their exact description is automatically done and don not make any problems [11]. As for the description of the structure of amorphous materials, the situation is quite different. Lack of order in the arrangement of atoms i.e. lack of periodic arrangement in space, metastable character as well as chemical and topological disorder are making a large barrier for the precise description of the structure of these alloys. Explanation of good soft magnetic properties, of ferromagnetic materials with amorphous structure is possible basing on accurate study of their structure [12,13]. It should be noted that the method of production of amorphous alloys have a significant impact on their functional parameters, and that the amorphous material of the same chemical composition can be obtained with different cooling rates [6]. In the process of rapid solidification it comes to the formation of structural defects in the form of free volumes or their conglomerates [6,14]. The cooling rate is the parameter which decide about formation of different types and quantities of structural defects. Therefore, knowledge of the real structure of amorphous alloys (and structural defects found in the volume of sample) and its influence on the soft magnetic properties is an important problem, but difficult for description. However, there is a method based on theoretical considerations by which it is possible to determine the effect of structural defects on the magnetization process of amorphous ferromagnetic materials characterized by good soft magnetic properties [14–17].

In this paper, studies by the approach to ferromagnetic saturation method for the $Fe_{61}Co_{10}Y_8Zr_1B_{20}$ alloy obtained by the use of two production methods is presented.

2. Material research

The research material was produced using chemical components with high purity of more than 99.99%at. Boron was added as a $Fe_{45.4}B_{45.6}$ alloy. Polycrystalline ingot of $Fe_{61}Co_{10}Y_8Zr_1B_{20}$ alloy was prepared by the arc melting in a protective gas atmosphere. Samples in the form of tapes were obtained by melt spinning technique, with 30 m/s linear speed of copper drum, 800 hPa pressure of neutral gas in vacuum chamber and 1000 hPa injection pressure of liquid alloy from quartz capillary. Obtained tapes had 30 μm and 3 mm, respectively thickness and width.

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The sample in the form of tiles were produced by injection casting method, with 700 hPa pressure of neutral gas in vacuum chamber and 1000 hPa injection pressure. The obtained plates had 0,5 mm thickness and 1 cm^2 of area.

The structure of the produced samples was examined using "BRUKER D8 Advance" X-ray diffractometer, equipped with a Cu radiation source with characteristic wave length of 1,541 Å. Measurement of magnetization as a function of magnetic field strength were performed at room temperature using a "LakeShore" vibrating sample magnetometer. Both structure and magnetization measurements as a function of magnetic field were carried out for the low-energy powdered material. In case of the structure studies powdering was necessary to gather information from the whole volume of the sample. In the case of magnetic studies, samples were powdered in order to avoid influence of factor associated with demagnetization field. The powder was mounted in a special holder which was preventing shifting of studied material fragments (see Fig. 1).

3. Theortical background

Structural defects present in amorphous materials can be distinguished into two types: point defects and two-dimensional quasidislocational dipoles [14]. Point defects are occurring between atoms with the assumption, that this free area is not less than the diameter of the smallest element which is component of the alloy (Fig. 2). Thus defined voids in the amorphous alloys have a similar role as vacancies in crystalline materials. Quasidislocation dipoles are formed as a result of the conglomeration of free volumes (Fig. 2) [14].

Determination of the presence of such defects in ferromagnetic amorphous alloys, and their identification is possible according to the theory proposed by Kronmüller [14,18]. Due to the high sensitivity of the magnetic structure to any inhomogeneities in the atomic structure, structural defects can be observed indirectly.

Magnetization in strong magnetic fields above anisotropy field ($H > \frac{2K_{eff}}{\mu_0 M_s}$) can be described by the equation:

$$\Delta M = \Delta M_{\mathrm{int}} + \Delta M_{para} + \Delta M_{def} \quad (1)$$

where (ΔM_{para}) – results from damping of thermally excited spin waves by an external magnetic field, (ΔM_{int}) is a factor which results from the internal fluctuations, such as the anisotropy of the density, (ΔM_{def}) – is related to the existence of structural defects.

Factor (ΔM_{int}) is small enough (in the order: $\Delta M_{int} \sim 10^{-6}$), that in comparison with the other factors may be omitted [18].

Finally, given the above, the magnetization near the area known as the approach to ferromagnetic saturation is defined as:

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

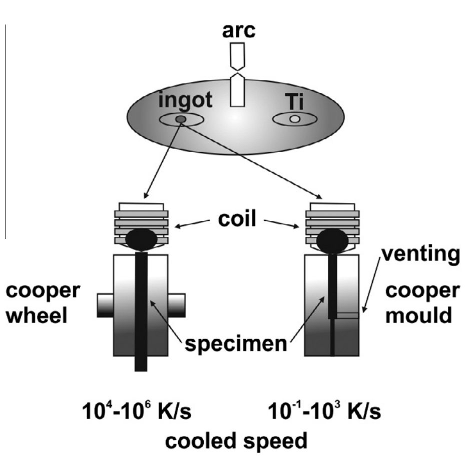

Fig. 1. A schematic description of the production cycle of conventional and massive amorphous materials: (a) initial preparation of polycrystalline ingots using arc melting, (b) amorphous strip casting process, (c) the process of production of massive tiles using the injection casting method.

where M_s – spontaneous magnetization, μ_0 – magnetic permeability of vacuum, H – magnetic field, a_i (i = ½, 1, 2) – angular coefficients of the linear fit, which correspond 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.

Terms appearing in Eq. (2) describes the dependency (3), (4) and (5) [19].

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

$$\frac{a_1}{\mu_0 H} = 1,1\mu_0 \frac{G^2 \lambda_s^2}{(1-\nu)^2} \frac{N b_{eff}}{M_s A_{ex}} D_{dip}^2 \frac{1}{\mu_0 H} \quad (4)$$

$$\frac{a_2}{\mu_0 H^2} = 0,456\mu_0 \frac{G^2 \lambda_s^2}{(1-\nu)^2} \frac{N b_{eff}}{M_s^2} D_{dip}^2 \frac{1}{(\mu_0 H)^2} \quad (5)$$

where ΔV – means the change in volume due to the occurrence of a point defect characterized by a bulk density of N, A_{ex} – exchange constant, G – transverse elastic shear modulus, r – Poisson's ratio, λ_s – magnetostriction constant.

Eq. (3) describes the relationship when i = ½, and is associated with influence of point defects on the magnetization process in the area known as the "knee". Eq. (4) for i = 1, assuming that $D_{dip} < l_H$ and Eq. (5) for i = 2 with the assumption that $D_{dip} > l_H$ are describing the effect of linear defects (the so-called quasidislocation dipoles) on the course of the further process of magnetization in the area of approach to ferromagnetic saturation. Exchange distance (l_H) is then defined as the distance within which they appear at least two dislocation dipoles [20].

$$l_H = \sqrt{\frac{2A_{ex}}{\mu_0 H M_s}} \quad (6)$$

where A_{ex} is the exchange distance defined as [21]:

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

where the D_{spf} is a spin-wave stiffness parameter and is determined from Eq. (8).

In the field values above the law (5) called approach to ferromagnetic saturation, magnetization process occurs by thermally induced suppression of spin waves (Holstein–Primakoff paraprocess) and it is described by factor $b(_0H)^{1/2}$ [19]. Term b can be determined from the formula:

$$b = 3.54 g\mu_0 \mu_B \left(\frac{1}{4\pi D_{spf}}\right)^{3/2} kT(g\mu_B)^{1/2} \quad (8)$$

where k – Boltzman's constant, μ_B – Bohr magneton, g – gyromagnetic factor.

If in the process of magnetization in strong magnetic fields point defects play a dominant role is possible to determine the bulk density based on the relationship:

$$N_{\max} = \frac{3}{4\pi} \frac{1}{l_H^3} \quad (9)$$

However, when in the process of magnetization in strong magnetic fields is associated with the presence of quasidislocation dipoles and law (4) is complied, the surface density can be estimated according to the relationship:

$$N_{dip} = \frac{1}{l_H^2} \quad (10)$$