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Magnetic properties of bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy near the Curie temperature

K. Błoch*
Institute of Physics, Faculty of Materials Processing Technology and Applied Physics, Czestochowa University of Technology, Al. Armii Krajowej 19, 42-200 Częstochowa, Poland
Corresponding e-mail address: bloch@wip.pcz.pl

ABSTRACT

Purpose: The aim of this study was to conduct studies of the magnetic properties for a massive amorphous alloy $Fe_{61}Co_{10}Ti_3Y_6B_{20}$.

Design/methodology/approach: The investigated samples were prepared in the form of rods by using the suction-casting method. The material structures were investigated using X-ray. The magnetic properties were studied using a completely automated set up for measuring susceptibility and its disaccommodation. The magnetization as a function of magnetizing field was measured using magnetic Faraday's weight as a part of magnetocaloric effect studies.

Findings: In the framework of this study, the structure and magnetic properties of the solid amorphous alloy $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ was examined. On the basis of the of X-ray diffraction obtained material was found to be amorphous alloy. Magnetic studies were carried out using a fully computerized system for magnetic susceptibility measures and its disaccommodation. It was showed that both susceptibility curve and isochoric disaccommodation curve maximum occurs in the transition from the state of ferromagnetic material into a paramagnetic state. This peak is called the Hopkinson maximum. From the curves of the magnetic susceptibility as a function of the temperature the value of the Curie temperature was established to about 550 K. Using the measurements of magnetisation as a function of magnetic field strength Arrott curves were constructed. The positive slope of the curves demonstrates the fact that the phase transition ferro-para is of the second kind. Using the magnetization curves the change of the magnetic entropy was determined. The biggest change of the magnetic entropy occur near the Curie temperature.

Research limitations/implications: Based on studies carried out as part of this work it was found that the magnetic properties of investigated alloy, ie. magnetic susceptibility and its disaccommodation, are showing a clear change near the Curie temperature.

Originality/value: The study of magnetic properties and their behavior in the vicinity of the Curie temperature.

Keywords: Bulk alloy; Curie temperature; Disaccommodation; Permeability; Magnetic entropy; Arrot's plots

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PROPERTIES

1. Introduction

Amorphous alloys are characterized by a unique magnetic properties arising from their structure [1-5]. Typically, they are obtained by quick solidification of the melt. Bulk amorphous alloys are produced at a relatively low cooling rate i.e., (10^2 K/s-10^0 K/s) and even during their preparation the structural relaxation occurs leading to the stabilization of their structure. These microscopic relaxation processes are leading to changes in a number of macroscopic properties and structure of amorphous alloys. As a result of the structural relaxation change in the microstructure and in the magnetic, mechanical and chemical properties of amorphous alloys is observed [6]. Structural relaxation can be studied by measuring the magnetic properties of amorphous alloys, e.g. the Curie temperature, magnetic susceptibility or coercive field.

Due to the fact that the amorphous alloys are heterogeneous and there are some regions of different concentrations of elements, they are showing slightly different Curie temperatures. Therefore, in the case of amorphous alloys Curie temperature is the average temperature of the transition from a ferromagnetic state to a paramagnetic state.

The magnetic properties of bulk amorphous alloys shows clear change near the Curie temperature.

On the curve χ(T) showing relation of initial ferromagnetic susceptibility from temperature (Fig. 1), at high temperatures there is a clear maximum - called Hopkinson's peak [7]. This peak occurs just below the Curie temperature of the alloy [8].

The occurrence of this maximum is related to decreasing anisotropy constant and magnetization constant with increasing temperature near the Curie temperature [10]. As is known, a ferromagnetic amorphous alloys contain one or more components of magnetic elements and stabilizing their structure. The most commonly used rapid solidification technique allows to obtain amorphous alloys, characterized by the changing environment of magnetic elements [11]. Therefore, observed on the χ(T) curve Hopkinson maximum is much wider than in the ferromagnetic crystal. This is due to the fact that, in amorphous alloys there is essentially a Curie temperature distribution. Nevertheless, utilizing the magnetic susceptibility of the initial temperature of phase transition in the vicinity of a ferromagnetic-paramagnetic transition, one can estimate the Curie temperature of the amorphous alloy.

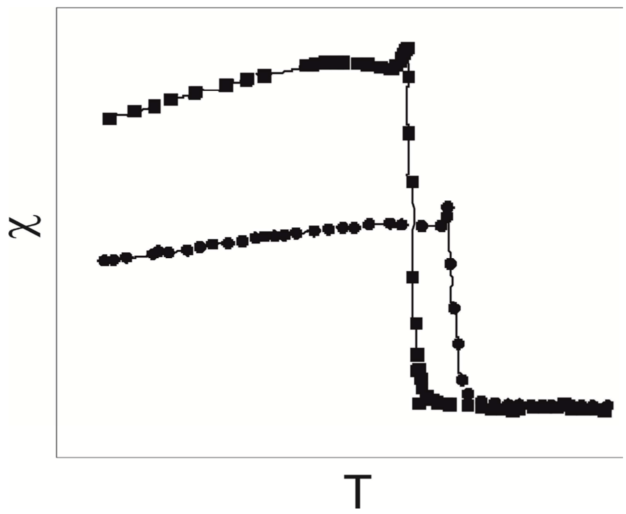

Fig. 1. The dependence of the magnetic susceptibility on the initial temperature of the amorphous alloy $Fe_{90}Zr_7B_2Cu_1$ [9]

The magnetic properties of ferromagnetic materials near ferromagnetic - paramagnetic phase transition can be described by equations that contain so-called. critical exponents β, γ, δ [12]:

$$M_s = M_0(-t)^{\beta} \quad \text{gdy} \quad T < T_c \tag{1}$$

$$M = DH^{1/\delta} \quad \text{gdy} \quad T = T_c \tag{2}$$

$$\chi_0^{-1} = Bt^{\gamma} \quad \text{gdy} \quad T > T_c \tag{3}$$

where: M_0, D, B - are constants of proportionality, $t = (T - T_c)/T_c$, T_c - Curie temperature. Exponents β and γ describe respectively the temperature dependence of the spontaneous magnetization M_s just below the Curie temperature $T < T_c$ and inverse susceptibility starting slightly above T_c. Exponent δ describes the relationship between the magnetization M and the intensity of magnetizing field H in the Curie temperature. Among the critical exponents occurs following relation:

$$\gamma = \beta(\delta - 1) \tag{4}$$

spontaneous magnetization, the initial permeability and Curie temperature are often referred to with the isothermal magnetization curves $M^2(H/M)$, called Arrott's curves [13]. Extrapolating Arrott curves to $H/M = 0$ i $M^2 = 0$ enables to find M_s for $T < T_c$ and χ_0^{-1} for $T > T_c$. By selecting appropriate values of β and γ, pattern of parallel straight lines is obtained near the Curie temperature, which can be easily extrapolated without low-field data, which allows precise determination of the spontaneous magnetization, the initial susceptibility and Curie temperature. Simple system near the Curie temperature can be described by following equation:

$$\left(\frac{H}{M}\right)^{1/\gamma} = \frac{T - T_c}{T_1} + \left(\frac{M}{M_1}\right)^{1/\beta} \tag{5}$$

where: T_1 and M_1 are constants, dependent on the material.

On the basis of measurements of magnetization as a function of the magnetizing field, the magnetocaloric effect may be indirectly measured. The magnetocaloric effect stands for reduce the temperature in the process of adiabatic demagnetization of ferromagnetic material. The magnetocaloric effect occurs in all materials, and magnetic coupling is due to magnetic subnet with a magnetic field that causes a change of the magnetic entropy parts $S_M(H,T)$ of the material [14].

2. Materials and methodology

Ingots of the alloys were prepared by arc melting of high purity elements in an argon atmosphere. The bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy was obtained in the form of rods 1 mm in diameter and 2 cm long by the suction casting method [15]. The structure of the samples was studied by X-ray diffractometry. The magnetic properties i. e. permeability, its disaccommodation were measured by a transformer method using a completely automated set-up. The amplitude and frequency of the magnetizing magnetic susceptibility measurements were respectively 0,26 A/m and 2 kHz. These measurements were performed for samples demagnetized field of variable frequency 100 Hz and amplitude decreasing to zero over time 1,1 s. Compliance measurements were performed at temperatures ranging from about 120 K to about 525 K. For the magnetic susceptibility measurements of samples at temperatures below room temperature, the flow thermostat was used, and the performance measurements in the high temperature range were done for samples placed in a vacuum furnance. The furnance's spiral was wound bifilar. Disaccommodation of magnetic susceptibility was calculated based on magnetic susceptibility measurements as a function of time from demagnetized sample at a fixed temperature. To measure the magnetization of the samples in the magnetizing field in the magnetocaloric effect studies the balance magnetic weight was used [16]. The measurements were performed in a wide temperature range. Entropy changes $\Delta S_M\left(\frac{T_1+T_2}{2}\right)$ In temperature $\frac{T_1+T_2}{2}$ were determined by subtracting the areas under the curves of magnetization $M(B)$, measured respectively at temperatures T_2 and T_1 and then dividing this difference by $T_2 - T_1$:

$$\Delta S_M\left(\frac{T_1+T_2}{2}\right) \approx \frac{1}{T_2 - T_1}\left[\int_0^{B_{max}} M(T_2,B)dB - \int_0^{B_{max}} M(T_1,B)dB\right] \tag{6}$$

The results ΔS_M presented as a function of temperature $T = \frac{T_1+T_2}{2}$.

3. Results and discussion

To study the microstructure of bulk alloy $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ X-ray diffraction was used (Fig. 2).

The presented pattern is characteristic for amorphous materials with one broad maximum in the vicinity of $2\theta = 50°$. No sharp peaks, characteristic for crystalline phases have been observed.

By measuring the magnetic properties such as magnetic susceptibility in weak fields and its disaccommodation it is possible to estimate the Curie temperature. The results of measurements of magnetic susceptibility and its disaccommodation in weak magnetic fields (the amplitude of the magnetizing equal to 0,26 A/m) for $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy is presented in Figs. 3 and 4.

Fig. 3 shows low field magnetic susceptibility versus temperature for the investigated samples.

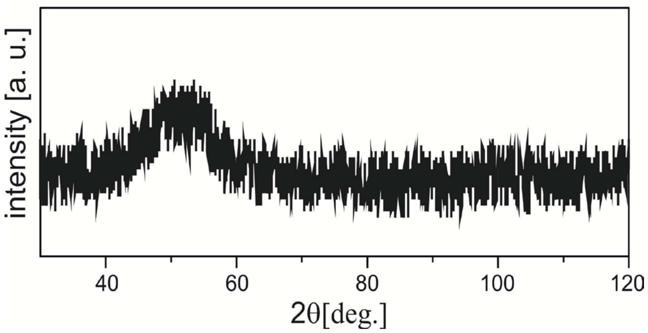

Fig. 2. X-ray diffraction patterns for $Fe_{61}Co_{10}Ti_3Y_6B_{20}$.

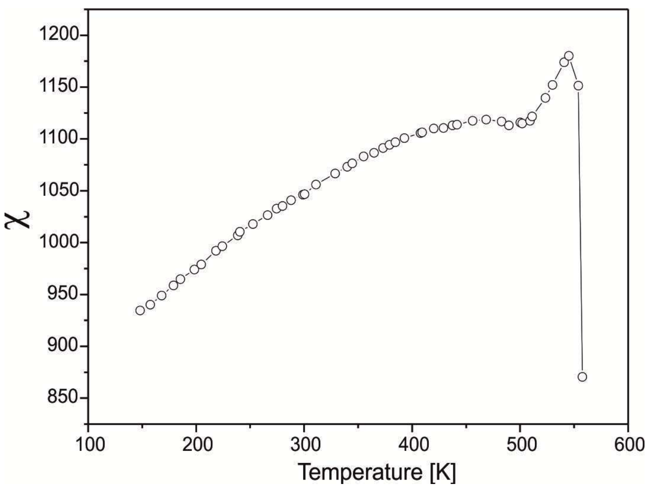

Fig. 3. Low field magnetic susceptibility versus temperature for $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy after solidification

Magnetic susceptibility of investigated alloy slightly increases with temperature and reaches a maximum at a temperature near the Curie temperature. With a further increase in alloys temperature, magnetic susceptibility decreases rapidly, which is associated with the transition from the ferromagnetic state into the paramagnetic state. On the curve of magnetic susceptibility as a function of temperature $\chi(T)$ observed maximum called Hopkinson peak [17], the position of the temperature scale is defined by a decline in anisotropy and a saturation magnetization [18]. On curve $\chi(\mathrm{T})$ prepared for the investigated alloy a clear narrow Hopkinson peak is not observed. This is due to the heterogeneity of amorphous alloys, which are in fact characterized by a Curie temperature distribution. A phase transition ferromagnetic - paramagnetic also accompanied by maximum for isochronous curve disaccommodation (Fig. 4).

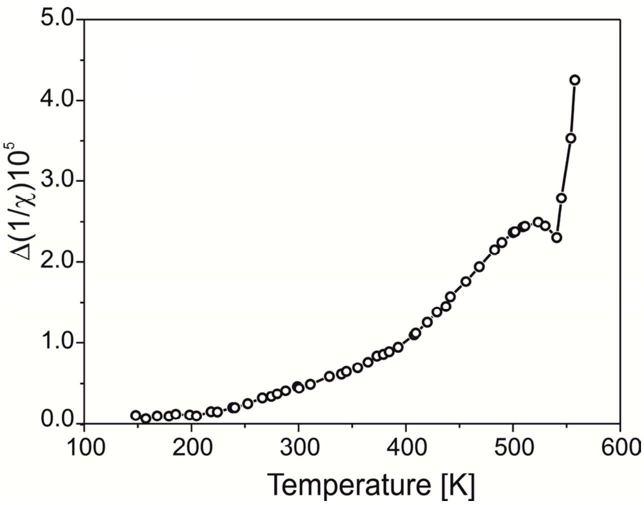

Fig. 4. The isochronal magnetic susceptibility disaccommodation curves $\Delta(1/\chi)=f(T)$ for $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy after solidification

At low temperatures on the isochronous disaccommodation curve there is only the background visible, the intensity of which increases approximately linearly with increasing temperature. At higher temperatures significantly increases the disaccommodation susceptibility and in a temperature of about 440 K a broad maximum is seen. Near the Curie temperature intensity of disaccommodation is clearly on the rise (Hopkinson peak), which is associated with the transition of alloy from a ferromagnetic state to the paramagnetic.

In the case of amorphous alloys can be assumed that the Curie temperature falls in a region of Hopkinson maximum and for investigated alloy is approximately 550 K.

Near the Curie temperature a significant change in entropy of ferromagnetic is also observed. This is due to the transition from a state in which the magnetic moments are ordered to a chaotic distribution of magnetic moments. Random distribution of magnetic moments after reaching the ferromagnetic Curie temperature leads to an increase in entropy.

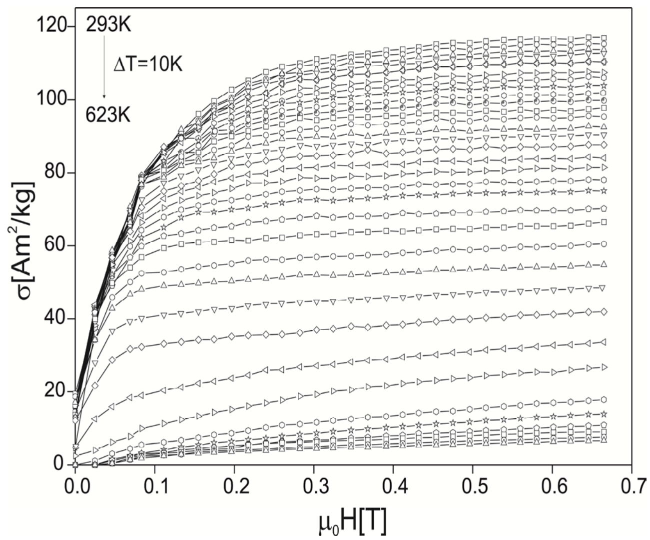

Fig. 5. Magnetization curves for a bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy

Figure 5 shows the magnetization curves $\sigma(\mu_0 H)$ for temperatures in range of 293 K – 623 K.

On the basis of these measurements Arrott curves were constructed $\sigma^2(\mu_0 H/\sigma)$. Dependence $\sigma^2(\mu_0 H/\sigma)$ is approximately linear in the temperature range of 540 K - 560 K for the alloy in the state after solidification (Curie temperature for this alloy determined from the curves of the magnetic susceptibility is about 550 K).

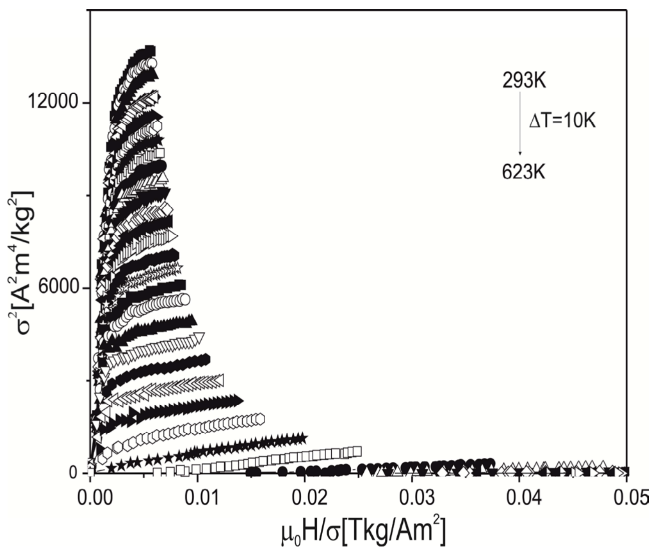

Fig. 6. Arrott curves $\sigma^2(\mu_0 H/\sigma)$ prepared for a bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy

The slope of the Arrott curves near the Curie temperature for this alloy is positive, which indicates that the ferromagnetic-paramagnetic transition is of the second kind [19, 20].

Entropy change for $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy (in terms of induction magnetizing fields of 0 to 0.74 T) calculated by the formula 6 and is given in Figure 7.

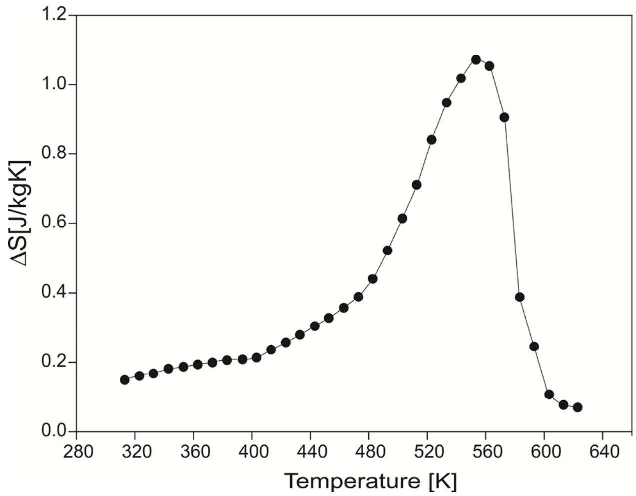

Fig. 7. Changes of the magnetic entropy versus temperature for the bulk amorphous alloy $Fe_{61}Co_{10}Ti_3Y_6B_{20}$.; in state after solidification

As can be seen from this diagram entropy change is the greatest in the Curie temperature, which is associated with disordering of magnetic moments. Maximum on curve $\Delta S(T)$ is broad, What is caused by the heterogeneity of the alloy and the presence of a certain distribution of Curie temperature.

4. Conclusions

Within the framework of this work the study of the structure and magnetic properties of the bulk amorphous $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy was carried out. The investigated alloy was obtained by suction of the melt into a water-cooled copper mold. Using X-ray diffractometer the amorphous structure of the obtained material was confirmed.

Based on studies carried out as part of this work it was found that the magnetic properties of investigated alloy, i.e. magnetic susceptibility and its disaccommodation, are showing a clear change near the Curie temperature. On curve $\chi(T)$ is a small peak associated with trasnition from a ferromagnetic state to a paramagnetic one. This peak is broad, which is related to the heterogeneity of amorphous alloy. The transition from a ferromagnetic state to a paramagnetic is accompanied by a maximum on the curve of isochronous disaccommodation. On the basis of magnetic susceptibility investigations value of the Curie temperature was determined, which for the investigated alloy is approximately 550 K.

As is known, near the Curie temperature a transition from the state in which the magnetic moments are ordered to the disordered state is observed, accompanied by the change of the magnetic entropy of the system. Changes in the entropy in function of temperature were evaluated based on the magnetocaloric effect for a bulk $Fe_{61}Co_{10}Ti_3Y_6B_{20}$ alloy. Maximum on curve $\Delta S(T)$ is broad, which is caused by non-uniformity of investigated amorphous alloy.

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