A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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STRUCTURE AND SOFT MAGNETIC PROPERTIES OF BULK AMORPHOUS $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ ALLOY

STRUKTURA I MIĘKKIE WŁAŚCIWOŚCI MAGNETYCZNE MASYWNEGO STOPU AMORFICZNEGO $(Fe_{0,61}Co_{0,10}Zr_{0,025}W_{0,02}Hf_{0,025}Ti_{0,02}B_{0,20})_{96}Y_4$

In this paper we present results of the structure and soft magnetic properties investigations for the bulk amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy after the solidification and annealing at 720 K for 15 min. We have stated that the as-quenched alloy is fully amorphous. However, from Mössbauer studies we have found that after the annealing a small amount of the grain nuclei in the sample occurs. The investigated alloy is a soft magnetic ferromagnet. It shows relatively high initial (higher than for crystalline soft magnetic materials) and maximum susceptibility and low core losses. Moreover, the magnetic susceptibility increases and core losses decrease after the heat treatment of the sample. It is due to the stress relieving of the sample. Additionally, this alloy is characterized by good thermal stability of the magnetic susceptibility.

Keywords: structure, bulk amorphous alloy, magnetic susceptibility disaccommodation, Mössbauer spectra, core losses

W pracy są prezentowane wyniki mikrostruktury oraz tzw. miękkich właściwości magnetycznych masywnego stopu amorficznego $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ w stanie po zestaleniu i po obróbce cieplnej w temperaturze 720 K przez 15 min. Na podstawie badań mösbauerowskich stwierdzono, że stop po zestaleniu jest w pełni amorficzny, natomiast po obróbce cieplnej w temperasturze 720 K przez 15 min. pojawia się niewielka ilość zarodków fazy krystalicznej. Badany stop jest ferromagnetykiem miękkim i wykazuje względnie dużą podatność początkową (wyższą niż miękkie magnetycznie materiały krystaliczne), dużą maksymalną podatnością magnetyczną i małe straty na przemagnesowanie. Po obróbce cieplnej, w wyniku odprężenia, próbki obserwuje się wzrost podatności magnetycznej i zmniejszenie strat na przemagnesowanie. Należy podkreślić, że stop $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ charakteryzuje się stabilnością termiczną podatności magnetycznej.

1. Introduction

Bulk amorphous alloys are interesting group of materials and exhibit good mechanical and magnetic properties [1, 2]. The preparation of these alloys is of scientific and technological interests because of their potential application in electrical devices. The bulk amorphous alloys are multicomponent systems and are known as functional materials. In order to obtain the bulk amorphous alloys, three empirical rules should be fulfilled [3, 4]: the alloy should contain at least three or more components, the atomic radii of main components should differ of about 12% and they should be characterized by a large negative heat of mixing. These alloys are prepared at relatively low quenching rates which enables to occur the relaxation processes during the sample preparation. Due to this process the structure of the as-quenched bulk amorphous alloys seems to be at least partially relaxed and they should show good thermal stability of magnetic properties.

The aim of this paper is to study the structure and soft magnetic properties such as magnetic susceptibility, its disaccommodation and core losses for the bulk amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy in the as-quenched state and after the heat treatment at 720 K for 15 min.

2. Experimental procedure

Ingots with the nominal composition $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ were prepared by arc melting of high purity elements: Fe, Co, W, Hf, Y and prealloys Fe-Ti, Fe-Zr, Fe-B in a protective argon atmosphere. Using these ingots, amorphous rods 2 mm in diameter and 2 cm long were obtained by a suction casting method [5, 6]. The amorphicity of the

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as-quenched and annealed samples was checked using a Mössbauer spectrometer and a X-ray diffractometer. X-ray diffraction patterns and transmission Mössbauer spectra were recorded for powdered samples. Additionally, from Mössbauer spectra analysis the average magnetic induction of hyperfine field at ^{57}Fe nuclei was determined. Magnetic susceptibility and core losses were measured by a transformer method using a completely automated set-up. From results obtained during magnetic permeability measurements the isochronal disaccommodation curves according to the expression $\Delta\left(\frac{1}{\chi}\right) = \frac{1}{\chi_{120}} - \frac{1}{\chi_2}$ (where χ_2 and χ_{120} are susceptibilities measured 2 s and 120 s after demagnetization of the samples) were constructed. All investigations were performed for the samples after the solidification and annealing at 720 K for 15 min.

3. Results and discussion

Fig. 1 shows X-ray diffraction patterns of powdered as-quenched and annealed $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods. Only broad maxima are seen near the diffraction angle 2Θ=50° for both samples confirming their amorphous state. The absence of the crystalline phase in the investigated samples was also confirmed by Mössbauer spectroscopy. The transmission Mössbauer spectra are asymmetric and consist of broad and overlapped lines (Fig. 2) which are characteristic of amorphous alloys.

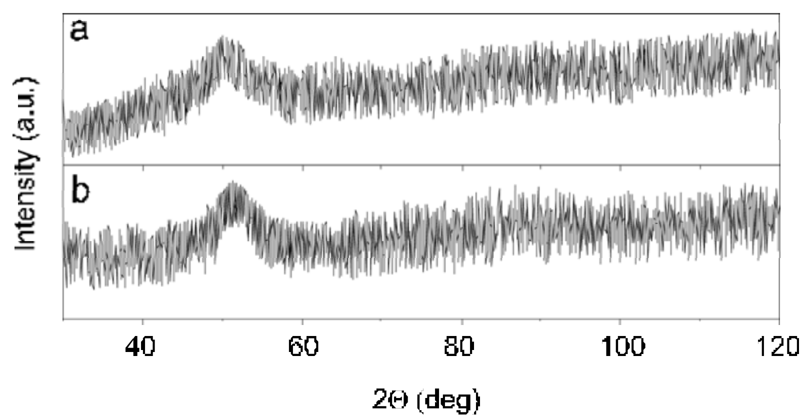

Fig. 1. X-ray diffraction patterns of the as-quenched (a) and annealed at 720 K for 15 (b) $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods after powdering

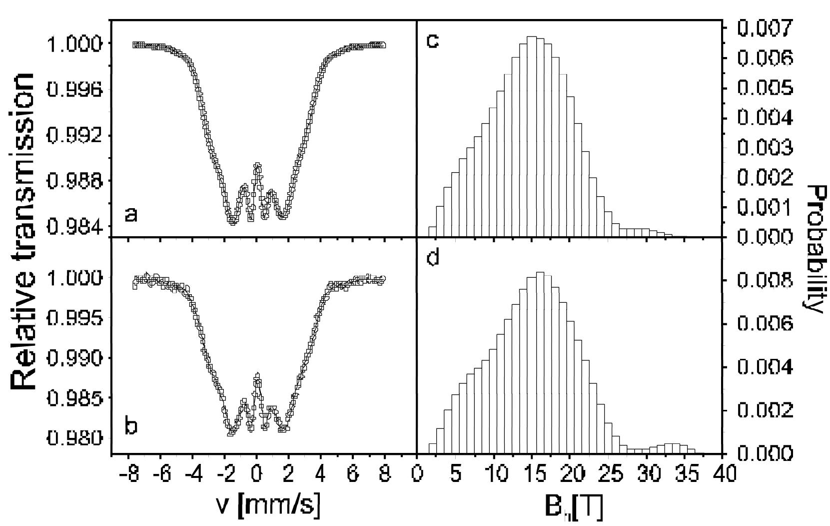

Fig. 2. Transmission Mössbauer spectra (a, b) and corresponding distribution of hyperfine field induction (c, d) for the as-quenched (a, c) and annealed at 720 K for 15 min (b, d) powdered $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods

Moreover, from these studies we have found that the alloy in the as-quenched state and after annealing is inhomogeneous. In the hyperfine field distributions obtained from Mössbauer spectra it is possible to distinguish at least three components indicating the presence of region with different iron concentration. Furthermore, very broad lines in the Mössbauer spectrum and the high field component in the hyperfine field distribution of the $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy after the heat treatment seems to indicate that the nuclei of the crystalline phase with medium range order in the sample are present [7]. The initial magnetic susceptibility of $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods as a function of temperature is depicted in Fig. 3.

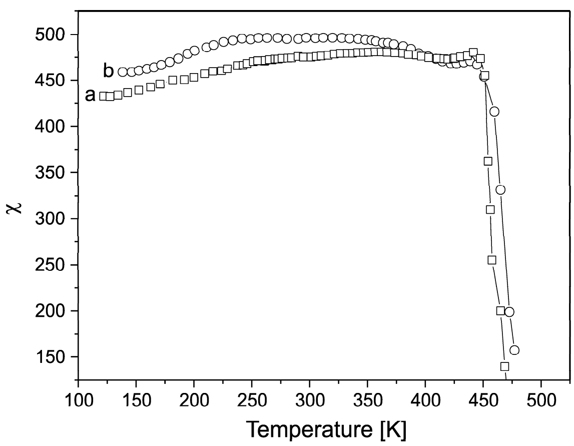

Fig. 3. Initial magnetic susceptibility of $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods versus temperature: in the as-quenched state (a) and after annealing at 720 K for 15 min (b)

The investigated alloy in the as-quenched state shows good thermal stability of the initial magnetic susceptibility which does not change distinctly in the temperature range from 130 K up to 420 K. Near the Curie temperature (440 K) the small so-called Hopkinson maximum [8] is observed due to the ferro- to paramagnetic phase transition. At higher temperature magnetic susceptibility distinctly decreases. The annealed sample exhibits similar behaviour of the magnetic susceptibility with temperature. However, it slightly increases in the temperature range from 135 K to 375 K which confirms that the nuclei of the crystalline phase found from Mössbauer spectroscopy studies are much smaller than the domain wall width and they do not act as pinning centers of domain walls.

In order to determine maximum susceptibility of that alloy the measurements of susceptibility were performed in the wide field range (Fig. 4 a, b). The increase of the maximum susceptibility after the annealing of the sample is observed. Mainly it is due to the stress relief of the sample.

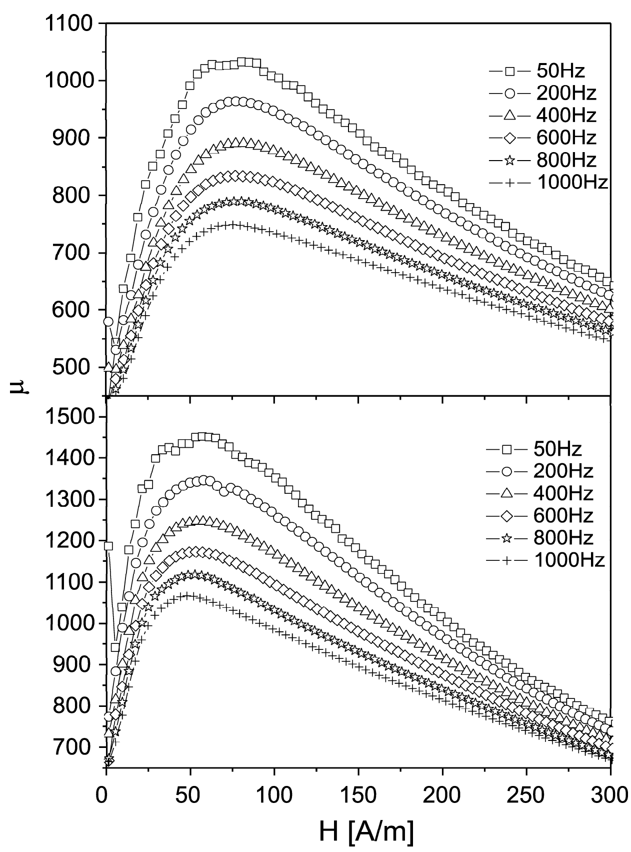

Fig. 4. Magnetic susceptibility of $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ rods versus the amplitude of the magnetizing field with different frequency: in the as-quenched state (a) and after annealing at 720 K for 15 min (b)

The amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy in both as-quenched and annealed states shows good time stability of the magnetic susceptibility. In Fig. 5 the isochronal disaccommodation curves $\Delta\left(\frac{1}{\chi}\right) = \frac{1}{\chi_{120}} - \frac{1}{\chi_2} = f(T)$ are presented. In the wide temperature range only linearly dependent on temperature background with very low intensity in the disaccommodation curves are observed. The rapid increase of the disaccommodation takes place near the Curie temperature.

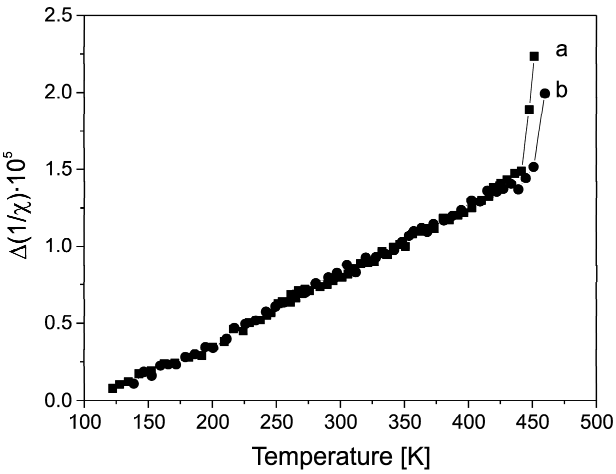

Fig. 5. Isochronal disaccommodation curves $\Delta\left(\frac{1}{\chi}\right) = f(T)$ of the amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy in the as-quenched state (a) and after annealing at 720 K for 15 min (b)

Fig. 6 shows the dependence of disaccommodation intensity versus the amplitude of the magnetizing field for the as-cast and annealed at 720 K for 15 min $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy. In both $\Delta\left(\frac{1}{\chi}\right) = f(T)$ curves the distinct maxima at H = 0.45 A/m and H = 0.24 A/m corresponding to fields of domain walls stabilization are seen. From the results obtained from magnetic susceptibility (Fig. 3) and its disaccommodation studies (Fig. 6) we may conclude that the heat treatment at 720 K for 15 min of this alloy improves its soft magnetic properties. It is also confirmed by measurement of hysteresis loops of the as-quenched and annealed samples (Fig. 7 a, b).

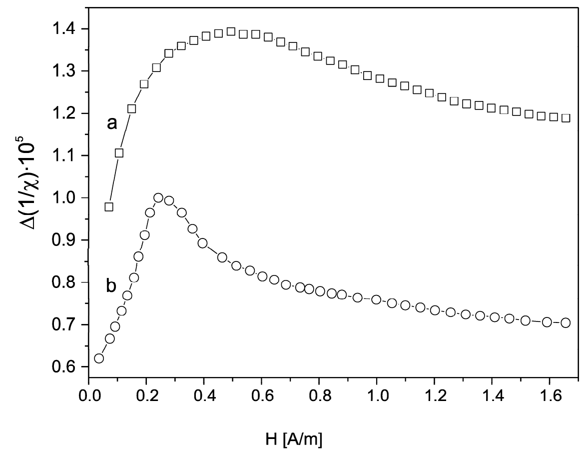

Fig. 6. Disaccommodation intensity versus the amplitude of the magnetizing field for the as-cast (a) and annealed at 720 K for 15 min (b) $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy

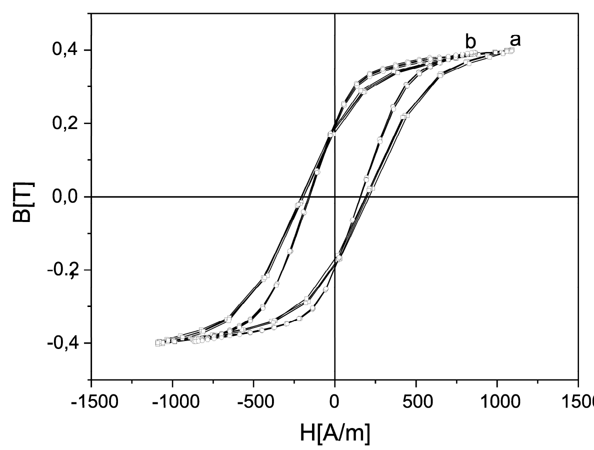

Fig. 7. Hysteresis loops measured at the magnetizing field frequency of 250 Hz for the as-cast (a) and annealed at 720 K for 15 min (b) $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy

It is seen that the annealed sample reaches the maximum induction at lower magnetic field than the as-quenched one. The values of core losses calculated from hysteresis loops are presented in Fig. 8 a, b.

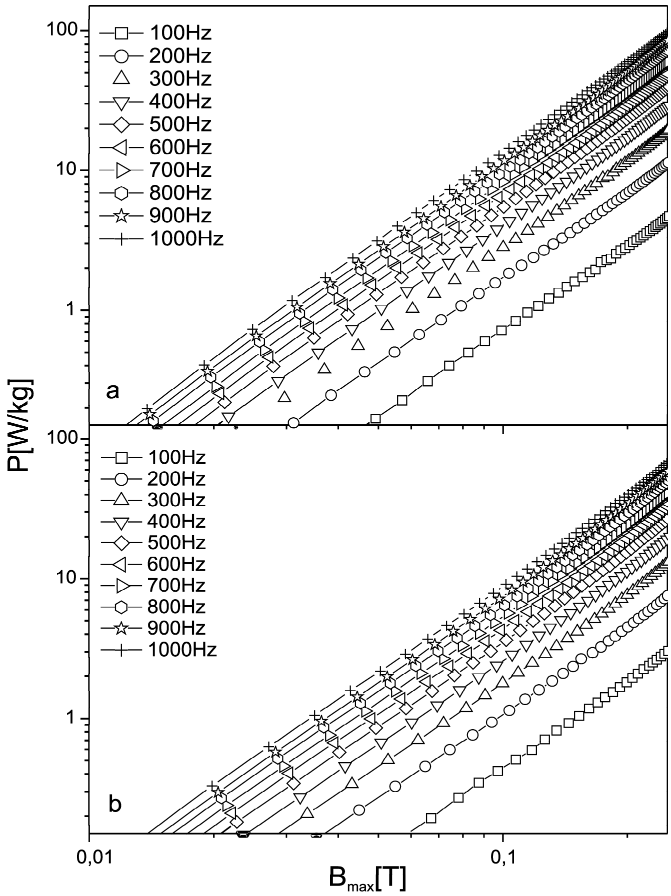

Fig. 8. Core losses versus maximum induction at different frequencies of the magnetizing field for the amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy after solidification (a) and after annealing at 720 K for 15 min (b)

The core losses dependence on the frequency of magnetizing field for maximum induction B_{max} = 0.2 T for the as-quenched and annealed samples is depicted in Fig. 9.

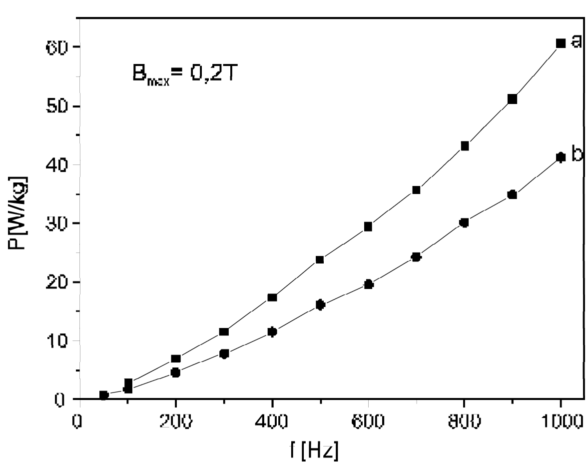

Fig. 9. Core losses as a function of frequency for the amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy in the as-quenched state (a) and after annealing at 720 K for 15 min (b)

The obtained results (Figs 7-9) indicate that the annealing of the sample below the crystallization temperature leads to the decrease of core losses. It is worth noticing that the observed core losses of this alloy are comparable with those of crystalline soft magnetic materials [9].

4. Conclusions

- The bulk $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy obtained by the suction-casting method in the form of 2 mm in diameter rods is fully amorphous.
- During annealing at 720 K for 15 min creation of small number of the grain nuclei takes place.
- The bulk amorphous $(Fe_{0.61}Co_{0.10}Zr_{0.025}W_{0.02}Hf_{0.025}Ti_{0.02}B_{0.20})_{96}Y_4$ alloy exhibits high initial magnetic susceptibility which slightly increases after the annealing of the sample.
- The investigated alloy shows good thermal and time stabilities of magnetic susceptibility.
- Core losses of the investigated alloy are of the same order that observed in other bulk amorphous alloys

of similar composition and soft crystalline ferromagnets.

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