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Magnetic Properties of Ion Irradiated $Fe_{75}Mo_8Cu_1B_{16}$ Metallic Glass

M. Hasiak[a,*] and M. Miglierini[b,c]

[a]Department of Mechanics and Materials Science, Wrocław University of Science and Technology, M. Smoluchowskiego 25, 50-370 Wrocław, Poland

[b]Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, V Holešovičkách 2, 180 00 Prague, Czech Republic

[c]Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology, Institute of Nuclear and Physical Engineering, Ilkovičova 3, 812 19 Bratislava, Slovakia

Microstructure and thermomagnetic properties of ion-bombarded amorphous $Fe_{75}Mo_8Cu_1B_{16}$ alloy are investigated. The Mössbauer spectroscopy shows that surface regions at the air side of the ribbons irradiated with 2×10^{16} ions/cm^2 were significantly affected by 130 keV N^+ ions. On the other hand, the opposite (wheel) side that was not exposed to ion irradiation is practically intact. The analysis of temperature dependences of magnetization shows the Curie points of 313 K and 316 K for as-quenched and irradiated samples, respectively. The maximum of magnetic entropy change calculated for the irradiated alloy in a magnetic field of 1.0 T occurs at 312.5 K and equals to 0.77 J kg^{-1} K^{-1} while that of the as-quenched sample is 0.74 J kg^{-1} K^{-1}.

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1. Introduction

Iron-based amorphous alloys are very attractive materials for variety of practical applications because of their unique magnetic properties [1–3]. Especially, magnetic materials with the Curie point close to the room temperature and large magnetocaloric effect are important for magnetic refrigerators [4]. The latter properties are strongly related to the microstructure. Therefore, understanding the impact of structural rearrangement upon magnetic parameters caused for example by ion irradiation of amorphous samples is of paramount concern.

In this paper we report on microstructure and thermomagnetic properties of $Fe_{75}Mo_8Cu_1B_{16}$ amorphous alloy irradiated with N^+ ions to the total fluence of 2×10^{16} ions/cm^2 as compared with the as-quenched state of this metallic glass. The magnetocaloric effect calculated in a wide range of temperatures and magnetic fields is also analyzed.

2. Experimental details

$Fe_{75}Mo_8Cu_1B_{16}$ metallic glass was prepared by the method of planar flow casting. For the sake of the Mössbauer spectrometry, iron enriched by ^{57}Fe stable isotope to 50% was used. The resulting ribbons with the width of 1–2 mm and thickness of ~ 20 μm were bombarded with N^+ ions into their air (shiny) side to the total fluence of 2×10^{16} ions/cm^2. The ion energy of 130 keV ensured their maximal penetration depth of ~ 148 nm.

The Mössbauer effect experiments were performed with a constant-acceleration spectrometer equipped with a ^{57}Co/Rh source. Surface regions were probed by conversion electron (CEMS) and conversion X-rays (CXMS) Mössbauer spectrometry to the depth of ~ 200 nm and ~ 5 μm, respectively. The obtained spectra were analyzed using the Confit evaluation program [5]. Thermomagnetic characteristics were recorded by Quantum Design VersaLab system in the temperature range 50–400 K and maximum magnetic field up to 1 T.

3. Results and discussion

Microstructural features of the investigated alloy were followed by CEMS and CXMS. Spectra taken from both sides of the ribbons were evaluated by distributions of quadrupole splitting $P(\mathrm{QS})$ and hyperfine magnetic fields $P(B)$ which correspond to non-magnetic and magnetic regions in the amorphous structure, respectively.

The wheel side of the ribbon which was not affected by ion irradiation demonstrates similar average hyperfine magnetic fields of $P(B)$ distributions of 7.5(2) T and 7.7(2) T for close to surface (CEMS) and deeper (CXMS) regions. Average QS value revealed by CEMS is, however notably smaller, 0.76(4) mm/s than that obtained from CXMS, 0.85(4) mm/s. At the air side, the non-magnetic regions show almost equal average QS values of 0.83(4) mm/s and 0.81(4) mm/s which means that the near surface regions were significantly affected by irradiation as the latter delivers extended energy to the depth of ~ 148 nm which is exactly within the screening depth of CEMS. The obtained Mössbauer spectra recorded at the air side of the ribbon are shown in Fig. 1 together with the corresponding $P(\mathrm{QS})$ and $P(B)$ distributions. Average values of the latter are slightly and notably higher, respectively, in comparison with the wheel side as revealed by CEMS and CXMS (see Fig. 1). The above mentioned effects are caused by structural rearrangement

*corresponding author; e-mail: Mariusz.Hasiak@pwr.edu.pl

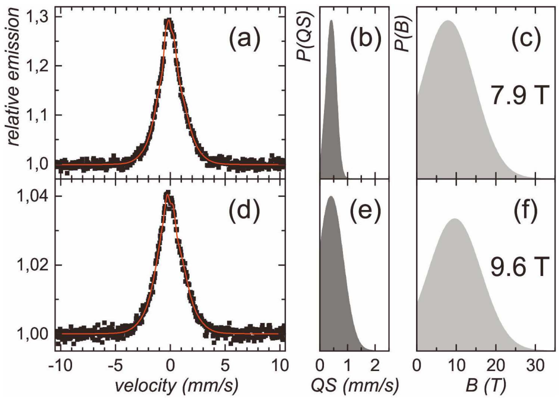

Fig. 1. CEMS (a) and CXMS (d) spectra of the $Fe_{75}Mo_8Cu_1B_{16}$ alloy irradiated with 2×10^{16} ions/cm^2 measured at the air side of the ribbon. P(QS) (b), (e) and $P(B)$ (c), (f) distributions are also plotted. In (c) and (f), average values of B are given.

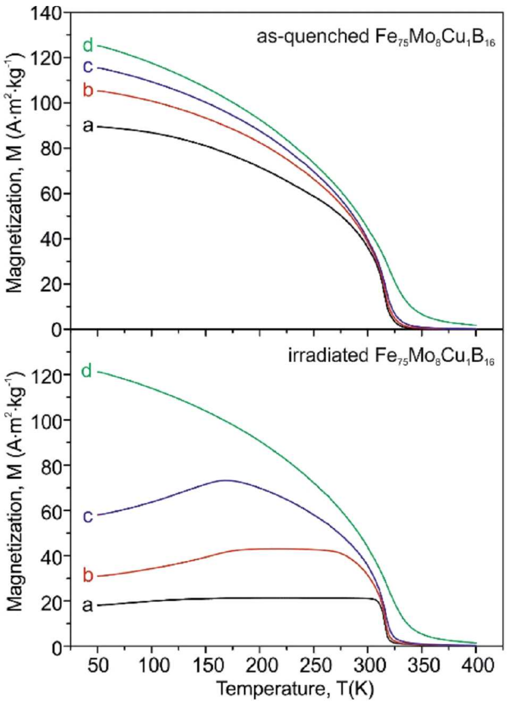

Fig. 2. Temperature dependence of magnetization for the amorphous $Fe_{75}Mo_8Cu_1B_{16}$ alloy in the as-quenched state (upper) and after irradiation with 2×10^{16} ions/cm^2 (lower) recorded in zero-field cooled mode at external magnetic field of 2.5 mT (a), 5 mT (b), 10 mT (c), and 100 mT (d).

of the resonant atoms that took place after ion irradiation [6].

Temperature dependences of magnetization measured in zero-field cooled (ZFC) mode for the as-quenched and irradiated $Fe_{75}Mo_8Cu_1B_{16}$ alloy measured in external magnetic field are presented in Fig. 2. While only subtle changes in magnetic parameters were reported after irradiation of a $Fe_{77}P_8Si_3C_5A_{l2}Ga_1B$ metallic glass [6], here notable deviations in temperature dependence of magnetization were revealed. They are governed by the alloy's composition and suggest magnetic anisotropy in low temperature region. Because of close-to-room Curie temperature T_C in Fe–Mo–Cu–B alloys [7] such structures are very sensitive to external effects. For this reason, we have chosen the present type of metallic glass.

Magnetizations of non-irradiated (as-quenched) sample in the upper part of Fig. 2 decrease with temperature as for a Heisenberg ferromagnet. For lower external magnetic fields (up to 10 mT) the magnetizations of the irradiated alloy slightly increase with temperature to their maxima at about 165 K and then decrease. In 100 mT, which is enough to fully magnetize the sample, a monotonous decrease of magnetization with temperature is observed. It should be mentioned that temperature dependences of magnetization for the irradiated alloy measured in field cooled (FC) mode are almost identical with the ZFC ones. The T_C defined as inflection point on the $M(T)$ curve recorded in ZFC mode at external magnetic field of 2.5 mT equals 313 K and 316 K for the as-quenched and irradiated sample, respectively.

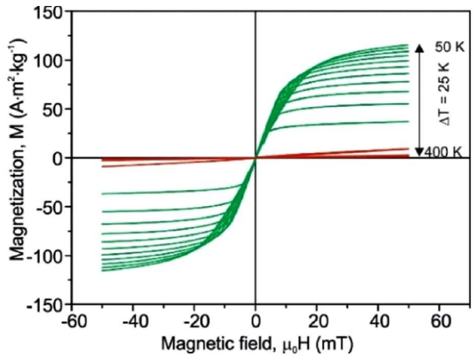

Fig. 3. Hysteresis loops for the irradiated $Fe_{75}Mo_8Cu_1B_{16}$ alloy recorded in the temperature range 50–400 K with step $\Delta T = 25$ K.

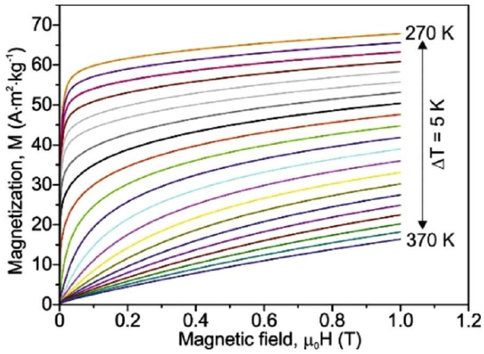

Fig. 4. Virgin magnetization curves for the 2×10^{16} ions/cm^2 irradiated $Fe_{75}Mo_8Cu_1B_{16}$ sample.

Hysteresis loops recorded in the temperature range 50–400 K ($\Delta T = 25$ K) are shown in Fig. 3. All characteristics recorded up to 300 K (green curves) are typical for a ferromagnetic soft magnetic material. The $M(\mu_0 H)$ curves recorded above T_C, i.e., at 325, 350, 375, and 400 K (red curves) show linear dependences which are characteristic for a paramagnetic state.

Isothermal virgin magnetization curves recorded from the irradiated alloy in the temperature range 270–370 K ($\Delta T = 5$ K) in Fig. 4 were used for calculation of magnetocaloric effect in the vicinity of T_C. With increase of temperature of measurement, the magnetization curves $M(\mu_0 H)$ change their shape and above T_C nearly linear behavior is observed. Determination of T_C can be accomplished also by the Arrott plots [8]. Here, we have used the Banerjee criterion [9] in which T_C is derived from the change in a slope of the M^2 curves plotted against $\mu_0 H/M$. Such situation occurs in the irradiated sample between 315 and 320 K as seen in Fig. 5.

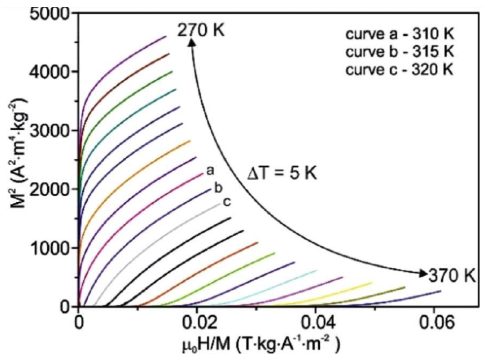

Fig. 5. M^2 versus $\mu_0 H/M$ for the irradiated $Fe_{75}Mo_8Cu_1B_{16}$ alloy.

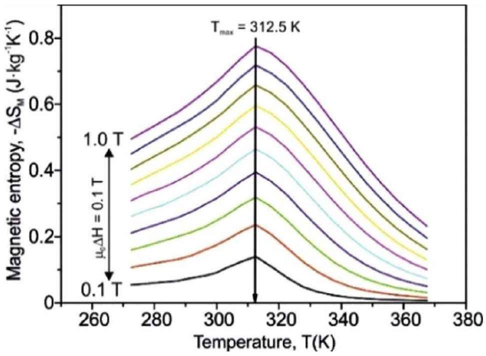

Fig. 6. Magnetic entropy changes versus temperature for the $Fe_{75}Mo_8Cu_1B_{16}$ sample after irradiation with 2×10^{16} ions/cm^2 calculated for maximum magnetizing field from 0.1 to 1.0 T with step $(\mu_0 \Delta H) = 0.1$ T.

The magnetocaloric effect of the irradiated alloy was analyzed as isothermal magnetic entropy change (ΔS_M). The latter is plotted in Fig. 6 for the maximum magnetizing field $\mu_0 H$ ranging from 0.1 T to 1.0 T (step 0.1 T). The obtained values were calculated according to the Maxwell thermodynamic relation using the numerical approximation

$$|\Delta S_M| = \sum_i \frac{1}{T_{i+1} - T_i} (M_i - M_{i+1})_H \, \Delta H_i$$

where M_i and M_{i+1} are magnetizations measured for magnetizing field H at temperatures T_i and T_{i+1}, respectively. With increase of the maximum magnetizing field from 0.1 T to 1.0 T an increase in $|\Delta S_M|$ from 0.14 J kg^{-1} K^{-1} to 0.77 J kg^{-1} K^{-1} is observed. Moreover, the maxima are located at 312.5 K which is close to the Curie point (316 K).

The refrigerant capacity defined as amount of heat which can be transferred in one thermodynamic cycle is derived by taking into account the width and height of the $|\Delta S_M|$ curves as 4.52 J kg^{-1} and 33.74 J kg^{-1} for magnetizing field of 0.1 and 0.5 T, respectively.

4. Conclusions

Microstructure and thermomagnetic properties of the irradiated and as-quenched $Fe_{75}Mo_8Cu_1B_{16}$ alloy were investigated. Notable changes were observed namely in temperature dependences of magnetizations. The Curie temperature derived from the as-quenched and irradiated alloy equals 313 K and 316 K, respectively. CEMS and CXMS investigations show differences in microstructure of the irradiated air side and non-irradiated wheel side of the ribbon.

The maximum of magnetic entropy change calculated for magnetic field of 0.1, 0.5, and 1.0 T occurs at 312.5 K, i.e., close to T_C and equals 0.14, 0.46, and 0.77 J kg^{-1} K^{-1}, correspondingly. The latter value equals 0.74 J kg^{-1} K^{-1} for the as-quenched alloy. The refrigerant capacity of the irradiated sample for maximum magnetizing field of 0.1 T and 0.5 T equals 4.52 J kg^{-1} and 33.74 J kg^{-1}, respectively.

Acknowledgments

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