Proceedings of the 16th Czech and Slovak Conference on Magnetism, Košice, Slovakia, June 13–17, 2016

Temperature Behaviour of Hyperfine Magnetic Fields in a Fe–Co–Si–B–Mo–P Metallic Glass Followed with ^{57}Fe Mössbauer Spectrometry

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Amorphous glass with nominal chemical composition $Fe_{51}Co_{12}Si_{16}B_8Mo_5P_8$ was studied by combination of the Mössbauer spectroscopy and magnetic measurements in order to characterize magnetic and structural features. Temperature evolution of the Mössbauer spectra revealed presence of broad distribution of hyperfine magnetic field at lower temperatures which vanishes with increase of temperature. The Curie temperature estimated from the Mössbauer spectroscopy experiments is $T_C \approx 392$ K. This value is in a good agreement with that obtained by magnetic measurements ($T_C = 397$ K). The Mössbauer spectroscopy spectra of the sample annealed at 823 K revealed a presence of crystalline components. This temperature is notably lower than the expected temperature of the onset of crystallization observed by differential scanning calorimetry (≈ 835 K).

DOI: 10.12693/APhysPolA.131.744
PACS/topics: 75.50.Kj, 75.60.Ej, 75.75.–c, 76.80.+y

1. Introduction

Metallic glasses (MG) or metallic amorphous alloys have attracted attention due to their unique soft magnetic properties and low cost which makes them applicable in the field of power engineering [1–3]. The unique properties of these materials are mostly caused by the lack of long-range atomic order. Formation of such a material is strongly dependent on their microstructure. Relatively high glass forming abilities have been observed in multicomponent systems [4]. Addition of Si to Fe-based MG could improve both the glass forming ability and saturation magnetization as it was shown in [5]. Other elements as Co and P could improve their thermal stability, saturation magnetization, and the Curie temperature [6].

This paper focuses on characterization of structural and magnetic properties of a NANOMET-type MG by ^{57}Fe Mössbauer spectroscopy (MS) and magnetic measurements. Combination of these two methods can reveal important information namely about magnetic behavior of this multicomponent MG for which the Mössbauer data are still missing. In particular, we focus on hyperfine magnetic fields and their evolution with temperature.

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2. Experimental details

Iron-based MG alloy with the nominal chemical composition $Fe_{51}Co_{12}Si_{16}B_8Mo_5P_8$ was produced by the method of planar flow casting in a form of ribbons about 6 mm wide and ≈ 20 μm thick. The preparation was done without any protective atmosphere. The nominal chemical composition was confirmed by atomic emission spectroscopy with inductively coupled plasma (B, P) and flame atomic absorption spectroscopy (Fe, Co, Si, Mo).

Amorphous state of the prepared alloy was checked by X-ray diffraction (XRD) and the thermal behavior was studied by differential scanning calorimetry (DSC). Magnetic properties were characterized by temperature dependences of magnetization curves measured in the range 50–400 K using a VersaLab (Quantum Design) apparatus. Magnetic properties and structural features were studied by MS performed with a constant acceleration spectrometer with a ^{57}Co/Rh source. Calibration was performed at room temperature using a 12.5 µm thin α-Fe foil. MS spectra were recorded in the temperature range 4.2–413 K in order to determine the Curie temperature T_C. All spectral parameters were refined by the NORMOS software.

3. Results and discussion

XRD measurement revealed only diffuse peaks which confirm amorphous nature of the alloy without traces of any crystalline phase. This fact is in a good agreement

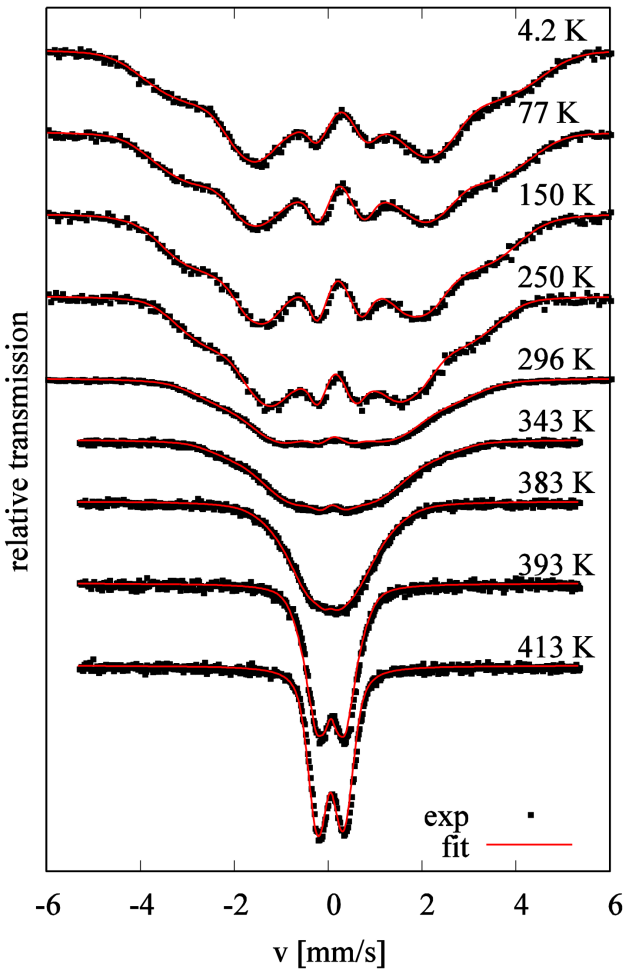

Fig. 1. Temperature evolution of Mössbauer spectra.

with the results of MS. Spectra obtained from the as-quenched (AQ) sample exhibit broadened spectral lines that are characteristic for an amorphous material. Temperature evolution of the MS spectra is shown in Fig. 1.

It can be observed that the broad sextet which represents a magnetic part of the alloy continuously narrows with increasing temperature and the associated magnetic interactions gradually vanish. On the contrary, a distributed doublet which is associated with a non-magnetic part of the sample appears at 383 K and its spectral area fraction rises with increasing temperature. Coexistence of such ferromagnetic and paramagnetic components might be explained by existence of atomic regions with different short range order (SRO). As it was discussed earlier in [7–9] local atomic arrangements affect magnetic ordering of ^{57}Fe resonance atoms.

Decreasing tendency of the average hyperfine magnetic field values with increasing temperature is shown in Fig. 2. The temperature of ferromagnetic to paramagnetic transition can be derived from the behaviour of the hyperfine magnetic field at temperatures close to the Curie point assuming the critical exponent $\beta = 0.36$ for a Heisenberg ferromagnet [10]. The inset in Fig. 2 shows

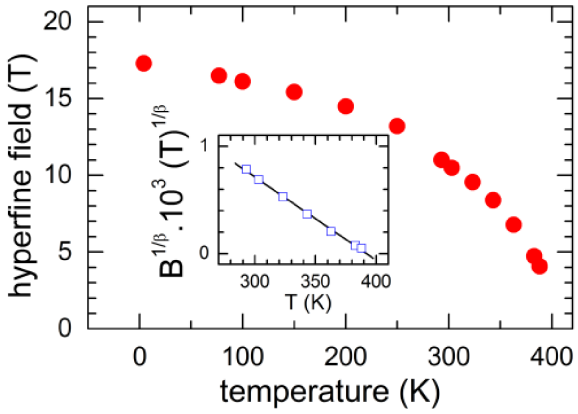

Fig. 2. Temperature dependence of mean values of distributions of hyperfine magnetic fields derived from MS spectra. The inset shows its critical behaviour in the vicinity of T_C with a linear fit.

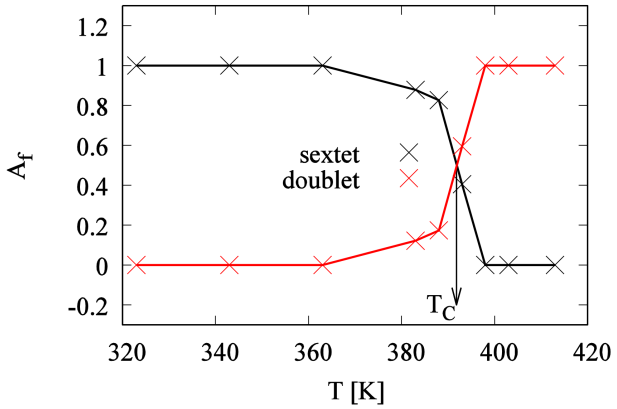

Fig. 3. Temperature dependence of area fraction of magnetic and non-magnetic MS spectral components.

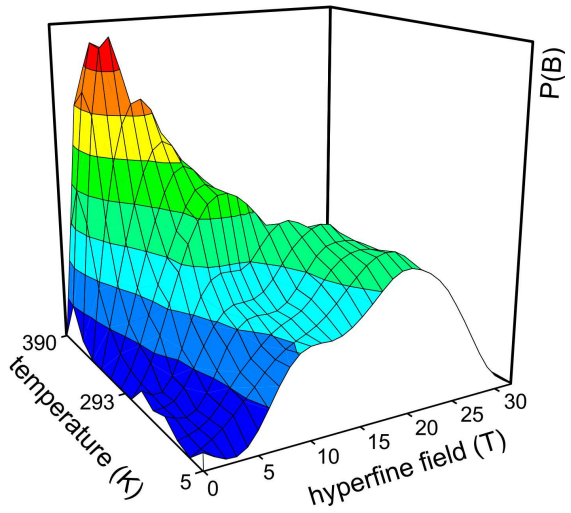

Fig. 4. 3D mapping of hyperfine magnetic field distributions $P(B)$ obtained from MS spectra.

a linear form of the original temperature dependence. Its fit provides the value of $T_C = 392$ K. The same $T_C \approx 392$ K is obtained from a temperature dependence of area fractions corresponding to the magnetic and non-magnetic MS spectral components as seen in Fig. 3.

Distributions of hyperfine magnetic fields $P(B)$ obtained from MS spectra are plotted in Fig. 4 in a form of 3D mapping. Broad distributions at low temperature exhibit two clearly distinct peaks that are assigned to atomic regions with high and low magnetic fields. With increasing temperature, the latter prevail. Finally, when T_C is reached, magnetic dipole interactions vanish completely.

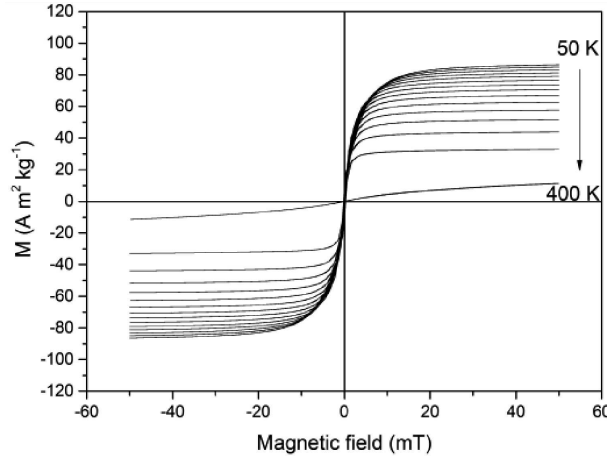

Fig. 5. Magnetization curves recorded in temperature range from 50 K to 400 K.

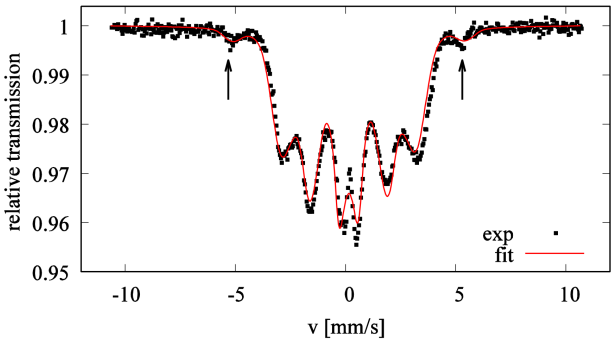

Fig. 6. Room temperature MS spectrum of sample annealed at 823 K. The arrows indicate position of MS lines corresponding to the crystalline components.

Magnetization curves in Fig. 5 were recorded in temperature range from 50 K to 400 K with a temperature step of 25 K. The magnetization curve taken at 400 K exhibits close to linear dependence of magnetization. Such a behavior is characteristic for paramagnetic materials. This indicates that the temperature of 400 K is higher than T_C.

At a DSC curve (not shown) a presence of two crystallization peaks can be revealed. The first onset of crystallization is at the temperature $T_{x1} \approx 835$ K and the second one at $T_{x2} \approx 986$ K.

The AQ samples were additionally annealed at various temperatures in a vicinity of T_{x1} in a protective Ar atmosphere in order to follow possible structural changes in the studied alloy. After annealing at 823 K for 1 h, presence of crystalline phases is clearly seen in the corresponding MS spectrum in Fig. 6 which was recorded at room temperature. The newly formed crystals are represented by a narrow sextet with the value of magnetic hyperfine field close to 32.3 T. Nevertheless, a positive isomer shift of ≈ 0.1 mm/s indicates that this spectral component does not belong to pure α-Fe. Due to complexity of its chemical composition, inclusions of Co, Si, Mo into the bcc-Fe matrix are expected. XRD shows several reflections that are attributed to this crystalline phase.

4. Conclusions

Temperature evolution of MS spectra of the AQ $Fe_{51}Co_{12}Si_{16}B_8Mo_5P_8$ MG shows decrease of hyperfine magnetic fields with increase of temperature and subsequent extinction of magnetic regions above T_C. Simultaneous increase of non-magnetic part of the spectra was observed. These phenomena are better documented by the help of 3D mapping of $P(B)$ distributions. Such information is unique and can be obtained only from the Mössbauer spectra.

The Curie temperature determined by MS is $T_C \approx 392$ K which is in a good agreement with the results obtained from magnetic measurements in which case $T_C = 397$ K. MS spectrum of the annealed sample shows presence of a crystalline component that has formed at lower temperature in comparison with the temperature of the onset of the first crystallization detected by DSC.

Acknowledgments

This work was supported by the project GACR 14-12449S, VEGA 1/0182/16 and VEGA 2/0189/14.

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