

## Mössbauer temperature study of the $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$ amorphous alloy

Janusz E. Frąckowiak,  
Adam Tomczyk,  
Aneta Hanc,  
Grzegorz Haneczok

**Abstract.** Temperature studies in the range 300–800 K of amorphous  $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$  alloy using Mössbauer spectroscopy are presented. It is shown that at a temperature close to 700 K iron clusters with non-collinear magnetic structure are formed. The observed magnetic permeability enhancement effect in the annealed at elevated temperatures alloy, which takes place in amorphous phase, is due to the strong ferromagnetic exchange between Fe clusters via the amorphous matrix and reduction of internal stresses.

**Key words:** amorphous alloys • magnetic properties • structural relaxation

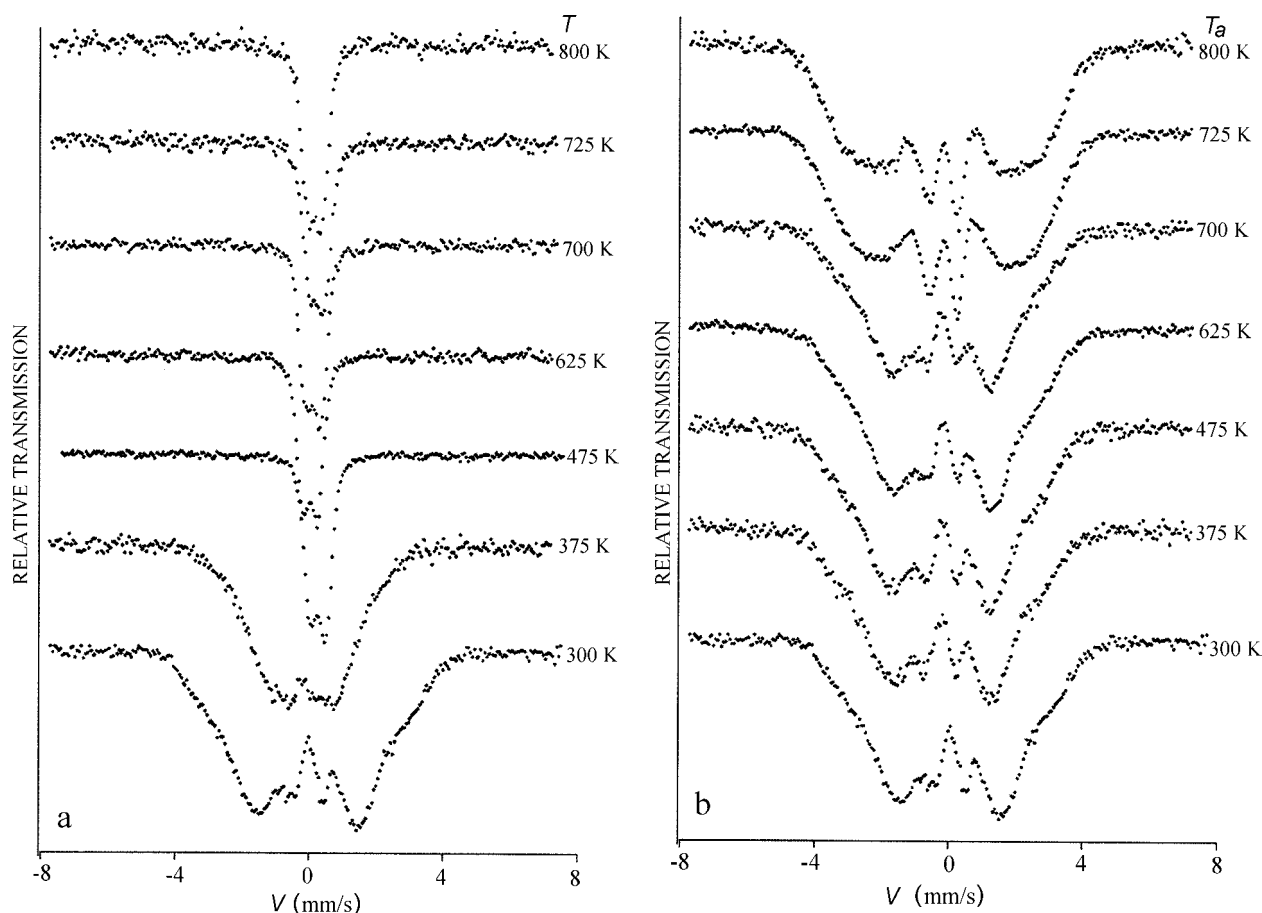
### Introduction

In recent years a great interest is focused on nanocrystalline alloys obtained by a suitable thermal annealing of amorphous alloys at temperatures close to the crystallization temperature [8]. It was shown that the soft magnetic properties of the so-called nanoperm and finemet amorphous alloys can be significantly improved by formation of a nanocrystalline phase,  $\alpha\text{Fe}$  and/or  $\alpha\text{Fe}(\text{Si})$  nanograins, embedded in amorphous matrix [3–9]. An enhancement of soft magnetic properties is observed when the after-annealing structure with randomly oriented nanocrystallite grains of dimension (typically 10–15 nm) much smaller than the ferromagnetic exchange length gives an averaging out of magnetic anisotropy. Recently, it was found [1, 2] that magnetic-permeability-enhancement effect in nanoperm type  $\text{Fe}_{86-x}\text{Nb}_x\text{B}_{14}$  ( $x = 5, 6$ ) alloys takes place in amorphous phase without forming nanograins. It was proposed that the enhancement in permeability is due to diffusion of free volume leading to formation of small iron clusters with different magnetic structures. The aim of the paper is to study the possible atomic-rearrangement events associated with structural relaxation which takes place in the annealed at elevated temperature  $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$  amorphous alloy. Mössbauer spectroscopy was applied to *in situ* measurements in the temperature range 300–800 K. The determined temperature dependences of the hyperfine parameters derived from Mössbauer spectra are presented and discussed.

J. E. Frąckowiak✉, A. Tomczyk, A. Hanc, G. Haneczok  
Institute of Materials Science,  
University of Silesia,  
4 Uniwersytecka Str., 40-007 Katowice, Poland,  
Tel.: +48 32 3591117, Fax: +48 32 2596929,  
E-mail: jfrack@us.edu.pl

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**Fig. 1.** Mössbauer spectra of  $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$  alloy determined: at temperature  $T$  for 8 h (a), at room temperature for the sample cooled from elevated temperatures  $T_a$  (b).

### Experimental details

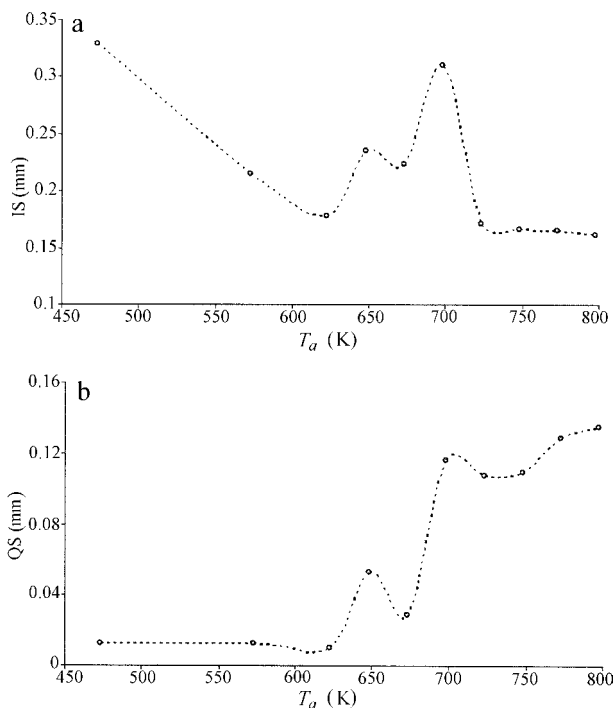
The examined alloy was fabricated by a melt-spinning technique in the form of strips with thickness and width of about 25  $\mu\text{m}$  and 10 mm, respectively. The results of systematic studies of the magnetic properties of the alloy were reported in [2] and can be summarized as follows. The Curie temperature of amorphous phase in as-quenched state is equal to  $T_C = 370$  K. The initial magnetic permeability  $\mu(T_a)$  determined at room temperature plotted versus annealing temperature  $T_a$  passes through a distinct maximum situated at the so-called 1 h optimization temperature  $T_o = 700$  K. The transmission electron microscopy examinations of annealed samples have shown that the first  $\alpha\text{Fe}$  nanocrystallites were detected in a sample annealed at  $T_k = 760$  K. This result is confirmed by Mössbauer spectroscopy; the additional narrow lines that correspond to iron nanocrystallites are detected at this temperature.

In this work, transmission Mössbauer spectroscopy based on  $^{57}\text{Fe}$  was employed. For investigation of structural relaxation phenomena, a special procedure of annealing of the sample in the range 300–800 K was applied. The sample was mounted in a high-temperature furnace and the Mössbauer spectra were measured *in situ* at elevated temperatures, starting from room temperature and the as-quenched state. The time of

collection for each measured spectrum was equal exactly to 8 h. After this time, the sample was cooled to room temperature and the Mössbauer spectrum was recorded again. Then, a higher temperature was applied and the procedure of annealing was repeated. Some selected spectra obtained are presented in Figs. 1 and 2. The Mössbauer spectra of the sample in the paramagnetic state were fitted by means of a discrete analysis (a single line and a quadrupole doublet). The magnetically splitted spectra were fitted by means of a hyperfine field distribution using the Hesse-Rubartsch method [5]. In order to take into account the asymmetry of lines, a linear relation between isomer shift (IS) and hyperfine magnetic field ( $H$ ) was assumed in the fitting procedure.

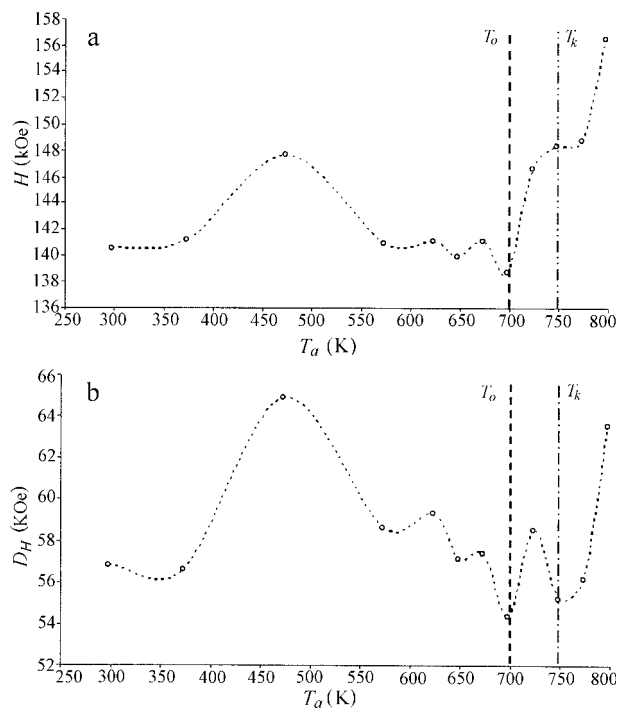
### Results and discussion

As can be seen from Fig. 1, the Mössbauer spectra recorded above,  $T = 375$  K, consist of asymmetric doublets. In the work, these spectra were fitted by a single line (PL) and a quadrupole doublet (PQ). The dependence of the isomer shift (IS) of PL component on temperature is linear with the slope  $d\text{IS}/dT = 0.0005$  mm/s/K as a result of occurrence of the temperature SOD (second order Doppler) shift. This suggests that the PL component represents iron atoms with the distinct disordered amorphous neighborhood. The



**Fig. 2.** The dependence of hyperfine parameters of PQ component in Mössbauer spectra recorded at elevated temperatures  $T_a$ : isomer shift (a), quadrupole splitting (b). The dotted line is added only for eye.

dependence of the IS and the quadrupole splitting (QS) of PQ component on temperature is complex and is shown in Fig. 2. Assuming that the PQ component is connected with the existence of a local topological and chemical ordering in the vicinity of the selected Fe atoms, we can describe the process of structural relaxation which takes place in the paramagnetic state. A strong increase in a value of QS in the range 625–700 K can be attributed to the process of formation of chemical short range order involved by diffusion of free volumes which leads to redistribution of B and Nb atoms in the vicinity of the selected Fe atoms – which is confirmed by an increase in a value of IS. An increase in values of QS and IS is observed for the optimization temperature  $T_o = 700$  K. These results suggest that formation of Fe clusters with specific configurations of magnetic moments (probably asperomagnetic, as is demonstrated in [9]), and with strong local anisotropies in the atomic Fe arrangement is the source of enhancement of magnetic properties in the amorphous state. At higher temperatures, near  $T_k = 760$  K, where the formation of  $\alpha\text{Fe}$  nanograins is starting, a significant decrease in IS is observed. In Fig. 3, the dependences of the mean value of the hyperfine magnetic field  $H$  and the dispersion  $D_H$  of the distribution of the magnetic fields  $P(H)$ , determined from the spectra measured at room temperature as a function of the annealing temperature  $T_a$  are presented. Two characteristic features are important, i.e. a minimum in  $H$  and  $D_H$  observed for the temperature 700 K and a strong increase for  $T_a > 750$  K due to nanocrystallization. The significant decrease in  $H$  occurs at the optimization annealing temperature  $T_o$  and is well correlated with the observed increase in IS and QS for PQ component of the Mössbauer



**Fig. 3.** The mean hyperfine magnetic field  $H$  (a) and dispersion  $D_H$  of the hyperfine field distribution (b) determined at room temperature for sample annealed for 8 h at elevated temperatures  $T_a$ . The dotted line is added only for eye.

spectrum measured at  $T_o$  temperature. It is worth to notice that a very similar dependence of  $H$  vs.  $T_a$  for  $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$  amorphous alloy after 1 h annealing at temperatures  $T_a$  was determined in [2]. This result indicates that the described early clusters of Fe atoms formed in the paramagnetic state at a temperature close to  $T_o$  are quenched and strongly influence magnetic properties of the investigated alloy at room temperature in the amorphous state. The observed minimum in the  $H$  value for the  $T_o$  annealing temperature is probably connected with a relatively small average magnetic moment of the clusters formed with non-collinear magnetic structure in an asperomagnetic state [7]. However, the strong ferromagnetic exchange between clusters via the amorphous matrix and the reduction of internal stresses, in contrary to the case when nanograins are formed, lead to the enhancement of magnetic permeability effect.

## Conclusions

The *in situ* temperature study in the range 300–800 K of the amorphous  $\text{Fe}_{80}\text{Nb}_6\text{B}_{14}$  alloy using Mössbauer spectroscopy showed that at a temperature close to 700 K specific clusters of Fe atoms with non-collinear magnetic structure are formed. In the annealed at elevated temperatures samples the strong ferromagnetic exchange between clusters via the amorphous matrix leads to the enhancement of the magnetic properties in the amorphous phase without forming a nanostructure. This makes it possible to obtain a good soft magnetic material free of embrittlement, in contrary to nanostructured materials.

**References**

1. Frąckowiak JE, Haneczok G, Kwapuliński P, Rasek J, Chrobak A (2004) The Mössbauer study of magnetic permeability enhancement effect in the  $\text{Fe}_{86-x}\text{Nb}_x\text{B}_{14}$  amorphous alloys. *Czech J Phys D* 54:109–112
2. Haneczok G, Frąckowiak JE, Chrobak A, Kwapuliński P, Rasek J (2005) Magnetic permeability enhancement effect in the  $\text{Fe}_{86-x}\text{Nb}_x\text{B}_{14}$  ( $x = 5, 6$ ) amorphous alloys. *Phys Status Solidi A* 202:2574–2579
3. Herzer G (1995) Soft magnetic nanocrystalline materials. *Scr Metall Mater* 33:1741–1748
4. Herzer G, Varga LL (2000) Structure and coactivity of nanocrystalline Fe-Si-B-Nb-Cu alloys. *J Magn Magn Mater* 215/216:506–512
5. Hesse J, Rübartsch A (1974) Model independent evaluation of overlapped Mössbauer spectra. *J Phys E* 7:526–532
6. Kwapuliński P, Rasek J, Stokłosa Z, Haneczok G (2001) Magnetic properties of  $\text{Fe}_{76}\text{X}_2\text{B}_{22}$  ( $X = \text{Cr, Zr, Nb}$ ) amorphous alloys. *J Magn Magn Mater* 234:318–324
7. Lorenz R, Hafner J (1995) Noncollinear magnetic structures in amorphous iron and iron-based alloys. *J Magn Magn Mater* 139:209–227
8. McHenry ME, Willard MA, Laughlin DE (1999) Amorphous and nanocrystalline material for applications as soft magnets. *Prog Mater Sci* 44:291–296
9. Škorvanek I, Duhaj P, Grössinger R (2000) Low-temperature magnetic behavior in amorphous and nanocrystalline Fe-Nb-B alloys. *J Magn Magn Mater* 215/216:431–439