EFFECT OF IONIZING RADIATION ON MAGNETIC PROPERTIES AND STRUCTURE OF $Fe_{80}Si_6B_{14}$ AMORPHOUS ALLOY

V.Yu.POVARCHUK, V.B.NEIMASH, A.M.KRAITCHYNSKII, V.V.MASLOV[1], V.K.NOSENKO[1], G.M.ZELINS'KA[1]

UDC 539.2

Institute of Physics, Nat. Acad. Sci. of Ukraine
(46, Nauky Prosp., Kyiv 03028, Ukraine),

[1]**G.V. Kurdyumov Institute for Metal Physics, Nat. Acad. Sci.of Ukraine**
(36, Academician Vernadsky Blvd., Kyiv 03142, Ukraine

Effect of gamma- (radiation source – ^{60}Co, energy of γ-quanta – 1.2 MeV) and electron (electron energy – 1 MeV) irradiation on the dynamics of primary crystallization processes and initial magnetic permeability μ_i in $Fe_{80}Si_6B_{14}$ alloy has been studied using the methods of X-ray structure analysis and magnetometry. Both γ- and electron irradiation are found to give rise to a reduction in μ_i. It is shown that, in the specimens of $Fe_{80}Si_6B_{14}$ amorphous alloy annealed at 420°C, a fraction of the crystalline phase increases by a third after a subsequent electron irradiation at room temperature. Influence of preliminary irradiation of the amorphous alloy on behavior of μ_i in the course of a further thermal treatment within the temperature range 380 – 470°C is analyzed from the viewpoint of the role of radiation in both the structure relaxation and primary crystallization processes. It is concluded that the principal reason for the μ_i reduction observed after irradiation of partly crystallized $Fe_{80}Si_6B_{14}$ alloy is radiation-enhanced crystallization at room temperature.

Introduction

Amorphous alloys based on Fe—Si—B are high-performance soft ferromagnets. In recent years, they have successfully replaced traditional crystalline materials in magnetic cores of transformers, chokes, and other inductive components. The utilization area of amorphous ferromagnets embraces devices operating under radiation, namely those serving as inductive components in the electronic and electrotechnical equipment of space technology, supervision and safety systems of nuclear power stations, deflection systems of elementary particles accelerators. Reliability and efficiency of such components are largely grounded on radiation resistance of their magnetic cores. However, the effect of γ- and electron irradiation on magnetic properties of amorphous alloys of the Fe—Si—B system has been poorly studied yet and scarcely described in professional literature. It is this point that underlies the motivation for setting and conduction of the present study.

Materials, Procedure of Preparation and Investigation

This work is devoted to studying $Fe_{80}Si_6B_{14}$ amorphous alloy. High-purity components were used for preparation of the starting alloy: Fe (99.96 %), Si (99.999 %), and B (99.9 %) (mass percentage). The alloy was prepared in an induction furnace under inert argon atmosphere. Its chemical composition was determined by X-ray fluorescence analysis.

Amorphous tape 10 mm wide and 24 μm thick was fabricated by the melt spinning technique in air. Magnetic ring cores for investigation of magnetic properties were prepared from the amorphous tape with the use of equipment specially designed for minimal-tension winding.

Effect of γ-irradiation on magnetic properties of the alloy was studied on winded ring specimens with dimensions 12×20/10 mm (inner diameter×outer diameter/height), while that of electron irradiation – on cores with dimensions 20×22/10 mm. Tape fragments with a length about 25 mm were used for structural studies, which made it possible to determine the fraction of the crystalline phase.

Works on γ-irradiation (radiation source — ^{60}Co, energy of γ-quanta — 1.2 MeV, flux density — 10^{11} quanta/(cm^2·s)) were performed at the Institute of Physics of National Academy of Sciences of Ukraine (IP NASU) on MPX-γ-25M apparatus. Electron irradiation (electron energy — 1 MeV) was carried out at IP NASU on a LEA "Argus".

Initial magnetic permeability was measured by the induction continuous method [5] in a weak field H_m = 0.2 A/m with a frequency of 10 kHz.

The fraction of the crystalline phase in the amorphous-crystalline alloy after its thermal treatment was determined from X-ray diffraction data obtained in

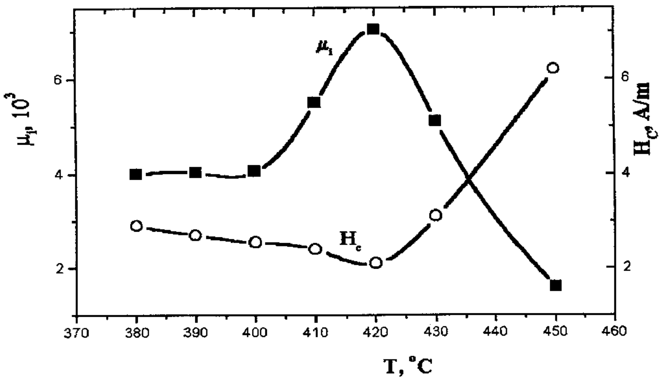

Fig. 1. Initial magnetic permeability μ_i and coercivity H_c as a function of the temperature of heat treatment for $Fe_{78.5}Si_6B_{14}Ni_1Mo_{0.5}$ amorphous alloy

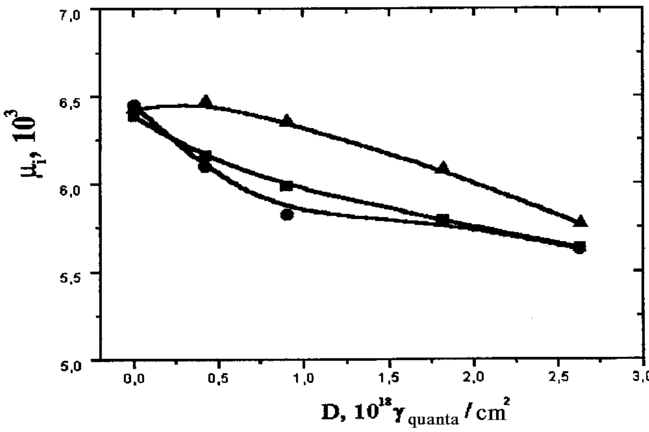

Fig. 2. Dependence of initial magnetic permeability on the dose of γ-irradiation for the alloy preliminary subjected to annealing

monochrome MoK_α-radiation (diffraction vector range $s= 0.77 \div 12.5$ Å^{-1}) with employment of the procedure described in detail in [3].

Before the experiment was performed, a thickness of the layer of electron "half-absorption" had been estimated, which proved to be 1.25 mm. Dimensions of the magnetic cores were chosen, taking account of these data and features of the investigation technique. Specimens' rotation under the electron beam ensured uniformity of their irradiation.

Experimental results and discussion

X-ray structure studies of the initial amorphous tape conformed amorphousness of its structure — the height of the first maximum of the structure factor amounted to 3.65 units. Amorphous state is characterized by a topology (geometrical) and composition (chemical) short-range order. In amorphous alloys based on iron (Fe–B, Fe–Si–B, Fe–M–B, where M=Ni, Co, Cr, and others), basic magnetic properties are mainly determined just by short-range order in the arrangement of atoms. Absence of long-range ordering negligibly influences such values as magnetic moment, Curie temperature, saturation magnetostriction, and constant of local anisotropy. Defects within a short-range environment play a role of barriers to the motion of domain walls, thus reducing initial magnetic permeability and increasing alloy coercivity [1]. Amorphous tapes obtained by the melt spinning technique predominantly contain structural defects of the vacancy type (free volume) and internal strains associated with them and resulted from ultrafast melt quenching (cooling rate approximately equals 10^6 K/s). Initial magnetic permeability of such materials is about 350—400 [11]. Heat treatment gives rise to the relaxation of internal strains and, as a consequence, to a substantial increase in μ_i and a reduction in coercivity. This phenomenon is illustrated in Fig. 1, which shows the effect of thermal treatment on magnetic properties of $Fe_{78.5}Si_6B_{14}Ni_1Mo_{0.5}$ alloy [14]. It is seen that, upon the temperature increase up to 420°C, both a growth of initial magnetic permeability μ_i and decrease in coercivity H_c occur. Such a modification of the characteristics is commonly associated with a structure relaxation of the amorphous alloy turning into a more ordered state. After heat treatment of such kind, the hysteresis loop becomes narrower and the number of Barkhausen jumps decreases [2, 12]. Deterioration of magnetic properties of soft magnetic amorphous alloys at temperatures higher than 420°C is related to the rapid development of primary crystallization processes (largely to the formation of α-Fe(Si) solid solution). Both structure defects in amorphous alloys and large (more than 100 nm) crystallites reduce mobility of domain walls at magnetization reversal [1, 12]. Thus, in applications are used magnetic circuits made from amorphous alloys that underwent optimizing heat treatment at the temperature of maximum on the dependence of Fig. 1. We have studied the influence of gamma irradiation on the behavior of just these magnetic circuits. Initial magnetic permeability is the most structure-sensitive characteristic of amorphous metallic alloys. It is this parameter that was chosen as a sensor for investigation of irradiation effect on the alloy structure. For the tape magnetic cores made from $Fe_{80}Si_6B_{14}$ alloy, heat treatment at $T_a = 420$°C for $t = 15$ min enabled us to achieve optimal magnetic properties. Such a treatment resulted in formation of crystallites with a size less than 100 nm and volume fraction from 2 to 3 % [3].

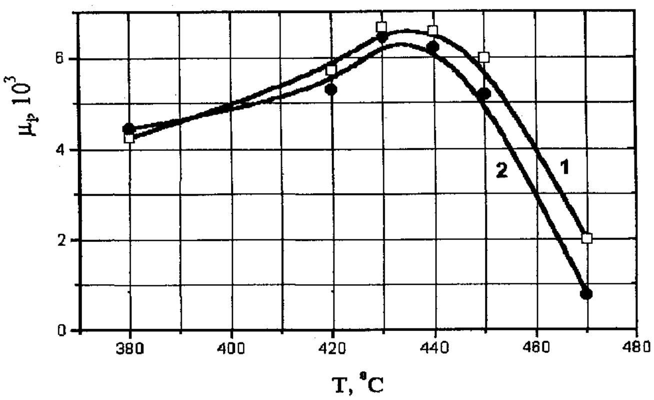

Fig. 3. Initial magnetic permeability as a function of annealing temperature for preliminary irradiated (*2*) and reference (*1*) specimens

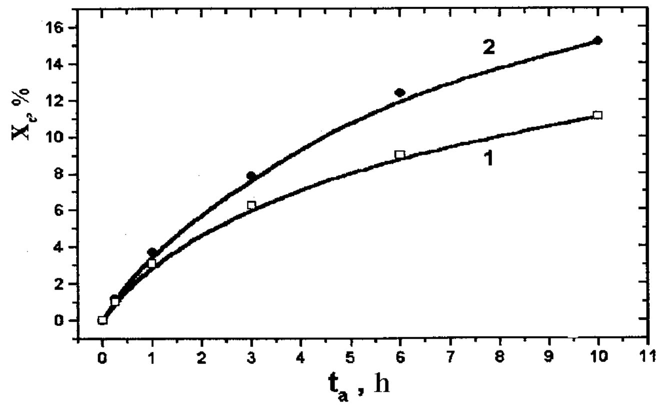

Fig. 4. Change of the volume fraction of the crystalline phase in electron irradiated (*2*) and reference (*1*) specimens

Irradiation of the annealed specimens was carried out at room temperature with doses ranging from 0 to 2.7×10^{18} γ-quanta/cm^2. Fig. 2 shows initial magnetic permeability as a function of γ-radiation dose for three specimens of the alloy. The $\mu_i(\Phi_\gamma)$ dependence is seen to be a drop-down curve.

As follows from the above arguments, radiation influence on μ_i might be associated with the modification of either short range order or crystallization processes. In other words, γ-irradiation is suggested to lead to the enhancement of defectiveness of the amorphous matrix or to the initiation/ acceleration of crystallization processes in the alloy. To define more precisely the role of these mechanisms, we performed the experiment described in detail below.

Initial magnetic permeability was studied as a function of annealing temperature (Fig. 3) for both preliminary irradiated (curve *2*) and reference (curve *1*) specimens. The specimens of both groups were subjected to annealing at temperatures ranging from 380 to 470°C. The experiment on electron irradiation was carried out at room temperature. Radiation dose was equal to 2×10^{17} electrons/cm^2. It follows from Fig. 3 that preliminary electron irradiation scarcely influences the left-hand side of $\mu_i(T_a)$ curve, the behavior of which is governed by the structure relaxation processes. Actually, at temperatures not exceeding 430°C, the difference in initial magnetic permeability between preliminary irradiated and reference specimens is negligible. However, at higher temperatures, where the behavior of μ_i vs T_a is determined by the development of primary crystallization processes, the decrease in μ_i is more pronounced in the former group of specimens. From these data, we can conclude that preliminary electron irradiation favors crystallization processes in the starting alloy. This experiment, however, does not allow one to distinguish if irradiation gives rise to formation of new crystallization nuclei, which turn into crystallites under further heat treatment, or it enhances growth of existing microcrystalls.

In what follows, we describe the results of the work aimed at specifying the effect of electron irradiation on crystallization mechanism, especially on the volume fraction of the crystalline phase X_c [3].

For the alloy under investigation, the dependence of X_c vs duration (t_a) of the heat treatment at 420°C (curve *1*) is presented in Fig. 4. It is seen that, upon an increase in t_a, the fraction of the crystalline phase rises from 0 to 11 %. Each point on the plot corresponds to a separate specimen. After performing the measurements, which had formed the data for plotting curve *1*, the specimens were subjected to electron irradiation. The experiment was conducted at room temperature. The dose of radiation was the same for every specimen and was equal to 10^{17} electrons/cm^2. As can be seen from curve *2*, electron irradiation gives rise to a growth in X_c, but the value of the growth is not the same, although the irradiation dose is completely identical. The total increase in the fraction of the crystalline phase is the more, the larger it was before the irradiation. For all the specimens, the relative change in X_c is almost equal and is about 32 – 36 %. This result implies that irradiation gives rise to a growth of crystallites present in amorphous-crystalline alloy, rather than formation of new crystallization centers. It should be noted that radiation-enhanced growth of crystallites formed at preliminary annealing of the amorphous alloy occurs at room temperature, whereas the alloy not subjected to irradiation has not shown any evidence of the increase in the fraction of the crystalline phase, even over a few years [15].

Conclusions

In our opinion, the reduction in μ_i observed upon γ-irradiation of amorphous alloys subjected to the heat treatment is originated from the radiation-enhanced development of crystallization processes, which give rise to a substantial reduction of the mobility of domain walls.

As follows from the above experimental results, utilization of penetrating radiation makes it possible to change the dynamics of structure rearrangements in metastable amorphous alloys, including those occurring on atomic scale. This may be used as an effective tool to single out thermodynamically stable compositions of amorphous alloys displaying high-efficient magnetic characteristics.

1. *Amorphous* Metallic Alloys/ Ed. by F.E. Lyuborsky. — Moscow: Metallurgiya, 1987 (in Russian). — P. 137 — 164.
2. *Sudzuki K., Fujimori X., Hasimoto K.* Amorphous Metals. — Moscow: Metallurgiya, 1987 (in Russian).
3. *Illinsky A.G., Maslov V.V., Nosenko V.K., Brovko A.P.* // J. Mater. Sci. — 2000. — **35**. — P. 4495.
4. *Maslov V.V., Nemoshkalenko V.V. et al.* // Metallofiz. Noveish. Tekhn. — 1994. — **16,** N 1. — P. 5 — 9.
5. *Measurements* methods. GOST 29004-91 (MEK 367-1-82). — Moscow: Izd. Komitet Standartizatsii i Metrologii, 1991.
6. *Zelinskaya G.M., Paderno D.Yu, Maslov V.V. et al.* //Metallofiz. — 1990. — **12,** N 3. — P. 48 — 52.
7. *Krulikovskaya M.P., Kozub A.A., Olihovskaya L.A., Chirko L.I.* // Ibid. — 1989. — **11**, N 1. — P. 114.
8. *Demkin N.A., Lyashenko B.G., Perstnev P.P.* //Fiz. Khim. Obrabot. Material. — 1990. — N 5. — P. 33.
9. *Polotnyuk V.V., Efimova T.V., Shalaev A.M., Shkapa V.M.* // Metallofiz. — 1992. — **13**, N 11. — P. 123.
10. *Andriyevskiy R.A., Glezer A.M.* // Fiz. Met. Mater. — 1999. — **88**, N 1. — P. 50.
11. *Maslov V.V., Nakonechna O., Nosenko V.K. et al.* // Funct. Mater. — 2000. — **7,** N 4(2). — P. 822.
12. *Magnetism* of Amorphous Systems/ Ed. by R. Levi, R. Hasegava. — Moscow: Metallurgiya, 1981 (in Russian).
13. *Shalaev A.M.* Radiation-stimulated Processes in Metals. — Moscow: Energoatomizdat, 1988 (in Russian).
14. *Maslov V.V., Nosenko V.K., Neymash V.B., Povarchuk V.Yu.* // Metallofiz. Noveish. Tekhn. — 2002. — **24,** N 6. — P. 747.
15. *Metallic* Glasses/ Ed. by J.J. Gilman, H.J. Limi. — Moscow: Metallurgiya, 1984 (in Russian).

Received 24.04.03.
Translated from Ukrainian by A.I.Tovstolytkin

ВПЛИВ IОНIЗУЮЧОЇ РАДIАЦIЇ НА МАГНIТНI ВЛАСТИВОСТI ТА СТРУКТУРУ АМОРФНОГО СПЛАВУ $Fe_{80}Si_6B_{14}$

В.Ю.Поварчук, В.Б.Неймаш, А.М.Крайчинський, В.В.Маслов, В.К.Носенко, Г.М.Зелiнська

Р е з ю м е

Методами рентгеноструктурного аналiзу та магнiтометрiї вивчено вплив гама- (випромiнювання ^{60}Co з енергiєю γ-квантiв 1,2 МеВ) та електронного (з енергiєю електронiв 1 МеВ) опромiнення на динамiку розвитку процесiв первинної кристалiзацiї та початку магнiтну проникнiсть μ_i в сплавi $Fe_{80}Si_6B_{14}$. Виявлено, що як γ-, так i електронне опромiнення приводить до зниження μ_i. Показано, що в зразках аморфного сплаву $Fe_{80}Si_6B_{14}$, вiдпалених при 420°C, на третину зростає частка кристалiчної фази пiсля наступного електронного опромiнення при кiмнатнiй температурi. Вплив попереднього опромiнення аморфного сплаву на поведiнку μ_i при подальшiй термообробцi в дiапазонi температур 380—470°C проаналiзовано з точки зору ролi радiацiї в процесах структурної релаксацiї та первинної кристалiзацiї. Зроблено висновок, що основною причиною зменшення μ_i пiсля опромiнення частково закристалiзованого сплаву $Fe_{80}Si_6B_{14}$ є радiацiйно стимульована кристалiзацiя при кiмнатнiй температурi.