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ScienceDirect

Nuclear Energy and Technology 2 (2016) 50–53

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Radiation-induced nanostructuring of the amorphous alloy

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Available online 6 May 2016

Abstract

Structural changes in the metallic glass $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$, following the irradiation by Ar^+ ions with the energy 30 keV at temperatures of 100–300 °C and post-irradiation annealing to a temperature of 600 °C, were studied by differential scanning calorimetry, atomic probe microscopy and electron microscopy techniques. It has been shown that irradiation at lower temperatures than the crystallization temperatures (430 and 548 °C) leads to the nanostructuring of metallic glass. The nanostructure consists of clusters sized 20–40 nm grouping together to form grains sized 100–150 nm. The nanostructure results from a heavy plastic deformation caused by ion irradiation and extends to a depth of tens of microns, much deeper than the projective ion range. The crystallization heat of this glass increases by 30% as compared to the crystallization heat of the initial non-irradiated glass. The radiation-induced formation of nanostructures is accompanied by the segregation within the glass of the metastable boride (Co_3B) particles which disappear with an exothermic effect after post-irradiation annealing with return to the X-ray amorphous state.

Keywords: Metallic glass; Ion irradiation; Plastic deformation; Nanostructure.

Introduction

Metallic glass is a high-strength material with high elasto-plastic characteristics. Controlled crystallization of amorphous alloys is broadly used to create nanostructured materials. Depending on the metallic glass heating rate and isothermal hold time and temperature, it is possible to obtain nanocomposites with different phase compositions and in a broad range of structuring scales [1,2]. Thanks to being corrosively resistant and stable to radiation swelling, such materials may be used in cladding and fuel components of nuclear reactors [3].

It was found in [3–6] that crystallization in conditions of radiation exposure differs qualitatively from crystallization in normal annealing conditions, and the structure of the clusters and crystallites formed in an amorphous matrix is not equilibrium. Structural changes in the metallic glass $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$, following ion irradiation and post-irradiation annealing, were studied as part of an investigation by differential scanning calorimetry (DSC), atomic probe microscopy (APM) and electron microscope (EM) methods.

Structural changes in metallic glass after ion irradiation

The amorphous alloys $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$ obtained by melt spinning technique had the form of a band with a width of 13 mm and a thickness of 30 μm. All initial samples were in an X-ray amorphous state. A two-step process of the metallic glass structural relaxation was observed during the heating at a rate of 5/min in a NETZCH 204F1 scanning calorimeter. Two crystallization temperatures (430 and 548 °C) with no glass transition point can be seen in the DSC curve (Fig. 1, curve 1).

The alloys were irradiated by Ar^+ ions with the energy of 30 keV and a current density of 50 μA/cm^2 to a dose of 1.5×10^{18} ion/cm^2 at temperatures of 100–300 °C. The changes in the microstructure of the irradiated glass were

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Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

Russian text published: Izvestia Visshikh Uchebnikh Zavedeniy. Yadernaya Energetika (ISSN 0204-3327), 2015, n.4, pp. 53-60.

http://dx.doi.org/10.1016/j.nucet.2016.03.010

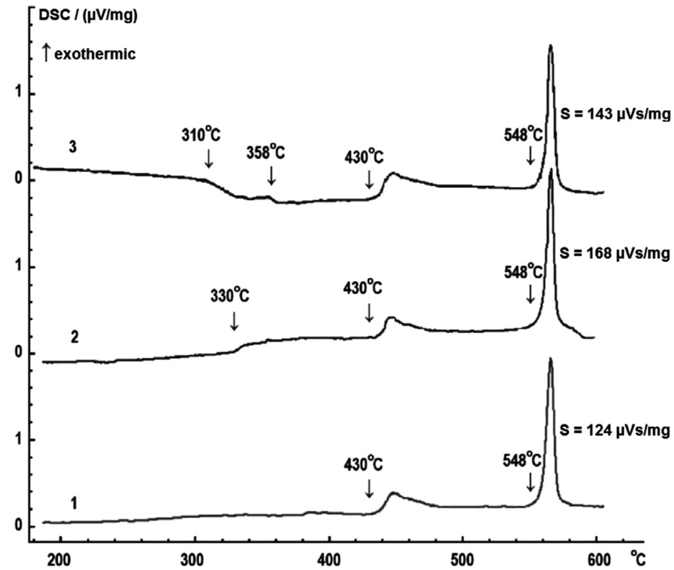

Fig. 1. DSC of the amorphous alloy $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$: 1 – in initial state; 2 – after ion irradiation at 200 °C; 3 – after ion irradiation at 240 °C (*S* – crystallization peak area (enthalpy)).

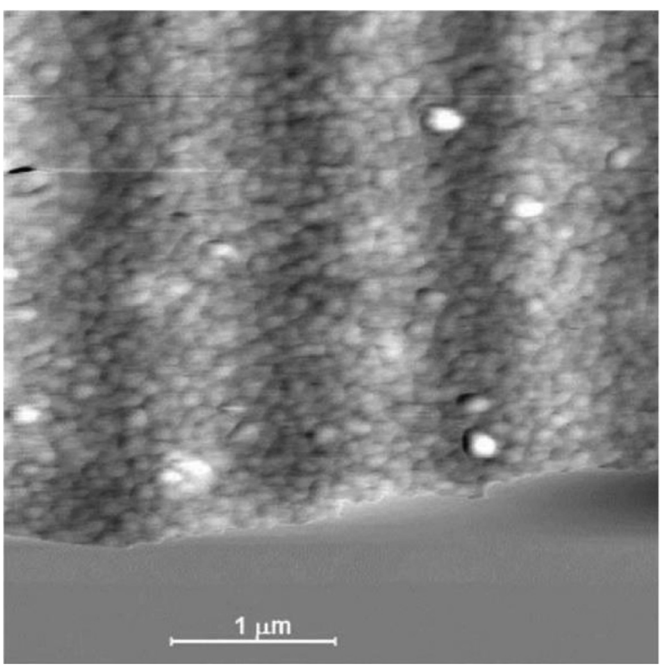

Fig. 2. Atomic probe microscopy. Ion irradiation boundary area for the $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$ alloy.

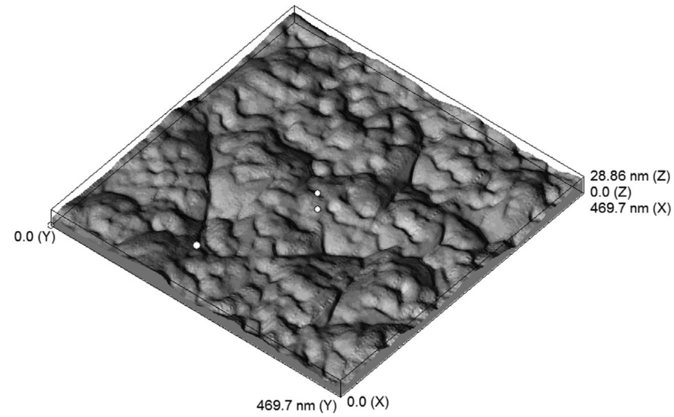

Fig. 3. Atomic probe microscopy (3D). Nanostructure of the irradiated amorphous alloy $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$.

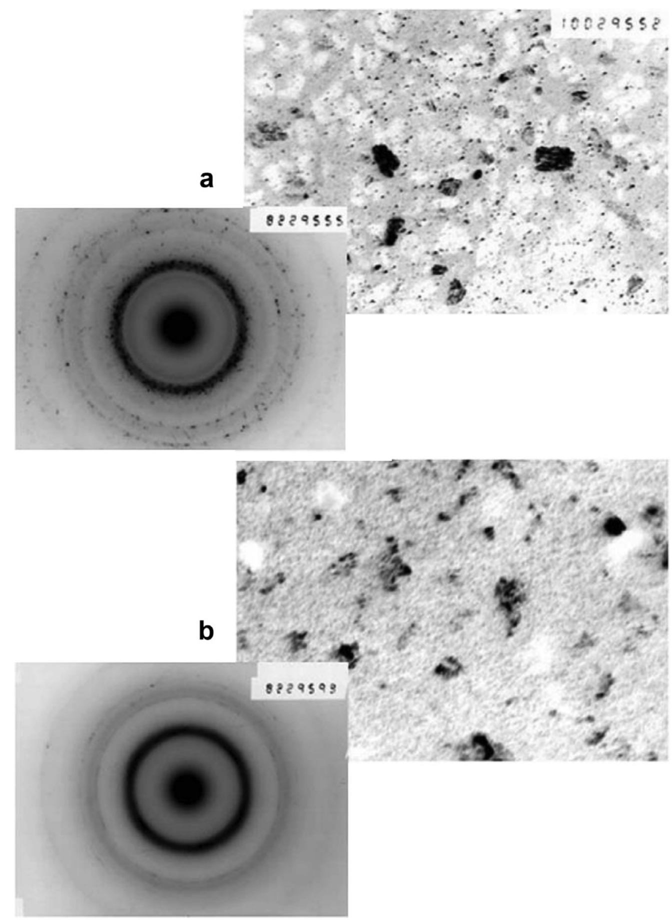

Fig. 4. XRD and dark-field images of the $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$ alloy samples irradiated at 200 °C (a) and following post-irradiation annealing at 300 °C (b). Magnification 100,000.

studied using an SMM-2000 scanning multimicroscope in the APM mode. Fig. 2 shows the ion irradiation boundary area for the $CoFe_{3.2}Si_{2.5}Mn_{3.1}B_{15.7}$ alloy at a temperature of 200 °C. It can be seen that irradiation leads to the nanostructuring of the metallic glass. The nanostructure consists of clusters sized 20–40 nm grouping together to form grains sized 100–150 nm (Fig. 3). The grains on the surface form a relief in the form of parallel bands spaced at about 1 µm.

Fig. 4 presents the EM results for the irradiated alloy. The electron diffraction image displays reflexes from the particles of the formed boride (Co_3B) and solid solution seen against the background of a halo. The Co_3B phase particles in the dark-field image have a specific "banded" structure. Besides, one can see small particles of an unknown nature equally spaced across the amorphous matrix. Simultaneously, diffraction peaks of crystalline phases – borides (CoB, Co_2B, Co_3B)