Effects of Heavy-Ions on Soft-Magnetic Metallic Glasses

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In this work, influence of 238U swift (5.9 MeV/u) heavy ions on the as-prepared Fe–Cu–Nb–Si–B metallic glass was investigated by in situ temperature X-ray diffraction of synchrotron radiation. It was observed that ion irradiation strongly affected the temperature evolution of the parameters of the first diffuse peak. It is hypothesized that ion irradiation induced structural rearrangement that increased the degree of disorder of the amorphous structure. During heat treatment, structural relaxation and annealing out of this ion-induced degradation took place. Consequently, the original structure was recovered as demonstrated by the behaviour of the first diffuse peak broadening and devitrification process.

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1. Introduction

Metallic glasses (MGs) represent the group of materials lacking a long-range atomic-scale structure. Fe-based MGs are additionally well recognized as excellent soft-magnetic materials [1]. Due to their homogeneous disordered structure, they are expected to be more resistant to radiation damage than their crystalline counterparts. This is the reason why the Fe-based MGs are considered as appropriate materials for applications in radiation environment, such as accelerator radio-frequency cavities [2]. Therefore, studies of the ion-induced damage of the Fe-based MGs are of high importance. However, these studies showed that ion bombardment with even a few MeV ions at fluences of 5 × 1010 ions/cm2 caused microstructural modifications in subsurface regions of the Fe81Mo10Cu1B10 NANOPERM-type alloy [6]. Increased hardness and Young’s modulus in the Ti45Cu45Zr5Ni5Sn5 MG is accompanied by the shortening of atomic pairs [7]. The influence of swift (few MeV per nucleon) heavy-ion bombardment on the amorphous structure of binary and ternary Fe-B-based MGs and VITROPERM-type alloy has been investigated by means of small angle X-ray scattering (SAXS) and X-ray diffraction (SXD) of synchrotron radiation, respectively [8, 9]. SAXS proved creation of ion tracks of cylindrical shapes with radius about 5 to 10 nm. SXD helped to describe structural relaxation processes after swift heavy-ion irradiation.

The aim of this study is to investigate the structural changes induced by swift U ions on the amorphous structure of Fe73Cu11Nb3Si16B7 MG and its relaxation processes.

2. Experimental procedure

The amorphous ≈ 23 µm thin ribbons with the composition of Fe73Cu11Nb3Si16B7 were prepared by the melt spinning technique. The as-prepared ribbon samples of ≈ 5 × 20 mm2 were irradiated in vacuum by 5.9 MeV/u 238U ions at fluences 5 × 1011, 1012 and 5 × 1012 ions/cm2. The non-irradiated as-prepared sample served as a reference. The influence of the swift heavy-ion irradiation on the samples’ structure was studied by synchrotron X-ray diffraction (SXD). The SXD experiments were carried out at the P02.1 beamline at DESY Hamburg using the photon energy of 59.923 keV (wavelength of 0.2069 Å). The samples were heated from room temperature up to 580 °C and cooled down to 200 °C at the heating rate of 10 °C/min. During the heat treatment, the continuous acquisition of X-ray diffraction patterns was performed in transmission mode with a two-dimensional Perkin Elmer 1621 detector. The acquisition time of one diffraction image was 20 s. The obtained 2D diffraction images were integrated along the radius of the diffraction circles in Q-space using the Fit2D software [10].

3. Results

Figure 1 displays diffraction profiles of all the irradiated specimens together with the non-irradiated one. The intensity curves I(Q)s consist of a broad diffraction peak at 3.08 Å−1 followed by series of damped oscillations observable up to 12 Å−1 reflecting the amorphous character.
of the studied samples. The absence of any sharp Bragg peaks corroborates that there is no crystalline phase after ion irradiation. Structural changes induced by the ion irradiation were evaluated from the width/broadening, \( w \), position, \( Q \), and amplitude/intensity, \( A \), of the first diffuse peak (FDP) that was fitted by a pseudo-Voigt function in the interval from 2.3 to 3.9 Å\(^{-1} \). It is seen that the peak broadening systematically increases with the irradiation fluence (see the inset in Fig. 1). It means that ion irradiation causes an increase of the disorder of the amorphous structure.

In order to follow the influence of ion irradiation on the thermal stability of the investigated MG, the \textit{in situ} SXD measurements were realized. Figure 2 shows the normalized peak position, \( Q_T/Q_0 \), the normalized peak broadening, \( w_T/w_0 \), and the normalized amplitude, \( A_T/A_0 \), as a function of temperature.

The \( Q_T/Q_0 \) behaviour is practically identical for all the specimens up to 290°C. Then a small “hump” representing a minimum of the curve slope is appearing at 380–400°C. Interestingly, the significance of this hump increases with the irradiation fluence.

The peak broadening depends strongly upon the irradiation conditions as well. The \( w_T/w_0 \) curves firstly increase modestly with temperature following the same values for all samples. At certain temperature, they start dropping rapidly. The starting temperature of this drop is shifted considerably to lower values for higher irradiation fluences.

The temperature evolution of normalized \( A_T/A_0 \) amplitudes is similar for all the samples up to temperature of 290°C above which they start to deviate from each other. When the ion fluence increases, the difference between the irradiated and non-irradiated sample becomes more pronounced.

It can be concluded that the temperature behaviour of the FDP parameters is undoubtedly influenced by the ion irradiation. Realising that the FDP reflects microstructure of the investigated alloy, the FDP modifications might be attributed to the atomic structural rearrangement induced by the ion irradiation. In contrast to the Bragg peaks of crystalline compounds, the interpretation of the FDP parameters for amorphous MGs is far away from being straightforward due to the absence of the long-range ordering. Changes in the FDP position are interpreted as free volume changes, and the increase of the FDP width is usually viewed as the increase of disorder in material.

The observed temperature behaviour of the FDP parameters (especially the width) could be explained in the
view of structural relaxation. In general, when the temperature is increased, the recovery of the material is initialized, which is reflected by the FDP narrowing. The temperature of the material recovery could be influenced by the level of the material damage. We suppose that higher ion fluences induce more radiation damage caused by swift ions using appropriate thermal annealing. This assumption is strongly supported by an additional analysis of the devitrification process of the investigated specimens. It is revealed that the crystallisation temperature is independent of applied fluence. It is the same (534.7 ± 3.3°C) for all the investigated samples within the experimental uncertainty.

![Fig. 3. Room-temperature diffraction profiles after completing the heating-treatment cycle of the samples.](image)

Figure 3 displays intensity curves collected after performing the whole heat treatment of the samples (the sample heating from room temperature up to 580°C and cooling back down to room temperature with the heating rate of 10°C/min). The formed Bragg peaks were indexed as those belonging to the cubic Fe₃Si phase. No differences are observed among temperature evolutions of the lattice parameter, a, and crystallite size, Dᵥ, of the Fe₃Si phase for particular samples, as it is demonstrated in insets of Fig. 3. The crystallite size and the lattice parameter are estimated to be about 11 ± 1 nm and 5.6727 ± 0.0004 Å for all the specimens after cooling down back to room temperature.

### 4. Conclusions

In the case of swift-U-ion-bombarded amorphous Fe₇₅Cu₁₁Nb₁₅Si₁₀B₇ alloy, the in situ SXD was used to reveal the structural variations and relaxation processes after ion irradiation. It has been observed that temperature behaviour of the FDP parameters was apparently influenced by ion irradiation. An interpretation has been proposed that ion irradiation increased the degree of disorder of the amorphous structure. On the other hand, it has been seen that the amorphous structure can be recovered from radiation damage caused by swift ions using appropriate thermal annealing. It has been shown that the ion irradiation did not influence the devitrification process of the Fe₇₅Cu₁₁Nb₁₅Si₁₀B₇ alloy. The crystallization temperature, the lattice parameter of the Fe₃Si phase, and crystallite sizes of the Fe₃Si phase were identical within the experimental uncertainty for all the investigated specimens of the Fe₇₅Cu₁₁Nb₁₅Si₁₀B₇ alloy.

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### References