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Anti-irradiation performance against helium bombardment in bulk metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$

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ABSTRACT

In order to compare the resistance to He^{2+} ion induced irradiation between metallic glass and polycrystal W metal, this paper used different fluences of He^{2+} ion-irradiated metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ and polycrystal W with an energy of 500 keV. The SRIM simulation calculation results showed that the range (1.19 μm) of He^{2+} in metallic glass was greater than the one (0.76 μm) in polycrystal W. The SEM analysis showed that there was no significant irradiation damage phenomenon on the surface of metallic glass, and there was only a damage layer 1.45 μm away from the surface when the fluence reached 2×10^{18} ions/cm^2. For W, there were surface peeling, flaking and other surface damages at a fluence of 1×10^{18} ions/cm^2; when the fluence increased to 2×10^{18} ions/cm^2, multilayer detachment phenomenon appeared. The surface root mean square roughness of metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ first increased and then decreased with the increase of fluence. The surface reflectivity of $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ decreased with the increase of fluence. Through detection by XRD, it was found that $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ always maintained amorphous phase after different fluences of radiation. The resistance to He^{2+} irradiation of metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ was superior to the one in polycrystal W.

1. Introduction

Amorphous alloy, also known as metallic glass, has high strength, corrosion resistance and reflective capacity due to the metastable structural feature of short-range order and long-range disorder. The disordered structure can resist irradiation-induced damage, and thus metallic glass also exhibits excellent irradiation resistance; therefore, it may be used as a reflector and a spatially reflective material in the reactor, or as a first-wall candidate material in the fusion reactor [1].

In recent years, ion beam irradiation as an effective means of material modification has attracted increasing attention [2–6]. The research on the irradiation damage in metallic glass materials has been valued due to the material features [7–11]. Compared with single-charged ions, highly charged ions can be used as one of the effective methods for material modification due to the greater energy loss in the solid and the faster damage to materials [12–13]. Meanwhile, highly charged ions are widespread in the universe, so irradiation with highly charged ion is of practical significance on studying the resistance to irradiation in metallic glass. Taking into account the possibility to use metallic glass as a first-wall candidate material of fusion reactor, He^{2+} is chosen as energy-carrying ion, and the ion-beam irradiation with He^{2+} ion as energy-carrying ion has unique advantages such as controllable experimental conditions, high rate of irradiation damage, high doping rate of generated He, etc.

This paper adopted highly charged He^{2+} irradiated metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ fusion reactor, and polycrystal W, currently the most promising first-wall material of fusion reactor, to study the impact of different fluences of He^{2+} irradiation on the structure and performance of metallic glass and polycrystal W [14], compare the irradiation damage between metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ and polycrystal W, and explore the behavior of resistance to highly charged ion irradiation in metallic glass.

2. Experimental methods

The metallic glass sample with the component of $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ was firstly prepared. The alloy was prepared in accordance with the given composition, the used raw materials had a purity of 99.99%, and the metallic glass rod with a diameter of 5 mm was obtained by suction casting. polycrystal W sample had a purity of 99.95%. A 2 mm-thick wafer was cut from $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ metallic glass rod, and the sample was subjected to ion beam irradiation treatment after pre-grinding, polishing and ultrasonic cleaning with acetone test solution.

The ion beam irradiation experiment was completed on the 320 kV ECR (electron cyclone resonance) experimental platform at Lanzhou Institute of Modern Physics in China. After acetone

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cleaning, the metallic glass and W samples were put into the target chamber to be fixed to the rotating target, at a target chamber vacuum degree of 10^{-6} Pa. The selected He^{2+} ion had an energy of 500 keV, and the irradiation respectively were 2×10^{17} ions/cm^2, 1×10^{18} ions/cm^2 and 2×10^{18} ions/cm^2. The SRIM simulation calculation results showed that the range of He^{2+} in the $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ is 1.19 μm while in the polycrystal W the range is 0.76 μm. After He^{2+} ion irradiation treatment, a scanning electron microscope (SEM) was used for the analysis of the damage to surface and cross-section of metallic glass and polycrystal W; atomic force microscopy (AFM) was used for the analysis of the root mean square roughness of the surface of metallic glass; X-ray diffraction (XRD) was used for the measurement of the phase structure change of metallic glass; M2000 ellipsometer was used for the measurement of the surface reflectivity of metallic glass, within the wavelength range of 600–1700 nm.

3. Experimental results and analytical discussions

3.1. Evolution of microstructure with He^{2+} irradiation

Fig. 1 shows the SEM morphology images before and after irradiation of metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$. It could be clearly observed from the images that after different fluences of He^{2+} ion irradiation, no significant irradiation damage occurred on the surface of metallic glass. Fig. 2 shows the SEM morphology images before and after irradiation of W. At a He^{2+} irradiation fluence of 2×10^{17} ions/cm^2, there was no significant irradiation damage on the surface of W; when the irradiation fluence increased to 1×10^{18} ions/cm^2, peeling, delamination, flaking and other irradiation damages occurred on the surface of W, and delamination and flaking mostly cracked along the grain boundaries. When the irradiation fluence continued to increase to 2×10^{18} ions/cm^2, the peeling, delamination and flaking phenomena of W sample became more serious, and multilayer peeling was found, as shown by the arrow in Fig. 2e.

The cross-sectional SEM images of $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ metallic glass and W before and after He^{2+} ion irradiation were shown in Fig. 3. It could be seen from the topography in Fig. 3 that, for metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ material, the cross-sectional morphology did not change significantly at the irradiation fluence of 1×10^{18} ions/cm^2 as shown in Fig. 3a; when the irradiation fluence increased to 2×10^{18} ions/cm^2, there appeared an apparent damage layer about 1.45 μm from the surface (in the vicinity of the range of He ion in the metallic glass) as shown in Fig. 3b. In the cross-sectional SEM image of W, Fig. 3c showed W was not subjected to significant irradiation damage at an irradiation fluence of 2×10^{17} ions/cm^2. Significant peeling and delamination phenomena were produced (Fig. 3d) at a fluence of 1×10^{18} ions/cm^2, and the thickness of the peeling layer was approximately 0.9 μm (approximating to the range of He ion in W). When the fluence increased to 2×10^{18} ions/cm^2, the damage to W caused by irradiation was more serious, and multilayer peeling phenomenon occurred on its surface.

The fluence of metallic glass under the circumstance that irradiation damage phenomenon began to occur was much greater than that of W, and the irradiation damage to metallic glass was far slighter than the one to W, showing that the resistance to irradiation in metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ was far better than that of polycrystal W.

Fig. 4 shows the XRD spectra of $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ metallic glass before and after He^{2+} ion irradiation. It could be drawn from the diffraction spectra that the metallic glass was always in amorphous state after different fluences of He^{2+} ion irradiation, that is, He^{2+} ion irradiation did not change the amorphous structure of the Cu-based metallic glass. Such superior GFA (glass forming ability) is found primarily due to the alloying effect of Y, which lowers the alloy liquidus temperature and brings the composition closer to a quaternary eutectic. Due to different constituent elements and mutual match in atomic size, the alloy reached a topological close-packed structure, and the negative mixing enthalpy among the various elements greatly increased the interaction among the elements, promoting the short-range structure to be formed among the elements and avoiding the formation of long-range order structure [15]. These characteristics made $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ more easily maintain its amorphism during irradiation.

3.2. Evolution of surface with He^{2+} irradiation

The surface roughness of the sample was measured using an atomic force microscope (AFM). Fig. 5 showed the surface topography image of metallic glass $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ before and after

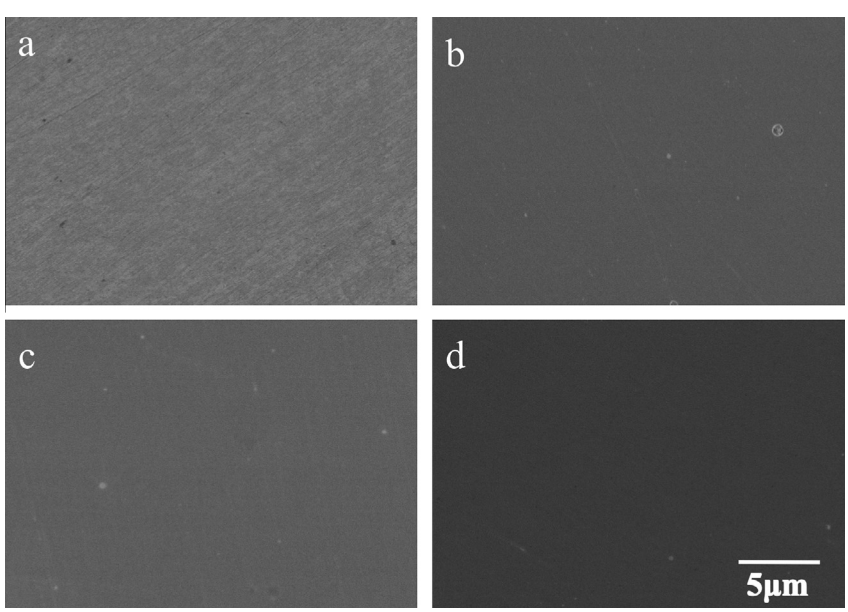

Fig. 1. SEM images of (a) pristine and 500kev He^{2+} irradiated $(Cu_{47}Zr_{45}Al_8)_{98.5}Y_{1.5}$ with fluences of (b) 2×10^{17} cm^{-2}, (c) 1×10^{18} cm^{-2} and (d) 2×10^{18} cm^{-2}.