doi:10.1017/S1431927622008170
Microsc. Microanal. 28 (Suppl 1), 2022

Revisit the Effect of He^+ Irradiation on the Structure and Mechanics of Metallic Glass

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Structural materials used in nuclear power plants (NPPs) often suffer from irradiation induced damage, such as swelling, hardening, and embrittlement, due to the existence of defects such as bubbles, voids, and dislocation loops. In particular for the fusion reactor, the plasma-facing components of nuclear fusion reactors will need to withstand even higher fluxes of helium ions with energies up to several thousand electronvolts. Therefore, an in-depth understanding of these degradations is crucial for the development of radiation resistance materials for operation in such a harsh environment.

Metallic glasses (MGs) as one class of amorphous materials that lack apparent defects such as grain boundaries and dislocation have exhibited superior mechanical performance in hardness, wear, toughness, strength, and corrosion resistance when compared to their crystalline counterparts with similar compositions. Moreover, MGs as the potential materials for future advanced NPPs exhibited unusual structural responses and high resistance to ion irradiation damage. For instance, it has been widely reported that no Frenkel pair defects will form during the irradiation process because of the absence of a lattice site. Self-healing effect was also observed in neutron irradiation-induced vacancy-like defects in MGs after structural relaxation by rearrangement of free volume. Some irradiated amorphous alloys became even more ductile while irradiation-caused embrittlement in almost all the crystalline alloys. These findings shed light on designing MGs with high structural stability against irradiation by tailoring the microstructures, or the compositions in alloys. The recent development of high-temperature Ir–Ni–Ta–(B) MGs with glass transition temperature over 893°C make a significant step towards high-temperature applications including NPPs.

In this study, we gained key experimental insights into the mechanism of helium-ion-induced swelling and flaking in model materials $Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$ using a Helium Ion Microscope for precisely localized irradiation in combination with surface imaging by Atomic Force Microscopy (AFM), and crucially, high-resolution imaging by transmission electron microscopy (TEM) of cross-sections of near-surface prepared site-selectively by gallium focused ion beam (FIB) milling. The changes of mechanical properties are revealed using nanoindentation and correlated with the evolution of microstructure. We showed the first direct experimental evidence of the coalescence of He bubbles at the shear bands. In addition, four-dimensional scanning transmission electron microscopic technique (4D-STEM) was applied to show the strain distribution at the near-surface and clearly distinguished the irradiated region with He bubbles. The systematic understanding in this work would not only be of significance to understand the effect of He irradiation and its impact on mechanical properties of MGs, but also will shed light on the fundamental mechanism of He bubbles formation.