§33. Irradiation Hardening and Embrittlement of Fusion Reactor Structural Materials under Irradiation with in situ He Injection

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Fusion first wall irradiations produce ≈ 2000 appm of He in Fe-based alloys at 200 dpa. Helium bubbles precipitate in the matrix as well as on dislocations, precipitate interfaces and grain boundaries (GB). The accumulation of He in the tempered martensitic steels (TMS) can cause a severe irradiation embrittlement in the form of ductile-to-brittle transition temperature shift, ΔT, synergistically with what is caused by irradiation hardening [1, 2]. That synergism was also well demonstrated in our previous research of compiling the irradiation hardening and embrittlement database from the literature, including results from neutron, spallation proton (SP) and He-ion (HI) irradiations that produce different levels of He per the level of displacement damage (dpa) in the materials – typically, low (≈ 0 appm He/dpa), high (≈ 100 appm He/dpa), and very high (≈ 6000 appm He/dpa), respectively. The analysis even among some scattered data derived a trend of irradiation embrittlement that is accounted for by a combination of a physically based Maken-Mitter type irradiation hardening model and embrittlement-to-hardening correlation as a function of He accumulation [1,2].

One of the possible mechanisms for the synergism is reduction of GB cohesive energy due to He accumulation as is suggested by some observation of intergranular (IG) fracture in the materials with high He accumulation [1,3]. Simple estimation of the amount of He that can cause single layer coverage of GB by He matches the threshold level of He ≈ 500 appm also support the suggestion. However, the fate of He accumulated in the materials is still not well understood. Hence the objectives of this research is to directly measure GB strength at different levels of injected He using ion accelerator irradiation combined with micromechanical approaches including nano-scale bending tests of focused ion-beam (FIB) machined fracture specimens.

Series of ion irradiations are carried out on mechanically and/or electro- polished surfaces of candidate fusion materials such as 8-9Cr-1-2W ferritic steels and V-4Cr-4Ti vanadium alloys. Some reference steels with Mn and Ni with high irradiation hardening sensitivity are also included as reference material. The ions for irradiation include He^{+} at the energy up to 2 MeV and $Fe^{2+ \text{ or } 3+}$ at the energy up to 6.4MeV. The He^{+} irradiations mainly make He precipitation at various microstructural sites including GB while Fe^{x+} irradiation produces displacement damages that induce irradiation hardening in the target materials. Micrometer-scale mechanical bend bar specimens are fabricated using focused ion-beam (FIB) machining, followed by nano-meter scale testing in a nano-indentation system with a flat punch. We also carry out nano-indentation tests with Berkovich-type indenter to evaluate irradiation hardening. Transmission microscope observation is also carried out on selected irradiation conditions.

This year series of Fe^{2+} irradiation were carried out in HIT facility in University of Tokyo at 290°C on F82H IEA and V-4Cr-4Ti NIFS-II heat along with reference Ni-Mn steels. Figure 1 shows an example of displacement damage profile in the steels calculated using SRIM2008 code for Fe^{2+} ion energy of 2.8 MeV. Peak dpa is located at the depth of 0.8 μm. Micro-scale cantilever beam bend specimens were fabricated as is shown in Figure 2. About 0.5 μm deep FIB notch was introduced so that the stress concentration occurs near the peak dpa location during bending test. The testing will be carried out once a flat punch is equipped in nano-indentation system at University of Fukui.

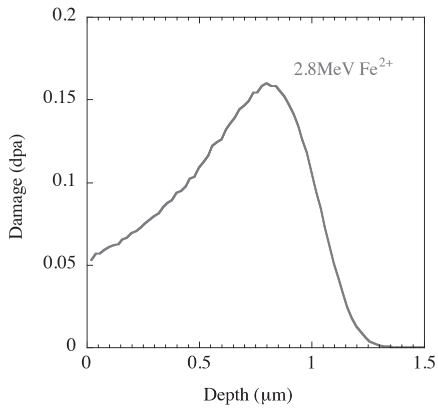

Figure 1 Displacement damage (dpa) profile in Fe^{2+} ion irradiated F82H and reference steels.

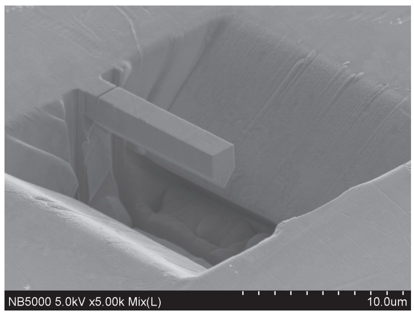

Figure 2 Focus ion beam machined fracture specimen in the irradiated damage region near the surface of F82H IEA.

[1] T. Yamamoto et al., J. Nucl. Mater. 356 (2006) 27.
[2] T. Yamamoto et al., *Trans. Am. Nucl. Soc.,* 98 (2008) 1111.
[3] G. R. Odette et al., J. Nucl. Mater. 323 (2003) 313.