doi:10.1017/S143192762100934X
Microsc. Microanal. 27 (Suppl 1), 2021

In-situ Irradiation, Helium Implantation and Heating to Elucidate Mechanisms in Tungsten Alloys

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High-Z materials, including tungsten (W), are proposed as plasma-facing materials in future nuclear fusion reactors. W has a high melting point, high thermal conductivity, and high physical sputtering threshold making it attractive for use in the harsh fusion environment. Plasma-facing materials in the divertor region of fusion reactors will be exposed to high heat fluxes (>10 MW/m^2), bombardment from 14 MeV neutrons, and low energy high-flux implantation of D/He ions (eV-keV range) [1]. The response of candidate materials to these synergistic stimuli must be examined in simulation environments to determine how they may respond in true reactor operation. High temperatures and heat fluxes can introduce surface roughening, cracking, and melting of W. Incident deuterium is trapped in the W matrix and can form surface blisters, while accumulating H isotopes can cause fuel inventory and reactor safety concerns [1]. Helium irradiation of W introduces sub-surface bubbles than can evolve at high temperatures to form surface nanostructuring (fuzz) and degrade the mechanical properties [1]. There is a need to design W-based materials with microstructures tailored to tolerate these conditions. The design, microstructure, and composition of materials greatly influences the properties under high heat and particle loading. In W, the grain size and composition can be altered to improve the material performance under fusion reactor-simulated conditions.

In a materials-by-design approach, modifying material microstructures can take either a bottom-up or top-down path. In the bottom-up approach, materials are synthesized by-design with inputs introduced to achieve the desired structure during film growth or powder consolidation through spark plasma sintering [2, 3]. In the top-down approach, an existing microstructure is altered through external post-processing, for example to introduce texturing, reduce the grain size through severe plastic deformation, as seen in equal-channel angular pressing (ECAP) and high pressure torsion (HPT) [4].

Prior to studying material response in a fusion reactor, the early-stage, incubation-level mechanisms at low-fluence that evolve into late-stage phenomenon must be elucidated. To study the fundamental mechanisms of He bubble nucleation, growth, and migration processes on the nm-scale, in-situ ion irradiation transmission electron microscope (I^{3}TEM) facility is an ideal platform. The I^{3}TEM is a 200 kV JEOL 2100(HT) TEM equipped with a 6 MV Tandem, 1 MV Tandem, and 10 keV Colutron ion accelerators, and an 1064 nm laser which can introduce MeV-level heavy ion irradiation, keV-level D/He ion irradiation, and heating up to ~2000 ˚C, respectively [5, 6]. All these stimuli can be driven simultaneously and concentrically onto a TEM sample of interest to investigate the effects of all 3 to simulate various fusion reactor operating conditions. Using the I^{3}TEM facility, pure W and Ti doped W films were irradiated with 1.5 MeV Au$^+$ to investigate the influence of dopants on the microstructural stability of nanocrystalline W [7]. Defect evolution was mapped in-situ up to the saturation dose (~20 dpa) and then bridged to extreme dose behavior (~400 dpa) through ex-situ measurements. Defect densities and sizes were estimated through grain characterization via enhanced Automated Crystal Orientation Mapping (ACOM; Figure 1b). In-situ capabilities of the I^{3}TEM facility were utilized to a confirm the correlation between grain size and defect density trends, showing the formation of smaller defect loops (Figures 1c,d),a delayed saturation dose relative, and a delayed onset of void formation in W-20Ti compared to pure W(Figures 1e,f). Applying a thermal spike-based grain growth model revealed that the W-20Ti microstructure plateaus to a much finer nanocrystalline grain size relative to model predictions for pure W. In all, these results show the value of in-situ TEM experiments for fusion materials investigations that serve as the basis for future investigations with combined irradiation beams and high heat flux pulsing to best simulate fusion reactor conditions [8].

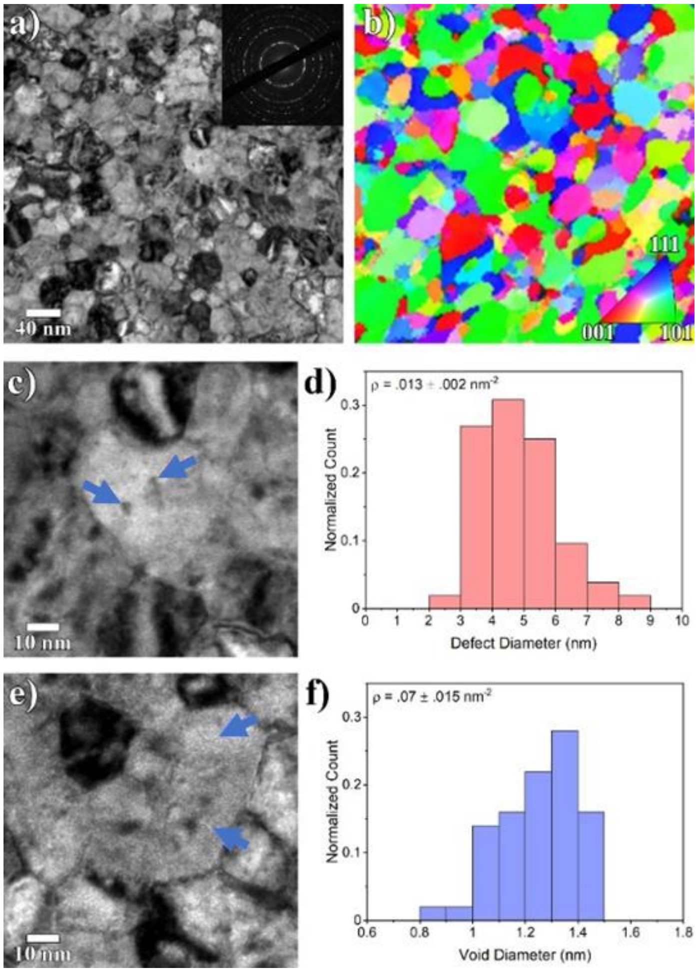

Figure 1. Fig. 1: (a) TEM bright-field micrograph of the W-20 at.% Ti film irradiated to 400 dpa with 1.5 MeV Au+. SAD pattern included in the inset. (b) Representative grain orientation map from PED enhanced ACOM; (c) TEM bright-field micrograph of the 400 dpa W-20Ti film showing black dot damage formation; (d) average defect size and density at 400 dpa. (e) Underfocused TEM bright-field micrograph of the 400 dpa W-20Ti film showing void formation at the highest fluence; (d) average void size and density at 400 dpa.

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[8] This work was supported by the U.S. Department of Energy Office of Fusion Energy Sciences through the Materials Research program and in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. DOE Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security

Administration under contract DE-NA-0 0 03525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.