The Role of High Damage Rates on Cavity Nucleation with Co-Injected Helium in Dual Ion Irradiated T91 Steel

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High fidelity emulation of neutron irradiation microstructures using ion beams requires understanding the influence of helium and high damage rates on the irradiated microstructure. However, a single ion beam cannot account for the effects of transmutation-produced helium which strongly influences the evolution of the microstructure of irradiated materials. Irradiations using 5 MeV Fe^{2+} ions to induce damage with co-injected He^{2+} to simulate transmutation gas buildup were performed at the Michigan Ion Beam Laboratory on a ferritic-martensitic alloy, T91. Irradiations were performed up to 35 dpa at 600 nm depth at 445°C with damage rates spanning from 5 x 10^{-5} to 3 x 10^{-3} dpa/s with a helium co-implantation rate of ~4 appm He/dpa. Additional irradiations were conducted to isolate the effect of helium co-implantation on cavity nucleation at 7-8 x 10^{-4} dpa/s to 16.6 dpa at 600 nm depth at 445°C with zero helium co-implantation, a low helium co-implantation rate of 0.02 appm He/dpa, an intermediate helium co-implantation rate of 0.22 appm He/dpa or a high helium co-implantation rate of ~4 appm He/dpa. Cavities and dislocation loops were characterized using scanning transmission electron microscopy (STEM) to understand the evolution of the irradiated microstructure with damage rate and helium co-implantation rate. No significant differences were observed in the average dislocation loop diameter or density within these damage rates or helium co-injection rates. A bimodal cavity distribution was observed consisting of high densities of small (< 2 nm diameter) bubbles and a wider distribution of cavities with diameter > 2 nm. The density of bubbles and cavities showed a strong dependence on the He/dpa ratio with increasing density of bubbles and cavities with increasing He/dpa ratio. The average cavity diameter at 16.6 dpa was the same across He/dpa ratios. Very few cavities were observed without helium co-implantation at these damage rates and damage levels, highlighting the strong impact of helium on cavity nucleation. For an increasing damage rate at the same temperature and He/dpa ratio, the bubble density increased while both the cavity density and diameter decreased. These trends are discussed in the context of the critical bubble model of cavity nucleation.