DOE-IRP on Emulating Reactor Irradiation with Ions at the Michigan Ion Beam Laboratory

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Reactor materials must withstand irradiation to extremely high doses while under stress at high temperature and in aggressive environments. Cladding and structural materials in fast reactors and fusion reactors will reach 200 dpa, and concepts such as the Traveling Wave Reactor could top 500 dpa. Test reactors have the capability of achieving only a few to perhaps 30 dpa per year, while ion irradiation has the potential to reach high dose levels in comparatively short amounts of time, at low cost and with minimal sample activation. The challenge is in determining how to conduct such high damage rate irradiations so as to replicate the reactor irradiated microstructure.

Ferritic-martensitic (F-M) alloys are attractive candidates for structural components of fusion reactors due to their excellent dimensional stability, thermal properties and low activation. Evolution of the irradiated microstructure (dislocation loops, voids, radiation-induced precipitates (RIP) and radiation-induced segregation (RIS)) has been studied in 5 MeV Fe^{++} (self-ion)-irradiated T91, HT9 and HCM12A at high doses ($\geq$100 dpa) in the temperature range 400-500°C with and without He pre-implantation. Samples were prepared by the focused ion beam (FIB) lift-out method for dislocation microstructure, voids, precipitates, and grain boundary RIS characterization by transmission electron microscopy and atom probe tomography.

Results showed that Cr, Ni, Si and Cu all segregate at the grain boundary following Fe^{++} irradiation at low dose (<10 dpa) and that the amounts of segregation change very little with increasing dose. The dislocation microstructure also develops rapidly and is relatively stable with increasing dose. However, precipitates and voids continue to evolve to high dose. Ni/Si/Mn-rich, Cu-rich precipitates, Cr-rich precipitates and chromium carbides all continue to evolve up through 500 dpa and their behaviors depend sensitively on the alloy composition. Voids begin to form over a dose range of 100-140 dpa (K-P quick calculation using SRIM) or 200-280 dpa (full cascade calculation using SRIM) in samples pre-implanted with He. He is found to be very effective in nucleating voids earlier but growth is slower than without He, in which nucleation occurs later but growth is more rapid.

Comparison of the irradiated microstructure resulting from self-ion irradiation to that from reactor irradiations in FFTF on a feature-by-feature basis show remarkably good agreement in trend, magnitude and dose dependence. Results of both will be presented and discussed with the goal of identifying the self-ion irradiation conditions that best emulate reactor irradiations. Status of the expansion of the Michigan Ion Beam Laboratory to provide for dual and triple beam ion irradiations will also be presented.