Dose Rate Effects on Microstructure and Hardening in Ion and Test Reactor Irradiated Reactor Pressure Vessel (RPV) Steels

Formation of displacement cascade-induced defects, cascade fragments (CF), in RPV steels, which can be enhanced in accelerated irradiations at high dose rates, was examined using ion irradiation, nano-indentation and atom-probe tomography. Radiation enhanced precipitation of Cu-Ni-Mn-Si clusters is significantly delayed at the high dose rate of ≈ 10^5 dpa/s, while at the same time non-Cu dependent large hardening is observed, which can be accounted for by the formation and spatial saturation of CFs.

Irradiation embrittlement of RPV steels, typically characterized by brittle to ductile transition temperature shift (TTS), must be accurately predicted for safe reactor operation. The current TTS prediction model under-predicts many high neutron fluence (ϕt) data mostly obtained in test reactor irradiations. This is partially due to cascade fragments (CF) formed in aged displacement cascades, which anneal continuously during reactor operation, but build up at high flux (ϕ) in test reactors. The CFs also enhance point-defect recombination, that delays radiation enhanced precipitation hardening and embrittlement. The objective of the research is to understand and build mechanistic models of defect formation in RPV steels irradiated at very high dose rate – neutron flux (ϕ) range $\phi > 10^{13}$ n/cm^{2}s or corresponding dpa (displacement per atom) rate greater than ≈ 10^{-8} dpa/s.

RPV model steels with systematically varied Cu and Ni contents were irradiated by Fe^{2+} ions with 2.8MeV energy at 290°C to 0.005 to 0.2 dpa at a dose rate of ≈ 10^{-5} dpa/s as a nominal value defined at the depth of 500 nm. Nano-hardness and atom-probe tomography measurements have been carried out for some of the steels.

Figure 1 shows atomprobe elemental maps of a 0.4%Cu-1.3%Ni-1.4%Mn steel irradiated to 0.2 dpa at two different dose rates: a) 10^{-5}; and b) 1.5×10^{-7} dpa/s. Cu rich solute cluster formation is significantly delayed at higher dose rate. Similar delay is also observed in other alloys. Figure 2 shows the volume fraction of precipitates formed in a 0.4%Cu-0.8N%Ni-1.4%Mn steel irradiated in reactors as well as by ions at various dose rates. Fastest precipitation trend is observed at 10^{-10}~10^{-9} dpa/s followed by 10^{-8}~10^{-7} dpa/s while significant delay is observed at the highest dose rate of ~10^{-5} dpa/s in ion irradiation. In spite of the delay in precipitation, significant hardening is observed, which for example reaches ΔH ≈ 300 MPa at 0.2 dpa in a 0%Cu steel. As illustrated in Figure 3, our growing database of ion irradiation hardening shows that 0, 0.1 and 0.2Cu steels show similar large hardening at low dose ion irradiation regardless the Cu content. It cannot be accounted for by precipitates or loops, but a CF hardening model including spatial saturation of the CFs at extremely high dose rates gives good representation of the trends. Residual hardening at higher dose is also consistent with precipitation hardening trend at lower dose rates when the recombination effects are taken into account.

Further study including positron annihilation with post irradiation annealing will be carried out when slow positron beam equipment in Oarai Center is recovered from the breakdown.

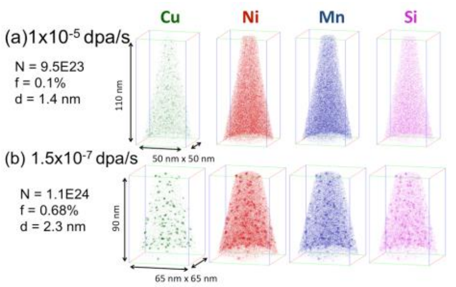

Figure 1 Atom probe elemental maps of 0.4Cu-1.3Ni-1.4Mn steel irradiated to 0.2 dpa at a) 1×10^{-5} dpa/s by Fe^{2+} ions and b) 1.5×10^{-7} dpa/s in BR2 test reactor, showing significant delay in cluster formation at higher dose rate.

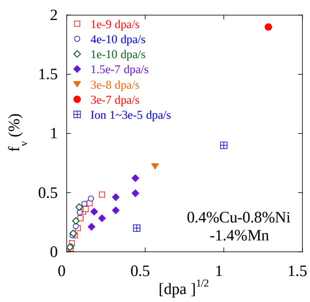

Figure 2 Volume fraction of Cu-Ni-Mn-Si precipitate in 0.4% Cu-0.8% Ni-1.4%Mn steel formed by radiation enhanced diffusion at various dose rates.

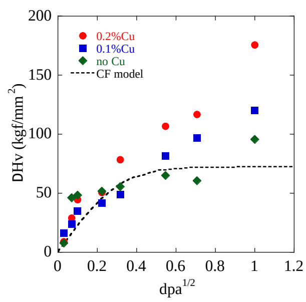

Figure 3 Irradiation hardening in 0, 0.1,and 0.2% Cu-0.8% Ni-1.4% Mn steels. Base hardening trend is consistent with newly developed CF hardening model.

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