Effects of Mn content on the characteristics of radiation induced defects in reactor pressure vessel (RPV) steels

Mn effects on the 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 high flux test reactor as well as Fe^{2+} ion irradiation. No hardening was observed in the alloy containing 0% Mn, while the hardening increases with Mn to reach commonly observed level of CF hardening in ion irradiation at Mn ≥ 1.4%, suggesting low Mn can suppress the CF formation.

The current prediction model of irradiation hardening and embrittlement of RPV steels under-predicts brittle to ductile transition temperature shift (TTS) of steels irradiated in test reactors to high neutron fluence (ϕt) [1] partially due to cascade fragments (CF) formed in displacement cascades. The CFs continuously anneal during reactor operation, but build up at high flux (ϕ) in test reactors, causing additional hardening. At the same time, higher flux accelerates point defects recombination to reduce the radiation enhanced solute diffusion, that delays formation of other types of hardening features. Thus in high flux test reactor, hardening and embrittlement trends are different from power reactor conditions. Never the less, utilizing test reactor data is necessary in order to predict long-term (high dose) TTS trends. Thus, the purpose of the research is to understand CF characteristics and the behavior, which will be used to develop a method that properly accounts for the effects of high flux and CF formation in evaluating test reactor irradiated specimens.

RPV model steels of chemistry variation including Mn varied from 0 to 1.6 % are irradiated in a Belgium test reactor, BR2, followed by micro Vickers hardness tests, which is complemented by nano-hardness measurements carried out on a subset of alloys irradiated by 2.8 MeV Fe^{2+} ion in HIT facility in University of Tokyo.

Figure 1 shows hardness change, ΔHv, as a function of neutron fluence for steelss with various Cu-Ni-Mn compositions. ΔHv is higher for 0.4% Cu steels and showed steeper increase at the highest dpa in high Ni alloys presumably due to Mn-Ni-Si precipitates (MNSP) formation. The trends are very consistent with our previous results on the steelss. Medium 0.8% Mn trend is similar to 1.4% Mn, while 0% Mn alloy showed ΔHv ≈ 0. Figure 2 shows nano-hardness based ΔHv in ion irradiated 0% Cu-0.8% Ni steels with 0 to 1.6% Mn. The figure also show CF hardening trend previously observed commonly in 0 to 0.2%Cu-1.4%Mn-0.8%Ni alloys. The 1.4-1.6%Mn data follow the common CF trend within the scatter, 0.8%Mn falls slightly lower, but 0%Mn shows much lower almost no hardening. Figure 3 summarizes the Mn dependence of hardening in these two series of irradiations. Here neutron dose is converted to corresponding dpa using dpa cross section of $1.5x10^{-21}$ cm^2. The most distinctively the ΔHv is ≈ 0 for 0% Mn, which generally increase with Mn except low dose conditions including ion 0.01 and BR1 0.04 dpa. In these cases, hardening is ≈ 0 for all Mn level. Since the hardening in ion irradiation is mostly due to the CF, low Mn seems to suppress CF formation at least in ion irradiation. For BR2 neutron irradiation, post irradiation annealing study will be carried out to isolate the CF hardening component from the total.

References

[1] G.R.Odette and R.K.Nanstad, JOM 61 (2009) 17

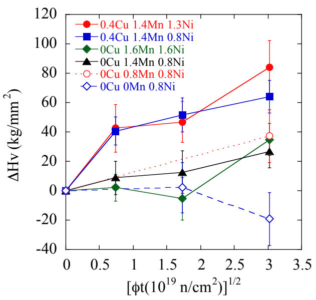

Figure 1 Neutron dose dependence of hardness change in RPV steels with 0-0.4Cu, 0-1.6Mn and 0.8-1.3Ni in BR2 test reactor.

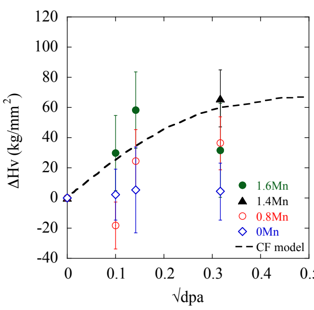

Figure 2 dpa dependence of hardness change in RPV steels containing 0%Cu, 0.8%Ni and various (0 to 1.6%) Mn irradiated by Fe2+ ion.

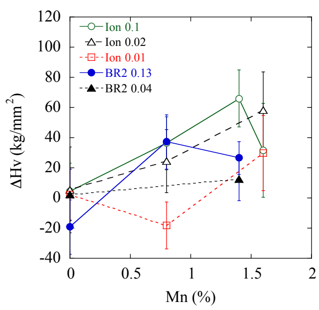

Figure 3 Mn dependence of hardness change in 0Cu-0.8Ni RPV steels to various doses in BR2 reactor or in Fe^{2+} irradiation.

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