Embrittlment trend curve (ETC) prediction of rector pressure vessel (RPV) steels

A type of unstable radiation-induced defect in RPV steels, which a key to understanding neutron flux effects, has been characterized by positron annihilation and hardness measurements including recovery anneal. The defect structure involves mono-vacancy equivalent open volume and the formation is accelerated with flux. Flux compensated hardening trend curves suggested severer embrittlement than current prediction model after a long-term operation.

Unstable matrix damage (UMD) is a type of defect formed in aged displacement cascades, that anneals out continuously during reactor operation [1]. UMDs build up at high neutron flux in test reactor irradiations, confounding the results in two opposite ways – adding hardening and delaying formation of more typical hardening sources in power reactor conditions. The delay is due to point defect recombination enhanced at higher flux including at UMD sites[1]. Utilizing test reactor data to predict RPV long-term embrittlement trend curve (ETC) requires properly accounting for these effects. Hence, the objective of this study is to clarify the character and behavior of UMD, as well as to develop models of long-term predictions of radiation embrittlement after the flux effect compensation.

Positron annihilation spectroscopy (PAS) and hardness measurements before and after UMD recovery anneal at 350 °C for 5 h have been performed on 5 model RPV steels with systematic chemistry variation, irradiated in BR2 test reactor to two neutron dose levels; 1 and 2.5 x 10^{20} n/cm^2 at 2 x 10^{13} n/cm^{2}s flux at 290 °C. PAS was also performed on the same set of alloys irradiated at other 10^{12} and 10^{14} n/cm^{2}s flux conditions. Hardening database combined with other studies was analyzed and compared with current ETC models.

Specimens irradiated at 2 x 10^{13} n/cm^{2}s or higher flux showed significantly larger low momentum component Fraction (LMCF) in PAS as well as longer average positron lifetime than at 10^{12} n/cm^{2}s. Both measures of vacancy type damage increase with dose and flux, but recovery anneals reduce them to the level for irradiations at 10^{12} n/cm^{2}s condition. The second lifetime component reaches ≈ 180 ps at high dose. These PAS results suggest that UMD contains mono-vacancy size open volume defects that build up at least up to mid 10^{20} n/cm^2 at a flux levels of the order of 10^{13} n/cm^{2}s or higher. The average UMD size may increase with dose. Hardness recovery also increases with dose, but is significantly smaller at 2x10^{13} than at 10^{14} n/cm^{2}s suggesting large flux dependence in the UMD number density. These new findings are to be considered in updating UMD models.

We obtain low flux long-time hardening estimates of the RPV steels by annealing out UMD and using effective dose after compensating for enhanced recombination at higher flux. Figure 1 shows an example for a Cu-free steel. It also shows that the current ETC models significantly under-predict the highest dose data in recent UCSB study (blue open diamond)[2]. The study confirmed the extra hardening is due to the formation of Mn-Ni-Si precipitates (so called late blooming phases, LBP), that were not observed at lower doses, but have long been predicted. This study clearly indicates that LBP hardening (dashed line) starts ≈ 5x10^{19} n/cm^2, typically ≈ 40 years of reactor operation, suggesting critical importance of ETC improvement. Further microstructural studies using atom-probe tomography and small angle neutron scattering are planned for future collaboration.

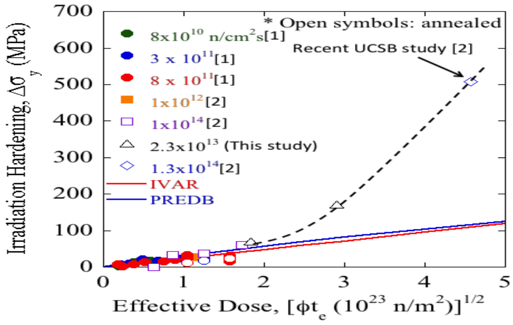

Figure 1 Irradiation hardening trend in a Cu free RPV steel

References

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