Advanced Microstructural Characterization of New Radiation Induced Defects in Reactor Pressure Vessel (RPV) Steels

Two types of radiation-induced defect features, namely unstable matrix damage (UMD) and late-blooming phases (LBP) in RPV steels, which need to be accounted for in more accurate embrittlement prediction, were examined in detail by positron annihilation and atom-probe tomography including recovery anneal. The UMDs involving mono-vacancy equivalent open volume formed faster at higher flux in low Cu steel. LBPs are Ni-Mn-Si precipitates that formed even in low Cu 0.8Ni steel to the volume fraction of 0.16% at 2.1×10^{20} n/cm^2 fluence.

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]. Previous studies suggest that this is due to: 1) UMDs formed in aged displacement cascades, that anneal continuously during reactor operation, but build up at high flux (ϕ) in test reactors; and/or 2) late blooming Mn-Ni-Si phases (LBP), that have long been predicted but recently found to grow to very high volume fractions at very high ϕt even in low Cu steels[1].

Accurate prediction of long-term RPV embrittlement requires properly accounting for these types of defects. Hence, the objective of this study is to clarify the character and behavior of UMD and LBP in detail as a function of irradiation and material variables.

14 model RPV steels with systematic chemistry variation were irradiated in BR2 test reactor to two $\phi t \approx 1$ and 2.1×10^{20} n/cm^2 at $\phi = 2.3 \times 10^{13}$ n/cm^{2}s and 290°C. Positron annihilation spectroscopy (PAS) and micro-hardness measurements have been performed before and after a UMD recovery anneal (PIA) at 350°C for 5 h. PAS was also performed on a subset of alloys irradiated at other $\phi = 10^{12}$ and 10^{14} n/cm^{2}s conditions. Atom Probe Tomography (APT) was carried out on selected alloys at $\phi t = 2.1 \times 10^{20}$ n/cm^2.

Figure 1 shows average positron lifetime (τ_{av}) for low and high Cu steels as a function of ϕt at $\phi \approx 10^{12}$, 2×10^{13} and 10^{14} n/cm^{2}s before and after the recovery anneal. Mono vacancy size open volume type defects are indicated by longer τ_{av} that significantly increases with ϕt at $\phi \geq 2 \times 10^{13}$. These features mostly recover during PIA with corresponding τ_{av} similar to a low $\phi = 10^{12}$ n/cm^{2}s condition. Further acceleration of UMD formation by ϕ for $\geq 2 \times 10^{13}$ n/cm^{2}s is only significant in the low Cu, but not in high Cu steels.

Figure 2 shows APT atom maps indicating formation of Ni-Mn-Si rich LBPs in two no Cu steels with a) 0.8% and b) 1.6% Ni. The respective precipitate volume fractions are 0.16% and 0.47%. The respective average precipitate sizes and number densities are ≈ 2.4 nm/2.3 $\times 10^{23}$m^{-3} and ≈ 2.4nm/6.3$\times 10^{23}$m^{-3}. The estimated precipitate hardening values are reasonably consistent with the measured extra hardening in these alloys compared to the current EONY model. The hardening model uses the obstacle strength factors obtained in recent UCSB study[2] for well developed LBPs in RPV steels irradiated to much higher $\phi t = 1 \times 10^{21}$ n/cm^2.

These data and insights are being used to develop new, physically-based models of embrittlement.

References

[1] G.R.Odette and R.K.Nanstad, JOM 61 (2009) 17
[2] P.Wells, T.Yamamoto, G.R.Odette et al., Acta Mater. accepted.

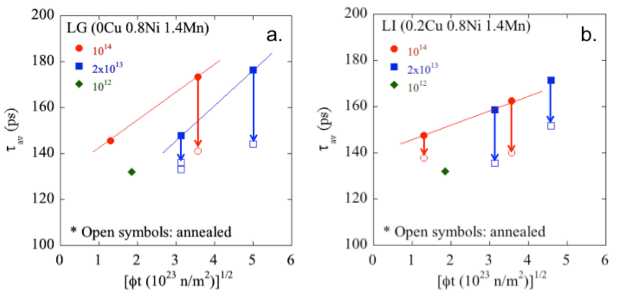

Figure 1 Average positron lifetime (τ_{av}) before (filled) and after (unfilled) recovery anneal versus neutron fluence (ϕt) for ϕ from 10^{12} to 10^{14}n/cm^2 in a) low and b) high Cu RPV steels.

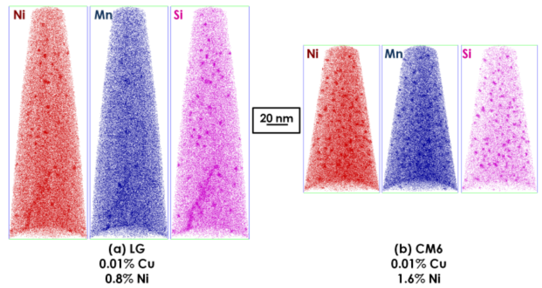

Figure 2 Elemental maps obtained in APT measurements showing formation of Ni-Mn-Si LBP in low Cu steels with a) 0.8%Ni and b) 1.6%Ni

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