Contributions of Fundamental Studies to Understanding RPV Embrittlement

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INTRODUCTION

Commercial nuclear reactor pressure vessels (RPV) are expected to last the lifetime of the plant, a time in the range of 30 to 60 years. These vessels have traditionally been fabricated from low-alloy Mo-Mn steels (e.g. ASTM A533, Grade B) in 6 to 8 in thick sections. Both rolled plate and ring forgings have been used, with individual sections joined by submerged-arc welds. The RPV is a large cylinder on the order of 12 feet in diameter and 20 feet long. Among other functions, it serves as a primary barrier to fission product release in postulated severe accident scenarios, rendering in-service vessel failure unacceptable.

RPV steels have relatively high strength and good toughness in the as-fabricated condition. However, in-service exposure to high energy neutrons leads to the formation of a fine-scale, radiation-induced microstructure that both further strengthens and embrittles the material. This embrittlement is observed as an increase in the ductile-to-brittle transition temperature (DBTT). At high neutron exposures, the DBTT can exceed room temperature, high enough to impact reactor operations and raise questions about RPV integrity under accident conditions.

Since the RPV is not a replaceable component, it is critical to understand the mechanisms that cause embrittlement in order to both develop mitigation strategies, and provide better predictions of embrittlement to reduce the regulatory burden associated with uncertainties in material properties. Although RPVs are large, low-technology engineering structures, the scientific challenge of developing an adequate understanding their embrittlement has required application of both advanced microstructural characterization methods and computational simulations. These methods and their use are discussed below.

CHARACTERIZATION OF DEFECTS IN IRRADIATED RPV MATERIALS

Microstructural Investigations

Advanced techniques for microstructural characterization needed to obtain a description of the defects responsible for the increase in DBTT. Early research indicated that the presence of low levels of copper (~10 to 30 wppm) as a tramp element increased embrittlement [1]. Later, more detailed investigations revealed the impact of other minor solutes and alloying elements [2]. However, transmission electron microscopy (TEM) examination revealed too few radiation-induced defects to account for measured mechanical property changes.

The use of field ion microscopy in various forms, including atom probe tomography (APT) played a key role in identifying the defect responsible for the embrittlement, namely small copper-enriched precipitates or solute clusters. Several are shown in the APT three-dimensional atom map in Fig. 1 which reveals a high number density of Cu-, Mn- and Ni-enriched precipitates in this RPV weld that had been irradiated to a neutron fluence of 0.8×10^{23} n. m^{-2} (E > 1 MeV) at a temperature of 288°C. Both their small size and the fact that they are coherent with the bcc ferrite matrix limits their visibility under TEM.

Small angle neutron scattering (SANS) has also been heavily used in this research. SANS provides information about the evolution of copper-manganese-nickel precipitates as a function of key irradiation and environmental variables. Fig.2 shows the evolution of mean precipitate radius with increasing fluence in two A533B model that contain 0.4% Cu, 0.8 and 1.25% Ni and 1.4% Mn for the circles and squares, respectively. Combined with the information on number density and volume fraction that is also obtained, the results indicate that the precipitates undergo a slow coarsening mediated growth with increasing fluence.

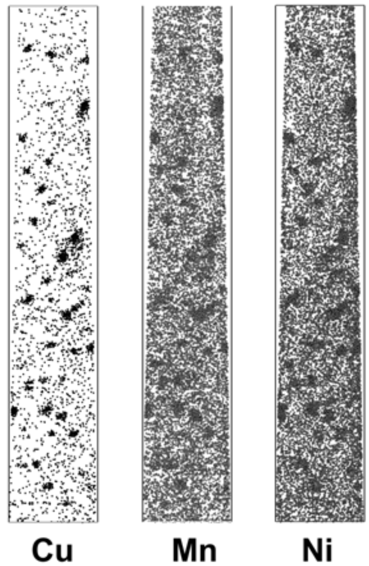

Fig. 1. Three dimensional atom map of defects in neutron irradiated RPV weld (box width=20 nm).

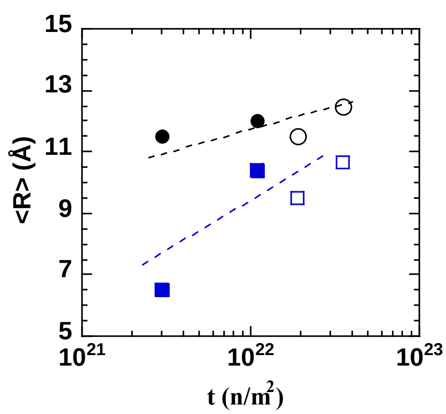

Fig 2. Mean precipitate radius for two irradiated steels obtained by SANS.

Computer Simulation

Atomistic simulation methods, including molecular dynamics (MD) and Monte Carlo (MC), have been used to investigate the formation and evolution of the radiation-induced defects. MD simulations displacement cascades of have provided a detailed description of primary damage formation [3]. Various MC methods have been used to both age the residual defect distributions obtained from the MD, and to investigate the clustering of solutes in an irradiated material. A typical result from the latter work is shown in Fig. 3. This figure shows a snapshot of an approximately 1.6 nm radius precipitate with a composition of 60% Cu, 5% Ni, 5% Si and 19% Mn. The Monte Carlo predictions are in good agreement with APT measurements that indicate enrichment of Mn and Ni at the precipitate/matrix interface.

MD simulations of the interaction between dislocations and radiation-produced defects have been used to investigate the details of hardening mechanisms. The information obtained from the atomistic simulations is being applied in kinetic models to predict the fluence and temperature dependence of embrittlement.

SUMMARY

Atomistic and mesoscale computer simulations and high resolution microstructral characterization have provided the basis for understanding the underlying physical mechanisms of radiation-induced embrittlement in RPV steels. This information is having an impact on reactor operations and regulatory decision making.

Acknowledgements

Research sponsored by the Division of Materials Sciences and Engineering, U.S. Department of Energy and the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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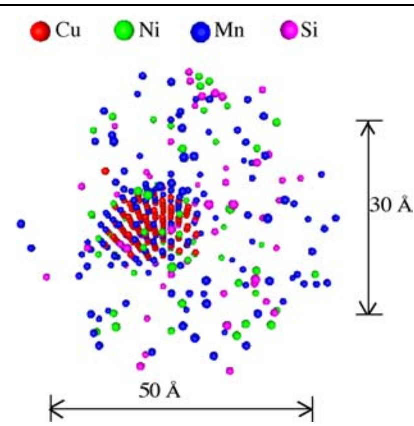

Fig. 3. Results of lattice MC solute clustering simulation in Fe-Mn-Ni-Cu-Si.