Effect of Irradiation Temperature on Mn-Ni-Si Clusters in RPV Model Alloys 03

*Xinrun Chen[1], Shihua Qiao[2], Liang Chen[2], Takeshi Toyama[3], Koji Inoue[3], Bo Li[1], Tatsuya Suzuki[4], Kenta Murakami[1]

[1]The University of Tokyo, [2]Shanghai JIAOTONG University,

[3]Tohoku University, [4]Nagaoka University of Technology

This study presents the third report in a series of investigations on irradiation-induced Mn-Ni-Si (MNS) cluster evolution in reactor pressure vessel (RPV) steels. Building on previous presentations at AESJ-2024 annual meetings, this work focuses on new insights into the interaction between irradiation-induced defects and MNS clusters, based on advanced STEM-EDS and atom probe tomography analyses under various irradiation temperatures.

Keywords: reactor pressure vessels, Mn-Ni-Si precipitates, irradiation hardening, atom probe tomography

1. Introduction

Embrittlement of reactor pressure vessel (RPV) steels under high neutron fluence is known to be closely associated with the formation of nano-scale Mn-Ni-Si (MNS) clusters. These clusters are observed in both high- and low-Cu steels; however, due to their extremely small size (typically a few nanometers), the detailed evolution process remains insufficiently understood. To gain deeper insight into the clustering and structural evolution of MNS phases, we utilized a RPV model alloy with intentionally elevated Mn, Ni, and Si concentrations, subjected to 2.8 MeV Fe^{2+} ion irradiation at temperatures ranging from 573 to 698 K up to 0.9 dpa. The effect of irradiation temperature on irradiation-induced hardening and cluster formation was partially reported in AESJ2024-Annual conference. In this extended study, we focus on the spatial solute distribution within and surrounding each MNS cluster, in conjunction with defect structures observed by STEM-EDS, to investigate the interaction between irradiation-induced defects and MNS clustering. Specifically, we aim to elucidate the role of dislocation loops in the nucleation and growth of Mn-Ni-Si clusters at different temperatures.

2. Experimental

Thin film specimens were prepared using focused ion beam (FIB) milling, followed by flash electro-polishing in a solution of 98% methanol and 2% perchloric acid at 20 V and 213 K to remove surface damage and reduce thickness to ~100 nm. STEM-EDS characterization (Talos F200X G2) was conducted to analyze precipitate composition and associated defect structures. Dislocation loops and black dots were observed using bright-field (BF) and dark-field (DF) techniques, and precipitate structure was investigated via weak-beam dark-field (WBDF) imaging. To quantitatively analyze solute distribution within clusters, regions of interest (ROI) shaped as cylinders and cubes passing through the cluster centers were extracted using IVAS software from 3D atom probe (3D-AP) datasets.

3. Results and Discussion

STEM-EDS observations revealed that MNS clusters frequently nucleate at or near dislocation loops formed during irradiation. IVAS analysis demonstrated a steep solute gradient, with the highest Mn-Ni-Si concentrations at the cluster core, gradually decreasing outward. These results suggest that the formation and growth of MNS clusters are strongly influenced by the evolution of irradiation-induced defects, particularly dislocation loops. Furthermore, the dependency of MNS cluster features on irradiation temperature appears to correlate with changes in defect structure and mobility, indicating that defect–solute interactions play a crucial role in the clustering process.

4. Conclusion

This study confirms that irradiation temperature significantly influences the microstructural evolution of MNS clusters in RPV model steels. The observed coupling between dislocation loop formation and MNS precipitation emphasizes the importance of defect-assisted nucleation mechanisms. These findings provide valuable input for understanding embrittlement behavior in RPV steels and contribute to the refinement of predictive models for long-term reactor operation.