Microstructural bases of embrittlement of VVER-440 RPV welds

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Introduction

Irradiation embrittlement is caused by formation of various lattice defects like dislocations and precipitates in the metal matrix. Practically no thermal embrittlement is observed even during long-term exposure at plant operation temperature (~300 ˚C). In radiation, field diffusion is enhanced by vacancies and interstitials created in collision cascades. Steels form thermodynamically unstable microstructures in fast cooling. E.g. solubility of copper in iron at 300 ˚C is very low, and Cu-enriched precipitates form in high copper steels enhancing embrittlement. In old VVER-440 welds embrittlement is caused primarily by phosphorus, but the mechanism is still subject to research.

Irradiation induced microstructures

With **small angle neutron scattering** (SANS) size distribution of small formations can be rigorously determined. Figure 1 shows the size distribution of formations in varying irradiation-annealing conditions.

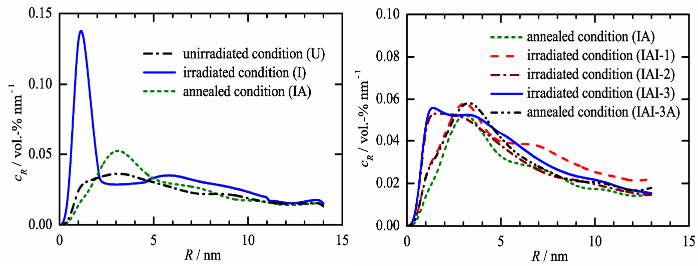

Figure 1. Size distribution of irradiation induced formations in model weld 501 measured by SANS. [1]

Figure 2 shows typical Cu, C, Si, Mn, Ni, P and V atom maps determined by **atom probe tomography** (APT) for un-irradiated (U), irradiated (I), post-irradiation annealed (IA) and re-irradiated (IAI) conditions. The APT results show the formation of Cu-rich solute clusters (CRCs) during the initial irradiation and the subsequent coarsening during annealing. After re-irradiation, new CRCs have emerged.

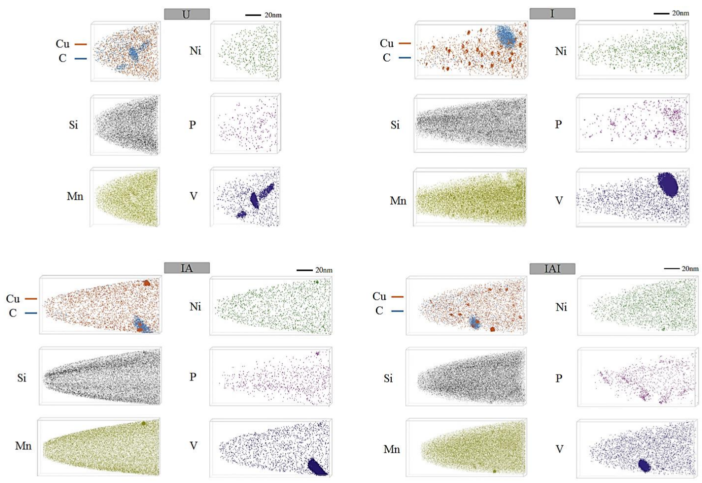

***Figure 2.** Typical atom maps of Cu, C, Si, Mn, Ni, P and V for model weld 501.* [2]

With APT, the atomic content and size distribution of defects can be determined. Figure 3 indicates the composition of the formations in various irradiation-annealing conditions. With annealing studies the formations can be classified based on the order of dissolution of the defects. [2, 3]

Electrical resistivity measures distortions of the Fe lattice. If Cu is dissolved in the matrix, resistivity is higher than in case of Cu bound in large precipitates. Resistivity as a function of annealing time is shown in Figure 4. During the first 5 minutes resistivity of the irradiated conditions grows by 1 %, where after it remains constant up to 30 minutes. This first reaction can be related to disappearance of P from the defects or dissolution of small defects. Finally resistivity of irradiated conditions grows slowly and monotonically. This can be related to dissolution of small or large defects. Resistivity of annealed conditions does not grow during the first 110 minutes.

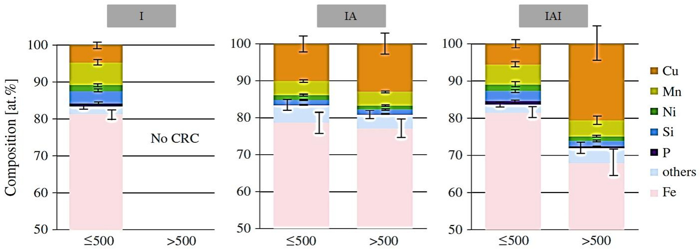

***Figure 3.** Composition of irradiation-induced defects measured by APT for a model weld 501. Average solute atom concentration in CRCs with less than 500 and more than 500 atoms.* [2]

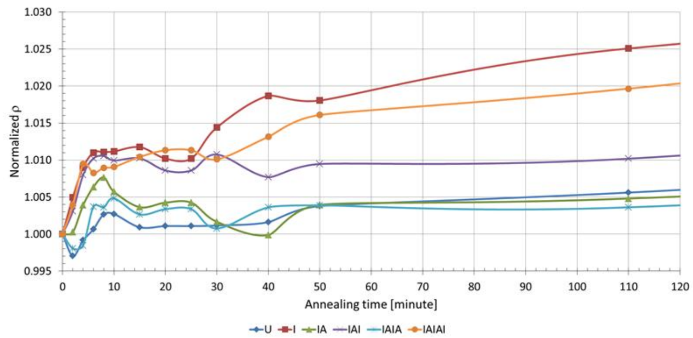

***Figure 4.** Electrical resistivity of model weld 501 as a function of annealing time in isothermal annealing at 420 ˚C.* [4]

Results

The defects formed during irradiation in high-phosphorus VVER-440 steels are rather similar to the defects found in other irradiated steels. They consist of Cu, Mn, Ni, Si and P atoms and the enrichment factors in the defects compared to un-irradiated matrix are approximately 30 for P, 30 for Cu, 20 for Ni, 10 for Si and 5 for Mn. The ~1 nm size defects disappear in annealing. During subsequent re-irradiation the small size population appears again and in each subsequent annealing it disappears. The large size population grows slightly. The defects are located in Fe-lattice but also on grain boundaries and dislocations. During annealing P migrates fully back to Fe-matrix and Si to a large extent. P and Si atoms are small compared to other constituent atoms and hence their mobility is high. P is not bound to the defects at the annealing temperature of 475 ˚C but the other elements are.

Conclusions

Irradiation-annealing-re-irradiation dynamics of irradiation induced defects was well characterized. Essential for reactor pressure vessel annealing is the full dissolution of small size defects (~1 nm) and growth of large size defects (~3 nm) during annealing, which leads to almost full recovery of mechanical properties. The role of phosphorus could not been identified and, for the identification, a correlation of mechanical properties with microstructure in well defined conditions, i.e. during isothermal annealing, is required.

References

[1] Philosophical Magazine Vol 87 No. 12 (2007).1855-1870
[2] Acta Materialia 61 (2013) 5236–5246
[3] Journal of Nuclear Materials 449 (2014) 207-212
[4] VTT Research Report VTT-R-00163-15

Acknowledgements

The work was financed by the State Nuclear Waste Research Fund (VYR), VTT, Fortum Ltd and SSM as part of the SAFIR2014/SURVIVE2014 project.

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