Effect of neutron irradiation on NF616 (Grade 92) at LWR and fast reactor relevant temperatures

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ABSTRACT:

Ferritic-martensitic (F-M) steels are being considered as candidate in-core structural materials for fast reactors and advanced light water reactors (LWRs) due to their excellent resistance to radiation-induced void swelling, microstructural stability, thermal conductivity, and superior irradiation creep properties. HT-9 (12Cr-1MoWV) being the first-generation F-M steel has a relatively large database for irradiation response, mechanical properties, and microstructure. The second-generation F-M steel is T91 (Mod 9Cr-1Mo; optimization of C, Nb, V, N) and its microstructures and mechanical properties after neutron irradiation have also been reported quite extensively. The third-generation F-M steel that shows promise with improved high temperature strength and radiation damage tolerance is NF616 (9Cr-2W-0.5Mo; partial substitution of W for Mo). Based on elevated temperature creep-rupture strength and impact toughness, NF616 is preferred over HT-9. NF616 is being considered for nuclear applications due to its greater strength that tends to provide greater safety margins, design flexibility and lower cost of components. Although elevated-temperature mechanical properties favor NF616, neutron irradiation data is very limited. Hence, to get a comprehensive understanding of the radiation tolerance of NF616, it is essential to study samples irradiated at various doses and temperatures and compare with HT-9 and other FM steels.

The objective of this NSUF (Nuclear Science User Facilities) post irradiation examination (PIE) project is to perform comprehensive transmission electron microscopy (TEM), atom probe tomography (APT) and neutron scattering studies on NF616 samples that were neutron irradiated in the Advanced Test Reactor (ATR) at various temperatures (240-469°C) and doses (3-8 dpa). Tensile and microhardness testing of neutron irradiated NF616 and HT-9 samples were recently completed at PNNL using NSUF RTE (Rapid Turnaround Experiment) awards #1687 and #2879. Our recent work showed that NF616 exhibited higher radiation hardening ($\Delta\sigma_y$) at slightly higher irradiation temperatures (ATR; 388°C and 452°C; 4 dpa) than HT-9 (that was side-by-side neutron irradiated; thus identical temperatures, doses, dose rates and irradiation species), however, it exhibited lower $\Delta\sigma_y$ than HT-9 and T91 at slightly lower irradiation temperature (ATR: 295°C/6 dpa). NF616 and HT-9 have considerable differences in their chemical composition (Cr: 9 vs. 12%; Mo: 0.5 vs. 1%; W: 2 vs. 0.5%; Ni: 0.2 vs. 0.5%; Si: 0.1 vs 0.2%; C: 0.1 vs 0.2%) and heat treatment. Maximum impact of this work will be obtained by performing microstructural characterization of these neutron irradiated NF616 samples to correlate the measured hardening with chemistry and microstructural features. This would the first comprehensive PIE study on neutron irradiated NF616 to obtain APT, TEM and neutron scattering data in order to correlate with the existing mechanical data on NF616, and to directly compare with HT-9 over a wide range of identical neutron doses and irradiation temperatures (from a side-by-side irradiation) to identify the effect of chemistry and heat treatment on the irradiation induced changes in the mechanical properties.

Efforts will be made to evaluate the irradiation-induced clusters, cavities, and dislocation loops, and identify the thermal and irradiation induced second phase precipitates (such as α′, Ni/Mn/Si) to understand their influence on the mechanical behavior. To understand the contributions to irradiation hardening, the dispersed barrier-hardening model will be employed to determine the changes in yield strength induced by each type of obstacles, and then compare the measured hardening (tensile and microhardness data obtained using previously funded NSUF projects) with microstructure-deduced hardening contributions obtained from the proposed APT, TEM and neutron scattering studies. By doing this work, our team can contribute to filling the gap in the literature on understanding the irradiation effects on NF616, HT-9 and F-M steels in general. The proposed work will benefit the NE R&D programs involved in developing advanced structural materials with greater radiation resistance. Thus, the proposed work is well-aligned with the Office of Nuclear Energy's missions and vision for the deployment of next-generation advanced reactors.