Environmentally Assisted Cracking in Light Water Reactors*

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Introduction

Environmentally assisted degradation problems that have been considered during this year include (1) stress corrosion cracking (SCC) of austenitic stainless steels (SS), (2) SCC of ferritic steels used in reactor piping, pressure vessels, and steam generators, (3) fatigue of Type 316 NG SS, and (4) erosion-corrosion of carbon steels in environments characteristic of the secondary system of nuclear reactors.

Cracking in sensitized austenitic stainless steel (SS) piping and associated components in boiling water reactors (BWRs) has been observed since the mid-1960s. Proposed remedies include procedures that produce a favorable residual stress state in the weld regions, replacement of the piping with materials that are more resistant to SCC, and modification of the reactor coolant environment. During this year, studies that have important implications for all three classes of proposed remedies have been carried out. These studies include fracture-mechanics crack-growth-rate tests on Type 316 NG SS and weld overlay specimens in impurity and high-purity environments, finite-element studies on weldments treated by the Mechanical Stress Improvement Process (MSIP) developed by O'Donnell and Associates, heat-to-heat studies of SCC in alternate alloys such as Types 316 NG and 347 Mod SS, and slow-strain-rate tests for the characterization of a variety of potential reactor coolant impurities. In addition, studies on the corrosion potential of irradiated stainless steel have been performed. This work is intended to provide a better understanding of the conditions associated with irradiation-assisted SCC (IASCC) in the core region.

Technical Progress

Fracture-mechanics crack-growth-rate studies of SCC of Type 316 NG SS have continued. Fractographic analysis of specimens from a long-term test that compared the behavior of a Type 316 NG SS specimen with that of a lightly sensitized ($EPR=2\text{ C/cm}^2$) Type 304 SS control specimen confirmed that the cracking in the Type 316 NG SS specimen was primarily transgranular while the cracking in the control specimen was primarily intergranular. Most of the tests were carried out with a maximum stress intensity of $\approx 30\text{ MPa}\cdot\text{m}^{1/2}$, a load ratio R of 0.95, and a frequency of 0.08 Hz, i.e., a nearly constant load with a small superposed cyclic ripple. Under these loading conditions, both materials cracked in water with 0.25 ppm dissolved oxygen and 0.1 ppm SO_4^{2-} . Despite the difference in mode of cracking the crack growth rates in both specimens were similar in this environment, although somewhat higher in the sensitized Type 304 SS specimen. In a high-purity environment with 0.2 ppm dissolved oxygen, crack growth stopped in the Type 304 SS specimen, but it continued in the

Type 316 NG specimen at almost the same rate as in the impurity environment. In simulated hydrogen-water chemistry environments, crack growth halted in both specimens even with sulfate present.

A long term (6000 h) fracture-mechanics crack-growth-rate test to compare the behavior of Type 347 Mod SS with that of a lightly sensitized Type 304 SS control specimen has been completed. The tests were performed in water with 0.25 ppm dissolved oxygen and 0.1 ppm SO_4^{2-} at a load ratio R of 0.95 and a frequency of 0.08 Hz. The maximum stress intensity was $28 \text{ MPa}\cdot\text{m}^{1/2}$ for the first ≈ 5300 h; the maximum stress intensity was raised to $32 \text{ MPa}\cdot\text{m}^{1/2}$ for the next ≈ 500 h and to $36 \text{ MPa}\cdot\text{m}^{1/2}$ for the last ≈ 200 h. No crack growth was observed in the Type 347 Mod SS specimen under any of these loading conditions. The test was finally halted because of excessive crack growth in the control specimen. Similar tests are now underway on a Sumitomo heat of Type 316 NG SS and a French CF3 cast SS.

Fracture-mechanics crack-growth-rate tests were also completed on specimens fabricated from a pipe with a weld overlay. One specimen was tested initially in a high-purity environment with subsequent impurity additions. The other specimen was tested in an environment with 0.1 ppm SO_4^{2-} . In the high-purity environment, no crack growth was observed after compliance measurements indicated that the crack had reached the weld-overlay interface. Sulfate additions to the feedwater (≈ 0.1 ppm) did induce apparent crack growth as indicated by compliance changes. In the companion test in the impurity environment significant changes in compliance were noted. However, subsequent fractographic analysis showed that in neither case did cracks penetrate into the overlay. Instead the cracks branched as they approached the interface and grew near the interface between the base metal and the overlay. Since the base metal had been heavily furnace sensitized before the application of the overlay, this behavior is not necessarily indicative of the case where sensitization is induced solely by the overlay process.

Finite-element calculations have been performed to assess the sensitivity of MSIP to variations in materials properties and modeling procedures and to parametrically study the effect of the applied strain on residual stresses produced by the process. These calculations show that the stresses are relatively insensitive to variations in materials properties or applied strain. However, the peak strain induced on the inner surface of the pipe in the region under the MSIP tool is a strong function of the applied strain. These calculations indicate that increasing the applied strain from 1 to 2% increases the magnitude of the compressive residual stresses in the vicinity of the weld by ≈ 20 –30%, but increases the magnitude of the peak plastic strain on the inner surface in the area under the tool from ≈ 1.8 –3.8%.

Additional tests have been performed to examine heat-to-heat variation in SCC susceptibility of Type 316 NG and Type 347 Mod SS. Despite the tight chemistry specifications imposed on these materials, significant heat-to-heat variations in susceptibility are observed. Although the microstructures and chemistries have been carefully examined, no consistent correlation has been obtained between these variables and SCC susceptibility. The effect of several organic acids commonly found in reactor coolant water on the SCC susceptibility of sensitized Type 304 SS was investigated. These substances, which arise from chemicals used in power plants, are difficult to detect and cleanup,

but fortunately none of the compounds showed a significant detrimental effect at concentrations of ≈ 1.0 ppm in water with 0.2 ppm dissolved oxygen.

SCC testing of a variety of ferritic steels used in piping, pressure vessels, and steam generators has been initiated. The initial baseline tests are being performed in high-purity water. As might be expected from related work on the fatigue crack growth of ferritic steels in simulated reactor environments, there appears to be a strong correlation between the impurity content of the steels (in particular sulfur) and susceptibility to SCC.

A 1:4 scale mockup of the the Surry Unit 2 tee-elbow geometry that suffered a catastrophic erosion-corrosion failure in December 1986 is being fabricated for testing in an ANL hydraulics facility. The mock-up will be used to perform flow visualization studies to better understand and quantify local mass transfer coefficients in this geometry and to compare these results with the actual wall thinning in the failed component.

Experiments were performed to characterize the effect of the local radiation field associated with a highly irradiated Type 316 SS specimen on the electrochemical corrosion potential (ECP) of the material. No significant differences were observed between the ECPs of unirradiated and irradiated materials. Large positive shifts in the ECP of SS were observed in low-oxygen water under high external gamma radiation fields. These results imply that experiments to study IASCC must be carried out either in reactor or with a strong external source of gamma radiation.