Developing a Mechanistic Understanding of Irradiation-Assisted Stress Corrosion Crack Initiation

Gary S. Was, Maxium N. Gussev, Thomas M. Rosseel
Materials Research Pathway

Irradiation-assisted stress corrosion cracking (IASCC) has been widely recognized as a major degradation mode for reactor core structural materials and is of most concern for reactors with a life extension of 60 to 80 years. Similar to stress corrosion cracking (SCC), IASCC occurs under the combination of applied stress and a corrosive environment in irradiated materials. Neutron irradiation induces a build-up of damage that leads to a change of microstructure (e.g., dislocation loops, precipitates, voids) and microchemistry (e.g., segregation), which can potentially enhance SCC susceptibility.

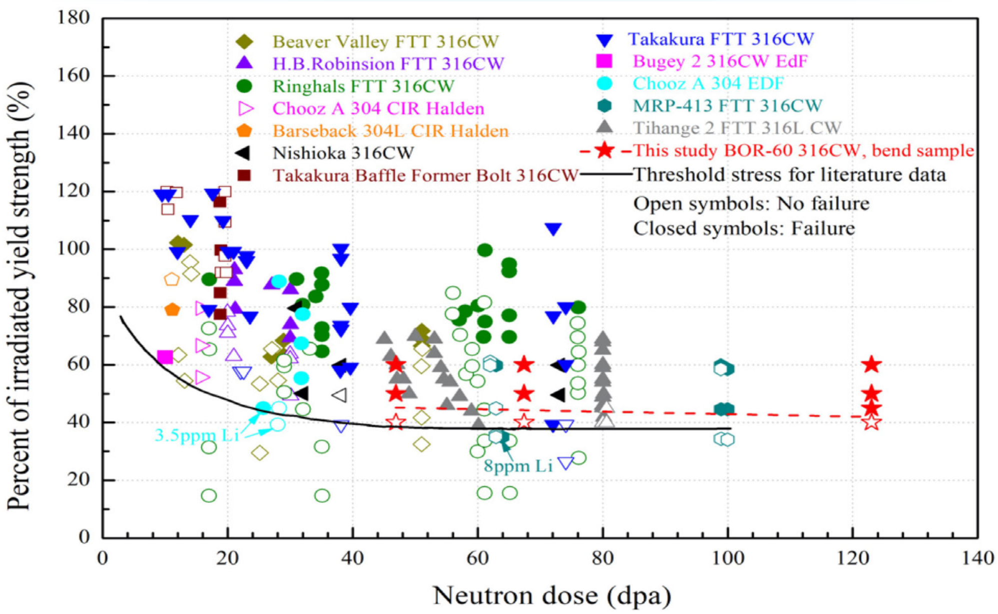
Dose and Stress Threshold Concept

Since the first observation of IASCC in 304 stainless steel fuel cladding in the early 1960s in boiling water reactors (BWRs) and PWRs, many studies have been conducted to investigate the correlation of IASCC susceptibility with irradiation damage. In PWR primary water, the practical IASCC threshold of austenitic stainless steel is approximately 3 dpa, below which no significant degradation of the resistance to SCC is observed. Above this number, IASCC susceptibility was observed to increase with dose up to 73 dpa.

However, it is still unknown whether susceptibility continues to increase with dose to very high dpa corresponding to a service lifetime of 60 to 80 years. IASCC of structural materials consists of two steps—crack initiation and crack growth. The crack growth rate of neutron-irradiated stainless steels (SS) is in the range of 10^{-7} to 10^{-5} mm/s; therefore, the lifetime of a core internal component is mainly determined by the crack initiation time.

Similar to the dose threshold of IASCC susceptibility, a stress threshold below which no IASCC crack initiation occurs has

Figure 10. Stress as a percent of irradiated yield strength vs. neutron dose for IASCC crack initiation in austenitic stainless steels in a PWR primary water environment as determined by O-ring tests [2] for the CW 316 SS samples tested in four-point bend mode in the program.



also been proposed. With the increase of data obtained at higher dpa, lower stress, and longer exposure times in PWR relevant environments, the semi-empirical threshold has dropped from 62% of the irradiated yield strength to 50% and further to 40%. It is not clear whether this value will continue to drop with additional higher dpa data or much longer exposure times, as shown in Figure 10.

Localized Strain as a Mandatory Condition for Crack Initiation

From previous work within the LWRS Program, we established that the intersection of discontinuous dislocation channels with grain boundaries are sites at which extremely high tensile stresses are generated, which are likely the cause of failure at applied stresses well below the bulk yield stress. However, while a necessary condition for SCC, stress alone is insufficient. Our research, described in detail in the sections that follow, has identified what we believe is a precursor condition for the initiation of grain boundary cracks.

Four-point bend samples of cold-worked 316 stainless steel were stressed in simulated PWR primary water at 320°C with 1,000 ppm B as H_3BO_3, 2 ppm Li as LiOH, and 35 cc/kg hydrogen at a strain rate of 4.3×10^{-8} s^{-1} to a fraction of the irradiated yield stress. Figure 11 shows the evolution of an IASCC crack with increasing stress in a cold-worked 316 SS sample irradiated to 125.4 dpa. No cracks were visible at 40% of the yield stress and at 45% of the irradiated yield strength (σ_y), a grain boundary is just visible by virtue of a slight degree of oxidation that appears dark in the secondary election image. At $0.5\sigma_y$, oxidation along the grain boundary is more prevalent and non-uniform, but there is no evidence of a crack. At $0.6\sigma_y$, the boundary has now cracked both above and below the triple junction. The backscattered electron (BSE) image also shows evidence of a localized deformation band (e.g., dislocation channel or twin) intersecting the grain boundary at the crack initiation site. Similar experiments on CW 316 SS samples irradiated to 46.7 and 67.4 dpa revealed that cracking started at $0.6\sigma_y$ and $0.5\sigma_y$, respectively, though the stress increments were larger. While a much different test than the O ring test used in many labs to assess the dependence of IASCC initiation susceptibility on damage level and stress, the bend test results agree well with this database, as shown in Figure 12. The agreement in the magnitude of the stress threshold for cracking between O-ring/C-ring tests and the four-point bend tests indicates that failure in the former test types is controlled by crack initiation processes.

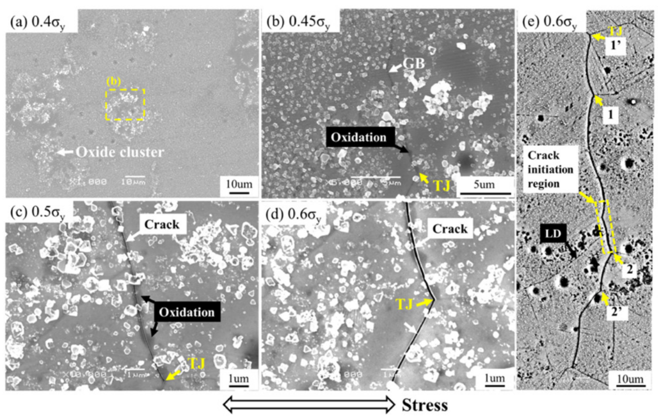


Figure 11. Stages of crack initiation and propagation in a CW 316 stainless steel sample irradiated to 125.4 dpa: (a) oxide cluster formation; (b) GB oxidation after straining to $0.45\sigma_y$; (c) crack initiation at triple junction (TJ) and localized deformation (LD) sites after straining to $0.5\sigma_y$; (d) crack propagation in the direction relatively normal to the applied stress after staining to $0.6\sigma_y$; and (e) BSE image of a long crack.

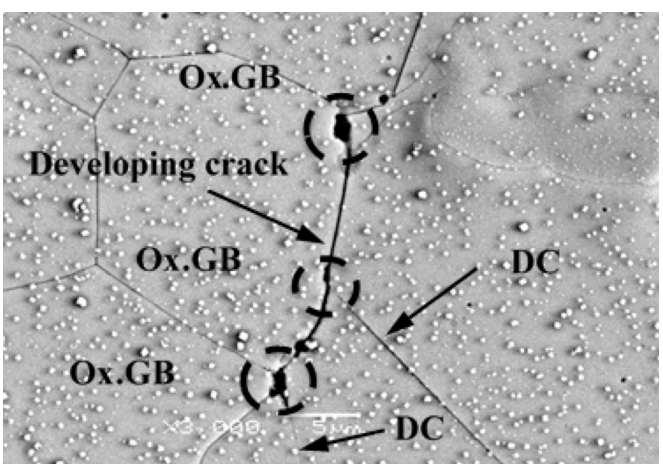


Figure 12. Complexity of processes during IASCC crack initiation: Ox.GB – oxidized grain boundaries, DC – dislocation channels. Dashed ovals show localized corrosion damage (pits) which correlate with DC. SA304L, 5.4 dpa. SEM-BSE image.

New Precursor to IASCC?

As shown in Figure 11, the value of the four-point bend technique developed within the LWRS Program is that this technique can capture the evolution of a crack with stress and in doing so, identify features of the microstructure that correlate with cracking, as well as precursor conditions to cracking such as grain boundary oxidation. Figure 12 provides a look at localized deformation in the form of dislocation channels or deformation twins and triple junctions. This process is sensitive to a mechanical stress level, as depicted in Figure 11, and damage dose. Being a precursor to the crack initiation, GB oxidation may be easy to detect using modern techniques like scanning electrochemical microscopy (SECM). Currently, SECM is a part of an IASCC task.

In summary, the IASCC task within the LWRS Program revealed a new, comprehensive picture of IASCC crack initiation and evolution that provide the opportunity to develop a better understanding of the mechanism by which IASCC cracks initiate. Once a sufficient level of understanding is gained, it will open the path to predictive model development and, ultimately, to developing advanced sensor(s) for detecting critical material conditions while in-service.

Contact Thomas M. Rosseel (rosseeltm@ornl.gov) for more information and a full list of references.