Techniques Towards Understanding the Role of Deformation Localization in Irradiation Assisted Stress Corrosion Cracking of Metals and Alloys

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A nuclear reactor in operation produces a harsh environment for the materials used to fabricate and construct the systems, structures, and components in close proximity to the reactor's power generation features. In addition to the high temperatures and mechanical stresses common to all power generation plants, radiation from fissioning of fuel in the reactor core introduces many new modes of material degradation. A rich literature exists on phenomena such as radiation hardening, radiation embrittlement, swelling, and radiation-induced segregation. However, many degradation processes still remain poorly understood due to their complex nature and multiple contributing variables and parameters. One such process is Irradiation-Assisted Stress Corrosion Cracking (IASCC)—a specific form of degradation that appears in an environment combining corrosive media, mechanical stresses, high temperatures, and elevated radiation levels, all over extended service periods. IASCC continues to impact the operational costs of nuclear power plants and may become more significant as the nuclear reactor fleet continues to age. Understanding, predicting, and controlling IASCC promises significant benefits for reactor operating lifetime extension and improving the understanding of available safety margins.

A significant achievement in understanding IASCC is the recent demonstration of the close connection between deformation processes and crack initiation [1]. A major focus of the Materials Research Pathway is to understand the mechanical behavior of reactor core materials and how deformation of irradiated materials influences corrosion behavior. Thus, an important aspect in gaining control over IASCC is understanding deformation mechanisms and strain localization in irradiated materials. As a metal deforms, it produces displacements along specific crystallographic directions, resulting in slip bands within the microstructure as well as at the surface of the metal. Think of a deck of cards being spread out. For non-irradiated metals, slip bands are generally very uniform (see Figure 2a). For irradiated materials, the generation of slip may be more difficult due to radiation-induced defects in the crystal. But, once started, the material forms stacks of slip bands (or dislocation channels) in which plastic deformation is localized due to the clearing of radiation-induced obstacles. Deformation localization is inhomogeneous in appearance (see Figure 2b).

Inhomogeneity in the dislocation distribution may affect material performance in many ways. First, the coarse slip bands will appear as steps at the specimen surface, and these steps may cause the rupture of the protective oxide film. Second, plastic deformation-induced slip may produce high local stresses at certain microstructural features such as grain boundaries (producing dislocation pile-ups) that are conducive to crack initiation (see Figure 2c). Third, localized and intense microstructure changes may result in differences in the local corrosion behavior further influencing the crack propagation rate (see Figure 2d).

The Materials Research Pathway is using a number of tools to characterize strain-induced processes related to crack initiation and development in materials. One effort is being employed at the University of Michigan, where a unique four-point bend test used in conditions simulating light-water reactor (LWR) environments is providing important results regarding crack initiation behavior. These results have shown that cracks do indeed nucleate at stresses well below yield. This is the first evidence showing that localized deformation occurs well below bulk yield stress and precedes crack initiation at the same site.

A second test method at Oak Ridge National Laboratory uses a scanning electron microscope (SEM) equipped with a miniature tensile stage allowing for in-situ SEM mechanical testing over a wide range of temperatures and loading conditions. In-situ SEM coupled with electron backscatter diffraction (EBSD) analysis allows for lattice misorientation evolution, detail studying of microstructure parameters (like grain orientation and size), estimating density of newly generated dislocations, and measuring in-grain stress distribution. More technical information and the most recent results are available in technical reports [3,4] located on the LWRS Program website at https://lwrs.inl.gov.

These methods of analyzing strain localization influence on IASCC susceptibility provide important insights on the behavior of materials used in core-internal applications of LWRs. Understanding the mechanisms of IASCC and how they affect core internals will improve our understanding of aging related phenomena and can be used to inform plant inspections of locations at increased risk for IASCC, the identification and timing of replacement options for materials where IASCC occurs, and the development of improved models for assessing or predicting IASCC including potential interactions with available plant safety margins.

References

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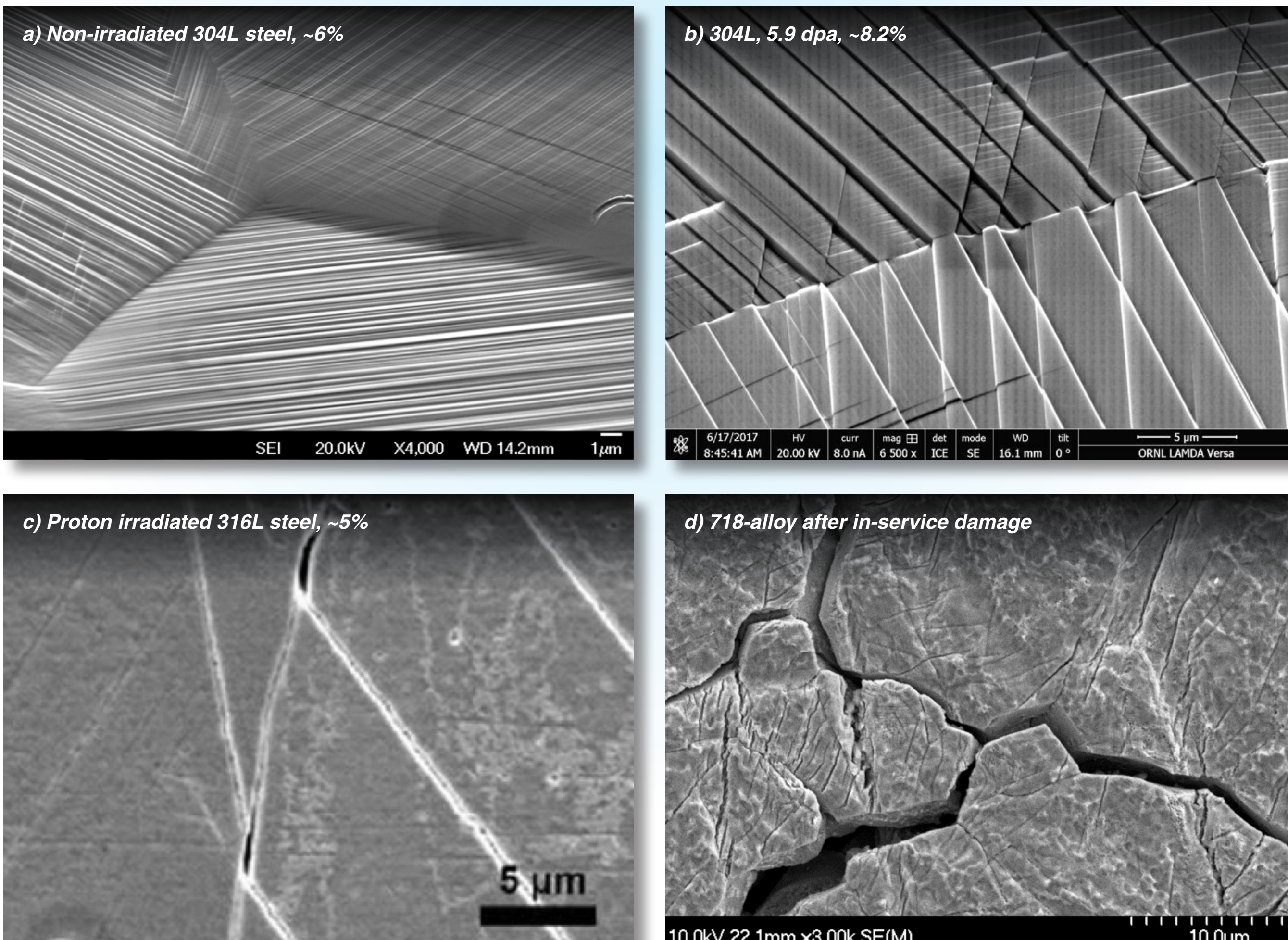

Figure 2. Examples of different strain-induced features on the surface of samples: a) multiple fine slip lines in non-irradiated austenitic 304L steel deformed at 6%; b) coarse deformation bands in neutron-irradiated steel; c) cracks initiated at dislocation channel-grain boundary intersections in proton irradiated 316L steel strained to approximately 5% in simulated nuclear reactor environment; and d) in-service induced stress-corrosion cracks in nickel-base alloy 718 showing multiple slip lines near failure cracks. In the latter, the slip lines have experienced corrosion attack during in-service exposure (the surface was cleaned to remove corrosion products, see [2] for details).