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Deformation microstructure of proton-irradiated stainless steels

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Abstract

The deformation microstructure of proton-irradiated stainless steels may play a key role in explaining their irradiation-assisted stress corrosion cracking (IASCC) susceptibility. In the present study, three model alloys (UHP-304, 304 + Si, 304 + Cr + Ni) with different stacking fault energies (SFEs) were irradiated with 3.2 MeV protons at 360 °C to 1.0 and 5.5 dpa and then strained in 288 °C Ar atmosphere. The deformation microstructure of the strained samples was investigated using scanning electron microscopy and transmission electron microscopy. The results showed that the slip lines interacted with grain boundaries by grain-to-grain transmission, grain boundary sliding or deformation ledge formation at grain boundaries. Expanded channels, which were formed at locations where dislocation channels intersected the grain boundaries or other channels, were found predominately in the low SFE alloys UHP-304 and 304 + Si. The steps and shear strain at grain boundaries caused by channel expansion may increase the IASCC susceptibility in low SFE stainless steels by producing strain concentrations and inducing cracks in the oxide film.

1. Introduction

Irradiation assisted stress corrosion cracking (IASCC) has been a problem in the nuclear industry for the last 30 years. It is most important in core component cracking in boiling water reactors (BWR) and is of growing importance in pressurized water reactors (PWR). An understanding of the mechanism of IASCC is required in order to provide guidance for the development of mitigation strategies. IASCC is affected by changes to both the water environment and the microstructure of the irradiated alloy [1]. However, the changes to the microstructure are the real concern since IASCC can be replicated in the laboratory by conducting post-irradiation stress corrosion cracking tests. In essence, changes to the environment can alter the severity of the cracking, but it is the irradiation-induced change to the microstructure that triggers the occurrence of IASCC.

One of the principal reasons why the IASCC mechanism has been so difficult to understand is the inseparability of the different material changes caused by irradiation. The principal changes due to irradiation; microstructure (formation and growth of dislocation loops, voids, bubbles, phases), grain boundary chemistry (segregation of alloying and impurity elements to or from the grain boundary), and hardening, all follow a similar dose dependence [2]. At any irradiation dose, all three types of

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radiation effects are proceeding together at roughly the same rate, and it is difficult to ascribe the resulting cracking behavior to one or any combination of them. Hence, identification of the primary factors contributing to IASCC is a challenge.

In searching for these primary factors, a systemic study of 14 austenitic alloys was carried out by Busby et al. [3] in simulated light water reactor (LWR) water. By isolating most of the metallurgical variables (microchemistry, microstructure, hardening, etc.) that control IASCC susceptibility of austenitic alloys, they tried to identify the ones with the strongest impact on IASCC. Their study suggests that neither RIS, nor irradiation microstructure, nor hardening alone controls IASCC. However, the potential exists for a correlation between localized deformation and IASCC, where deformation is controlled through stacking fault energy (SFE) or the irradiated microstructure.

Early work showed that SFE may be linked to stress corrosion cracking [4,5]. It has been hypothesized recently [6] that low SFE and irradiation can promote localized deformation by enhancing planar slip. Planar slip results in greater transmission of strain to the grain boundary, which may help rupture the oxide film and initiate a crack at the grain boundary. Furthermore, more dislocations are fed to a grain boundary crack tip through planar slip, which could result in crack extension and a higher crack growth rate.

Although many papers have been published on the deformation microstructure of neutron-irradiated stainless steels, very few deal with proton-irradiated samples. A fair comparison of the deformation microstructures between these two types of irradiations is not available. However, the overall microchemistry, microstructure, hardening and SCC behavior of proton- and neutron-irradiated 304SS and 316SS samples were found to be in excellent agreement [7]. The deformation mode and deformation microstructures are similar in both proton- and neutron-irradiated stainless steels. For example, twinning is the main deformation mode for 316SS at room temperature for both proton- and neutron irradiations [8,9].

As the deformation in an irradiated alloy is mainly localized in the dislocation channels, it is important to characterize the amount of strain accumulated in these channels. This work was done in a previous study [10] and the results showed that at low applied strain, the average strain in the channel is higher in the low SFE alloys than that in the high SFE alloy. The result correlates well with the cracking behavior of these alloys tested in simulated BWR normal water chemistry conditions. However, the deformation microstructure of these alloys may provide an understanding of how these channels can contribute to IGSCC. Therefore, the objective of this study was to understand the potential impact of stacking fault energy (SFE) and irradiation on IASCC susceptibility by examining the deformation microstructure of proton-irradiated alloys.

2. Experimental

2.1. Alloy selection and sample preparation

Three austenitic alloys were selected for this study: alloy E (base 304), alloy H (304 + Si) and alloy L (304 + Cr + Ni). The compositions of these alloys are listed in Table 1 together with their SFEs predicted by Pickering's equation [11]. Among these three alloys, Alloy L has the highest SFE because of its high nickel content and alloy H has the lowest SFE due to the addition of silicon. Generally, the addition of nickel will increase the SFE in an iron-base stainless alloy while the addition of silicon, even small increases within the acceptable limits for stainless steels will significantly decrease SFE.

Alloys were used in the solution-annealed condition without any additional processing or preparation other than surface polishing and cleaning. After the tensile specimens (dimensions are shown in Fig. 1) were made, the surfaces were ground using SiC paper to a final finish of #4000 grit. The samples were then electropolished in a 60% phosphoric,

Table 1
Compositions (wt%) and calculated stacking fault energies of selected alloys

Alloy	Cr	Ni	Fe	Mn	Mo	Si	P	C	S	N	SFE (mJ/m^2)
H	18.2	12.4	67.3	1.0	0.02	1.05	<0.01	0.020	0.002	0.0005	27.5
E	18.8	12.4	67.8	0.9	0.04	0.04	<0.01	0.021	0.003	0.0003	40.5
L	25.2	25.1	48.6	1.0	0.02	0.03	<0.01	0.020	0.002	0.0005	59.7