Effect of proton irradiation on reactor internal material in PWR primary water

Seong Sik Hwang[a*], Yun Soo Lim[a], Sung Woo Kim[a], Min Jae Choi[a], Hyung Ha Jin[a], G. Was [b], O. Toader [b]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero,Yuseong-gu, Daejeon 305-353*
[b]*Michigan Ion Beam Laboratory, University of Michigan, MI, 48109, USA*
[*]*Corresponding author: sshwang@kaeri.re.kr*

1. Introduction

Irradiation assisted stress corrosion cracking (IASCC) of the internals in a pressurized water reactor (PWR) has been considered critical for long-term operation. The cracking mechanism seems to be related with radiation assisted cracking under a high fluence, stress, and temperature environment. The effect of dissolved hydrogen (DH) concentration on the IASCC propagation has been studied [1-4]. It was noted that DH of 0 to 50 cc/kg accelerated the SCC in PWR environments. SCC was observed at up to 100 cc/kg of dissolved hydrogen [1]. The crack growth rate was not increased at high dissolved hydrogen level, but a significant decrease of the average crack growth rate was observed for the lowest dissolved hydrogen. Frutani [2] and Arioka [3, 4] also showed the same trend of DH effect of the SCC growth of stainless steel in a PWR environment.

On the contrary, the effect of DH concentration on IASCC initiation has not been studied much. Stephenson observed high crack initiation density in a primary water (PW) environment than normal water chemistry (NWC)[5]. This means that the low electrochemical potential in hydrogenated water chemistry (HWC) or PWR primary water suppresses the crack growth. This behavior was also observed by other researchers [6, 7]. It may be controversial to say that, regarding the effect of DH on the crack growth and crack initiation, a low DH decreases the crack growth, but a high DH suppresses the crack initiation.

As a background work to see DH concentration effect on IASCC initiation, the present work aims to evaluate the effect of proton irradiation on 316 stainless steels in terms of microchemistry change and IASCC susceptibility in PWR water.

2. Experimental

2.1 Materials

Type 316 stainless steel containing a little high carbon as the reactor internal materials in a PWR was selected for this work. The high carbon stainless steel is considered to be good to see proton irradiation effect clearly. The compositions of the alloy and the proton doses are given in Table 1.

Table 1 Chemical compositions of the test alloy (wt%) and proton dose levels

Material	Cr	Ni	P	Mo	Mn	Proton Doses(dpa)
316 SS	16.7	10.8	0.1	2.0	1.3	
	Si	S	C	Fe		1,3,5,10
	0.59	0.001	0.047	Bal.		

Fig. 1 shows a microstructure of the test alloy non-irradiated condition. It shows a low dislocation density and little grain boundary precipitates. SCC test specimens were fabricated with a gage length of 23 mm by electric discharge machining. Detail of the specimen preparation is described in the other presentation.[8]

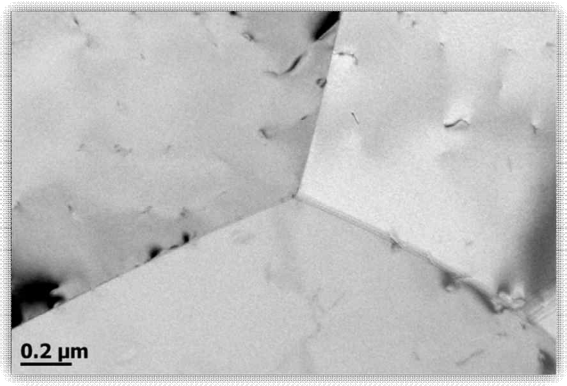

Fig. 1 Microstructure of the non-irradiated sample

2.2 Microstructure analysis

A TEM (Transmission electron microscopy) analysis was conducted in order to see microstructural changes such as the formation of radiation induced segregation at the grain boundary and formation of radiation defects including black dot damage, frank loop and void. Grain boundary composition profiles were measured by using scanning transmission electron microscopy (STEM model JEM 2100F), which is equipped with energy dispersive X-ray spectroscopy (EDS). For a chemical analysis at the grain boundary, we titled the TEM sample to set the GB plane parallel to the beam direction. The INCA system by Oxford, Inc. was used for identification of the chemical compositions at GB using EDS.

2.3 IASCC test

Slow strain rate tests (SSRT) on the non-irradiated and proton irradiated samples were conducted in a multiple-specimen SSRT test system, which can strain four samples in parallel. Water chemicals of the SSRT tests were 1200 ppm B (as H_3BO_3) and 2 ppm Li (as LiOH) chemistry conditions of the PWR primary water. Test details are described in the other presentation.[8]

3. Results and Discussion

3.1 Microchemistry change

The changes in the microchemistry at the grain boundary at a depth of about 10 μm were measured by using STEM-EDS. Fig. 2 shows the chromium and nickel concentration profiles at the grain boundaries of 5 dpa irradiated sample. Cr depletion and Ni enrichment were clearly observed at the grain boundary, which is normal phenomenon on irradiated stainless steels. Further detail analysis results will be presented in the future.

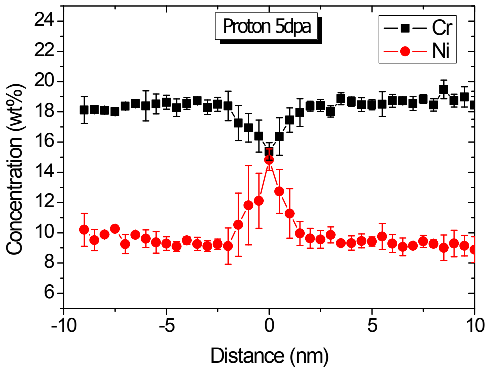

Fig. 2 Chemical concentration profiles at the grain boundaries after irradiation

Fig. 3 shows the TEM images of the proton irradiated austenitic stainless steels, which were taken at a depth of about 10μm. A significant radiation induced damages are clearly visible in the TEM images. Black dots and Frank loops were observed in those TEM samples. At 1 dpa, very fine defects showing black dots were mainly observed in the matrix. However, it is found that the formation of faulted dislocation loop is dominant above 3 dpa. We also measured the number density and average size of the Frank loop, which is visible as a sharp line contrast in these TEM images.

3.2 Cracking susceptibility evaluation

Fig. 4 shows a typical side view and fracture surface of SSRT tensile specimen. All cracks were initiated and propagated with intergranular mode.

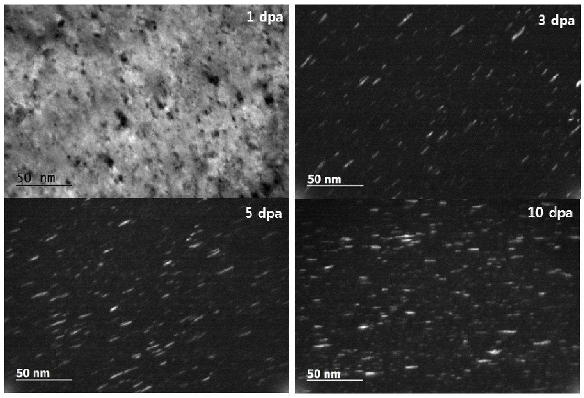

Fig. 3 TEM images of proton irradiated austenitic stainless steels

Preliminary results for evaluating the DH effect on the IASCC initiation under PWR conditions is described in this paper, and the results shown in this article were obtained in 25 cc/kg DH condition only. Similar tests and analyses under 10 cc/kg and 50 cc/kg DH conditions are ongoing.

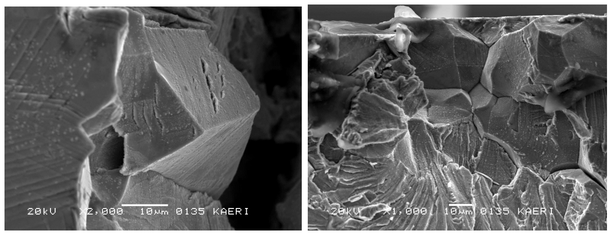

Fig. 4 IASCC fractured specimen after SSRT in PWR water: (a) side view and (b) fracture surface

A parameter of summation of total crack length at the side surface of the tensioned specimens showed a trend of IASCC susceptibility, as shown in Fig. 5. This analysis implies that a summation of the total crack length at the side surface is a good procedure of IASCC initiation susceptibility evaluation on surface damaged specimens such as proton irradiated materials.

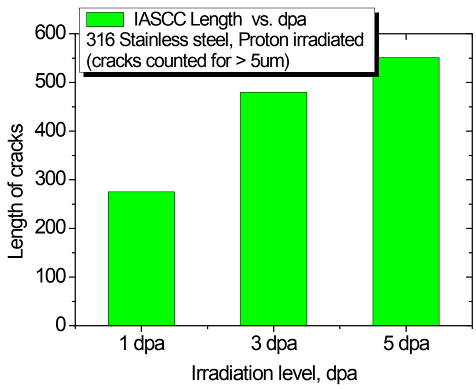

Fig. 5 IASCC initiation susceptibility of proton irradiated 316 stainless steel

4. Conclusions

Proton irradiation on reactor internal material (Type 316 stainless steel) was carried out by using Michigan Ion Beam Facility. Microchemistry change on the irradiated sample was measured; Cr depletion and Ni enrichment were clearly observed as usual. In addition that, faulted dislocation loop was dominant above 3 dpa irradiation. Stress corrosion cracks were initiated and propagated in intergranular mode for all samples. The total crack length at the side surface seems to be a good method for evaluating IASCC initiation susceptibility for proton-irradiated samples.

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REFERENCES

[1] D. Féron, E. Herms, B. Tanguy, J. Nucl. Mater., 427 (2012) 364.
[2] G. Frutani, N Nakajima, T. Konishi, M. Kodama, J. Nucl. Mater., 288 (2001) 179.
[3] K. Arioka, Y. Kaneshima, T. Yamada, T. Terachi, 11th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems -Water reactors, Stevenson, WA, USA, 10–14 August, 2003.
[4] K. Arioka, Effect of Temperature, Hydrogen and Boric Acid Concentration on IGSCC Susceptibility of Annealed 316 Stainless Steel, Colloque International Fontevraud 5, Fontevraud, France, SFEN publications, September, 2002.
[5] Kale J. Stephenson, Gary S. Was, J. Nucl. Mater., 444 (2014) 331.
[6] G.S. Was, Y. Ashida, P.L. Andresen, Corros. Rev. 29 (2011) 7.
[7] O.K. Chopra, J. Nucl. Mater., 409 (2011) 235.
[8] Seong Sik Hwang, et al., IASCC initiation of proton irradiated 316 stainless steels in PWR water, Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 29-30, 2014.