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Comparative Analysis of Crack Density of 20% and 35% Cold Rolled Type 304 SS according to Slow Strain Rate Test using IASCC Test Facility (ITF) Mock-up

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1. Introduction

Irradiation-Assisted Stress Corrosion Cracking (IASCC) has mainly been reported in the Baffle Former Bolts (BFBs) of Pressurized Water Reactor (PWR) power plants after a long operating history, and it has emerged as a major damage mechanism to be considered at the end of life, and during life extension. In IASCC, SCC is promoted by irradiation with high-energy fast neutrons, in addition to the three general SCC conditions, the combinations of materials, environment, and stress [1]. In Korea, the internal structural integrity of the reactor has become an issue after the observation of cracks in the BFB of Kori Unit 1, which was to be decommissioned. Consequently, it has become important to secure demonstration test technology that can conduct research on high-value Kori Unit 1 low-and intermediate-level irradiated materials that experience high utilization rates, for use in high-temperature and high-pressure environments. Based on the current status of domestic and international IASCC equipment construction, the Materials Safety Technology Research Department of the Korea Atomic Energy Research Institute has promoted the task of establishing a reliability verification system for Nuclear Power Plant (NPP) structural materials and parts as part of the project to establish an advanced nuclear power system. In addition, a plan was established to build a demonstration testing facility for neutron irradiated materials. As part of this, ITF (IASCC Test Facility) Mock-up equipment was built in the Korea Atomic Energy Research Institute, and it is being used for educational and testing purposes before the lead hot cell is operated in Research Building 2. Using this equipment, Small Tensile (ST) specimens were manufactured using the Type 304H SS (Stainless Steel) plates used in the internal structures of Shin-Kori Units 3 and 4, and SCC initiation tests were performed.

2. Experimental Methods and Results

In this study, a SSRT (Slow Strain Rate Test) was performed on plate-shaped ST specimens under high-temperature and high-pressure conditions using the ITF equipment, and after the test, cracks in the Type 304H SS specimens were observed using an Optical Microscope (OM) and a Scanning Electron Microscope (SEM). Based on the SSRT under high-temperature and high-pressure conditions, the triangle pattern of the SSRT program of the control panel was used as a representative. After the corrosion cracking test was completed, cracks were observed and the defect length measured. Then, the total crack defect length was divided by a certain area to determine the density of the specimen defects [2]. The specimens used in the test were plate-shaped tensile specimens manufactured separately considering the possibility of mounting inside the installed autoclave, and the SSRT was performed under high-temperature and high-pressure conditions of 325℃ and 15MPa, respectively, inside the autoclave.

2.1 Composition of Equipment

The ITF is a demonstration test equipment for evaluating the stress corrosion cracking characteristics of nickel alloys and stainless steels in an environment simulating the primary water of a PWR. It consists of a primary water circulation system simulating the primary water of a nuclear power plant and measuring and controlling water quality, an autoclave as a high-temperature and high-pressure reactor, and a SSRT that applies and controls stress to the specimen.

2.2 How to Make a Specimen

In this study, ST specimens for the corrosion tests were made by cutting the AR (as-received) specimens from the plate-shaped parent material and 20% and 35% Cold-Worked (CW) materials of the Type 304H SS storage material used in Shin-Kori Units 3 and 4 in Korea. The Heat No. of the Type 304H SS plate used to make the specimens is SD23795, and it was heat-treated at 1040 ℃ and then water-cooled. The chemical composition is as shown in Table **I** [3].

Table I: Mechanical properties of Type 304H SS

Specimen	Heat treatment condition	0.2% YS (MPa)	UTS (MPa)	El (%)	HRB
304H SS-AR	Min. 1040℃, WQ	235.8	710.4	53.4	83.1

Fig. 1 is a schematic diagram of the plate-shaped ST specimen used for the corrosion test. The specifications of the tensile specimen are a shoulder type with a total length of 26 mm, a width of 5 mm, a thickness of 1 mm, a gauge length of 9 mm, a gauge area width of 2 mm, and a shoulder radius R of 1.5 mm. For the corrosion test, one surface of the tensile specimen was polished in sequence with #800, #1200, and #2000 abrasives, and finally polished with a 1 µm alumina suspension. After the surface polishing, ultrasonic cleaning was performed with ethanol for 30 minutes and with pure water for approximately 30 minutes.

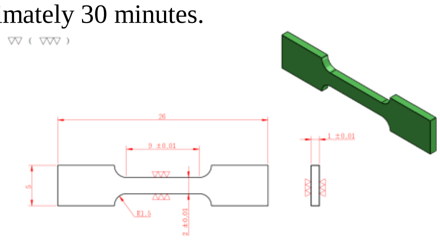


Fig. 1 Drawing of ST specimen for SCC initiation test

2.3 SCC Initiation susceptibility Experiment

To simulate the water quality of the primary system of a NPP, a mixed solution with concentrations of 1200 ppm B and 2.2 ppm Li was used. The water chemical conditions were controlled to be 5 ppb or less of dissolved oxygen, 10 to 30 cc/kg of dissolved hydrogen, 40 µS/cm or less of electrical conductivity, and 6 to 7 pH. The flow rate circulating inside the autoclave was approximately 10 L/h, and the strain rate of SSRT in the SCC initiation test was 1.85×10^{-7} /s. The target tensile length was set to 0.9 mm, which is 10% of the gauge length. After the corrosion test, an OM and SEM (JEOL IT100) were used to observe the microstructure of the specimen surface and the initiation of SCC. In this study, the sensitivity to SCC initiation was determined by measuring the total length of cracks (perpendicular to the tensile axis, Total Crack Length, TCL) using the SemAfore program (JEOL, v.5.21) in the SEM image, and quantifying this as the Total Crack Density (TCD) by dividing it by the observed surface area (Measured Area, MA) [4]. The test period was approximately 6.25 days, and the test was terminated when the tensile force elongation reached 0.9 mm, which is 10% of the gauge length. Fig. 2 is a representative graph showing the load and displacement changes of the Type 304H SS CW20% ST specimen after the IASCC test. Blue is load and light green is the displacement graph. When the initial temperature and pressure of the SCC initiation test of CW20% reached the test conditions of 325℃ and 15MPa, the initial displacement was 5.598 mm, the load was 0.0 kN, and the test was terminated at 6.5031 mm after the final 0.9 mm elongation of the specimen. At this time, the load value was 1.459 kN.

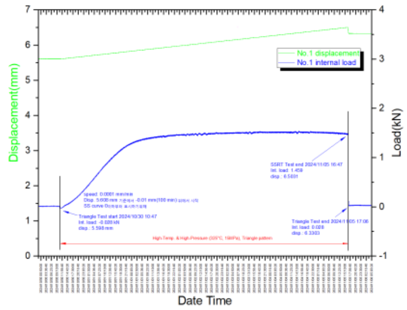


Fig. 2. Load & displacement of ST specimen SS 304H CW20% (Triangle pattern, target value △disp. 0.9mm)

Fig. 3 shows the stress-strain curves of the AR, CW20%, and CW35% specimens at room temperature in air. The yield strength, ultimate tensile strength, and total elongation of the AR specimen were 257 MPa, 852 MPa, and 0.81, respectively, while the yield strength, ultimate tensile strength, and total elongation of the CW 20% specimen were 769 MPa, 990 MPa, and 0.32, respectively, and the CW 35% specimen was 987 MPa, 1139 MPa, and 0.23, respectively. This is believed to be due to cold working.

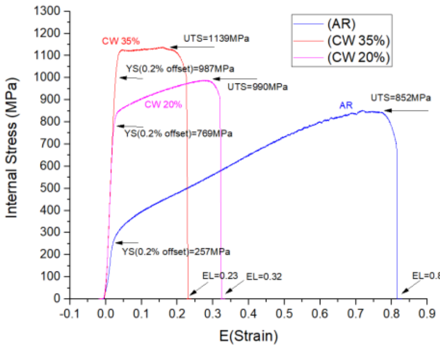
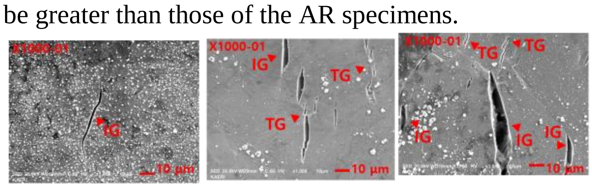


Fig. 3 Stress-Strain curve of AR, CW20% and CW35% ST specimen

Fig. 4 shows SEM images of cracks that occurred on the gauge area surface of the AR specimen, CW20%, and CW35% specimens at a magnification of 1000. In Fig. 4(a), the cracks in the AR specimen occurred in the form of IG (intergranular) along the grain boundary. In contrast, Fig. 4(b)(c), the cracks of the CW20% and CW35% specimens occurred in the TG (transgranular) form that propagated into the grains along with the IG form, and all cracks were determined to be SCC. Overall, the size and number of SCCs on the surface of the CW20% and CW35% specimens were confirmed to be greater than those of the AR specimens.



(a) (b) (c)

Fig. 4. Defect crack detail of SS304 AR(a), CW20%(b), CW35%(c) ST specimen in SEM (X1000)

In order to quantitatively compare and analyze the SCC initiation sensitivity of AR and CW20%, CW35% specimens, TCL was measured from 200x SEM images, and this was quantified as TCD divided by the observed MA, which is presented in Table II. L and C in Table II represent Center (C) and Left (L) in the gauge length area.

Table II: Total Crack Length (TCL), Measured Area (MA) and Total Crack Density (TCD) obtained from various regions on AR, CW20% and CW35% ST specimens after SCC initiation tests

Specimen	AR		CW20%		CW35%	
Measured region	L	C	L	C	L	C
TCL(mm)	2.40	2.44	14.52	16.14	14.16	11.57
MA(mm^2)	1.48	1.46	1.20	1.20	1.17	0.93
TCD(mm^{-1})	1.62	1.67	12.11	13.49	12.05	12.42
Average TCD(mm^{-1})	1.64		12.80		12.24	

When comparing the average crack density, the SCC initiation sensitivity of the CW20% and CW35% specimens was found to be approximately 7.8 and 7.4 times higher, respectively, compared to the AR specimens.

3. Conclusions

In this study, a SSRT was performed at a speed of 0.0001 mm/min under conditions of approximately 325 ℃ and 15 MPa using ITF equipment on plate-shaped ST specimens, and a large number of microcracks were observed in the Type 304 SS specimens using SEM. Most of the defects observed here were judged to be IGSCC defects. The initiation paths varied depending on the microstructure. Based on the results of the comparative analysis of SCC initiation sensitivity, it is estimated that the environmental properties of cold-worked specimens are more likely to be deteriorated by neutron irradiation than those of Type 304 SS parent material (AR specimens) in the internal structures of nuclear reactors. In addition, we will obtain a lot of data on the IASCC initiation characteristics of internal structures of NPPs through SSRT by securing Type 304 SS specimens of various materials, and use this to prevent damage to NPP components.

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