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IGSCC SUSCEPTIBILITY OF STAINLESS STEEL AND Ni BASE ALLOY IN SIMULATED BWR ENVIRONMENT

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ABSTRACT

In order to evaluate the corrosion performance of Type 304 SS and nickel base alloys, SCC tests were carried out under the simulated BWR in-reactor environment, focusing on the water chemistry parameters such as dissolved oxygen(DO), dissolved hydrogen(DH), hydrogen peroxide, and corrosion potential. The effects of short-lived radicals on SCC behavior were examined with Type 304 SS in gamma-ray field. A good correlation between IGSCC fracture surface ratio and corrosion potential was observed in slow strain rate tests for Type 304 SS, and no IGSCC was observed at the corrosion potential lower than -200 mV_{SHE}. When the environment comprised same DO, DH, and hydrogen peroxide concentrations at specimen surface, the effect of gamma ray irradiation was negligible. Alloy 182 exhibited the interdendritic SCC at the corrosion potential higher than 10 mV_{SHE}, while Alloy 600 was not susceptible to SCC in this study. The comparative susceptibility of tested materials to SCC was discussed in relation to the water chemistry modification technique with hydrogen dosage.

1. INTRODUCTION

In nuclear reactors, hydrogen peroxide and short-lived radicals are produced by radiolysis of water molecule, resulting in the corrosion environment different from the out-of-reactor environment. To understand the SCC behavior of reactor internal components, SCC tests should be conducted simulating the in-reactor aqueous environment. Relating to the water chemistry modification of BWR coolant with hydrogen dosage, radiolysis model calculation techniques have been developed(1,2,3), which enable us to estimate concentrations of radiolysis products in BWRs. Meanwhile, corrosion potential of stainless steel (SS) has been measured in the BWR reactor during hydrogen water chemistry (HWC) operation(4). Through these efforts, the corrosion environment in BWR are being elucidated. In the present study, SCC tests were conducted with Type 304 SS and Ni-base alloys in high temperature water, simulating the concentrations of oxygen, hydrogen and hydrogen peroxide in BWR. The concentrations were estimated with radiolysis model calculation for normal water chemistry (NWC) and HWC conditions. The effects of short-lived radicals on SCC behavior were examined with Type 304 SS in gamma-ray field.

2. EXPERIMENTAL METHOD

Test materials were Type 304 SS, Alloy 600, and Alloy 182 of which chemical compositions and heat treatment conditions are shown in Table 1. Alloy 600 specimens were machined from forged sample, while Alloy 182 specimens were machined from weld metal on Alloy 600. Different types of SCC tests were carried out in 4 laboratories as shown in Table 2. All SCC tests for Ni-base alloys were performed with a crevice, formed with graphite wool and a metal cover.

After SCC tests, all fracture surface was examined with SEM to verify the SCC occurrence, which was identified by rock-candy type morphology for Type 304 SS and Alloy 600, and interdendritic morphology for Alloy 182. In the slow strain rate tests (SSRTs), the area ratio of SCC in fracture surface, which is denoted "SCC ratio" in this paper, was used to present the comparable susceptibility to SCC. The results of uniaxial constant load (UCL) tests, creviced U-bend tests, and creviced bent beam (CBB) tests were evaluated by "SCC frequency" which is the ratio of the number of specimens in which SCC occurred to the number of test specimens.

3. WATER CHEMISTRY CONDITIONS

Prior to SCC tests, the concentrations of dissolved oxygen (DO), dissolved hydrogen (DH), and hydrogen peroxide in 1100 MWe BWR were calculated using radiolysis model(1,2) for the NWC and HWC conditions. The SCC test conditions on Type 304 SS were determined to simulate the concentrations of oxygen, hydrogen, and hydrogen peroxide at several locations in BWR. An example of calculated distributions of DO and hydrogen peroxide in BWR is illustrated in Figure 1. For Alloy 600 and Alloy 182, test environments were determined in terms of corrosion potential which was controlled mainly with dissolved oxygen.

The DO and DH concentrations were controlled with N_2, O_2, and H_2 gases bubbling into the conditioning tank of test loop. Hydrogen peroxide concentration was controlled by injecting its solution at constant flow rates to the upper stream of the test section. The decomposition rate of hydrogen peroxide in test autoclaves was measured, and excessive amount of hydrogen peroxide was injected to compensate the thermal decomposition. In the case of SSRTs in gamma ray field, radiolysis product concentration was calculated at specimen location. Solution conductivity of loop water was controlled to 0.1 μS/cm and 0.3 μS/cm; the latter was adjusted with sodium sulfate.

4. RESULTS

The SSRT results for sensitized Type 304 SS are summarized in Table 3. Corrosion potential and IGSCC ratio decreased with decreasing the concentrations of oxygen and hydrogen peroxide. A good correlation between IGSCC fracture surface ratio and corrosion potential was observed, and no IGSCC was observed at the corrosion potential lower than -200 mV_{SHE}. When the environment comprised same DO, DH, and hydrogen peroxide concentrations at specimen surface, the effect of gamma ray irradiation was negligible. This implied that short-lived radicals did not have much effect on corrosion environment, and the environmental effects of radiolysis can be simulated with hydrogen peroxide.

The results of creviced SSRT (C-SSRT) for Nickel base alloy are summarized in Table 4, and the results of UCL, creviced U-bend, and CBB tests are summarized in Table 5. Interdendritic SCC (IDSCC) was observed for Alloy 182 in C-SSRT and CBB tests at the corrosion potential higher than 10 mV_{SHE}, while no SCC was observed for Alloy 600 in this study. Alloy 182 exhibited a similar correlation between corrosion potential and SCC susceptibility to that of Type 304 SS, but the critical potential for the SCC occurrence was a little higher.

The effect of water chemistry modification with hydrogen dosage was discussed, utilizing the above SCC test results and the prediction of in-reactor environments with radiolysis model calculation. It is seen, from Fig. 1, that the radiolysis products are distributed heterogeneously in reactor, particularly in the case of partially hydrogenated condition. Sensitized Type 304 SS and Alloy 182, which are susceptible to SCC under the NWC condition, will be protected from SCC under the fully hydrogenated water chemistry condition. However, hydrogen amount should be limited to avoid the unfavorable side effects of hydrogen dosage. The required hydrogen amount should be determined considering the in-reactor location, stress, and microstructure of component materials which should be protected.

5. CONCLUSION

The following conclusions were drawn from SCC tests on Type 304 SS and nickel base alloys carried out under the simulated BWR in-reactor environment.

(1) A good correlation between IGSCC fracture surface ratio and corrosion potential was observed for sensitized Type 304 SS, and no IGSCC was observed at the corrosion potential lower than -200 mV_{SHE}.

(2) When the environment comprised same DO, DH, and hydrogen peroxide concentrations at specimen surface, the effect of gamma ray irradiation on SCC susceptibility of Type 304 SS was negligible.

(3) Interdendritic SCC (IDSCC) was observed for Alloy 182 in C-SSRT and CBB tests at the corrosion potential higher than 10 mV_{SHE}, while no SCC was observed for Alloy 600 in this study. Alloy 182 exhibited a similar correlation between corrosion potential and SCC susceptibility to that of Type 304 SS.

(4) It is expected that sensitized Type 304 SS and Alloy 182, are protected from SCC under the fully hydrogenated water chemistry condition. The required hydrogen amount should be determined considering the in-reactor location, stress, and microstructure of component materials which should be protected.

This study was carried out in the joint study program in Japan conducted by 6 BWR utility companies, 2 BWR plant vendors, and 2 reactor component suppliers.

6. REFERENCE

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Table 1. Chemical compositions (wt%) and heat treatment conditions of test materials.

Material	C	Si	Mn	P	S	Ni	Cr	Fe	Cu	Nb+Ta	Ti	Other	Heat Treatment
Type 304	0.06	0.42	0.83	0.028	0.005	8.41	18.32	bal.	-	-	-	-	620°CX24h,A.C.
Alloy 600 (BHK)	0.06	0.25	0.28	0.007	0.001	75.89	15.37	7.61	0.02	-	-	-	621°CX24h(SR*) + 500°CX24h(LTA**)
Alloy 182 (BHK)	0.047	0.24	2.3	0.003	0.002	71.7	15.1	7.80	0.04	2.1	-	-	
Alloy 600 (IHI)	0.06	0.30	0.49	0.001	0.001	74.84	16.03	8.09	0.00	-	-	-	615°CX10h(SR*) + 450°CX200h(LTA**)
Alloy 182 (IHI)	0.041	0.56	7.44	0.004	0.004	67.30	14.12	7.43	0.12	1.95	0.41	0.081	

* SR:Stress relief, ** LTA:Low temperature annealing

Table 2. Test methods and laboratories.

Materials	Test Method	Specimen	Mechanical condition	Laboratory
Type 304 SS	SSRT	Gage:4mmDX25mmL	$\dot{\varepsilon}=4X10^{-7}/s$	Toshiba
	SSRT (γ-field)	Gage:4mmDX25mmL		
	SSRT	Gage:3.5mmDX20mmL*		Hitachi
	SSRT (γ-field)	Gage:3mmWX2mmTX20mmL**		
Alloy 600	Creviced SSRT	Gage:6mmDX20mmL	***	BHK
600/182	Creviced U-bend	15mmWX4mmTX75mmL	$\varepsilon=20\%$	
	UCL****	Gage:3.6mmDX10mmL	$\sigma=3.5Sm(Sm=16.7\ kg/mm^2)$	
Alloy 182	Creviced SSRT	Gage:2.5mmDX20mmL	$\dot{\varepsilon}=8.3X10^{-8}/s$	IHI
	CBB*****	10mmWX2mmTX50mmL	$\varepsilon=1\%$	

Test temperature was 285 °C (Toshiba) and 288 °C (other laboratories).

* In test No.13, gage:3.5mmDX45mmL

** In Test No.21 & 22, gage:2.8mmWX0.3mmTX5.5mmL

*** $\dot{\varepsilon}=4.2X10^{-4}(\varepsilon=0\sim10\%)$, $\dot{\varepsilon}=4.2X10^{-7}/s(\varepsilon=10\sim40\%)$

**** Uniaxial constant load

***** Creviced bent beam

Table 3. SSRT results for Type 304 SS.

No.	Test environment*			γ-Ray	IGSCC ratio**	Corrosion potential
	O_2 (ppb)	H_2O_2 (ppb)	H_2 (ppb)	(R/h)	(%)	(mV SHE)
1	440	150	50	-	45	110
2	200	100	20	-	28	-15
3	<1	0	150	-	0	-585
4	<440> (336)	<150> (322)	<50> (51)	10^5	55	110
5	<440> (448)	<4> (0)	<0.1> (0)	10^5	24	-35
6	<200> (153)	<100> (214)	<20> (21)	10^5	31	-20
7	<200> (172)	<50> (108)	<0.1> (0)	10^5	25	-50
8	<100> (81)	<50> (108)	<50> (51)	10^5	21	-130
9	<50> (153)	<50> (214)	<0.1> (21)	10^5	16	-140
10	<20> (336)	<10> (322)	<0.1> (51)	10^5	16	-170
11	<20> (18)	<10> (22)	<50> (51)	10^5	15	-200
12	<1> (153)	<0.2> (214)	<150> (21)	10^5	0	-595
13	440	150	50	-	51	70
14	240	570	14	-	50	75
15	120	350	11	-	44	50
16	100	0	50	-	0	-200
17	50	100	10	-	0	-160
18	50	0	50	-	0	-550
19	10	0	150	-	0	-560
20	<240> (440)	<570> (0)	<14> (0)	10^7	48	25∼70
21	<120> (200)	<350> (0)	<11> (0)	10^7	30	45
22	<50> (100)	<100> (0)	<10> (0)	10^7	2	-190
23	<0.2> (<10)	<20> (0)	<1> (0)	10^7	10	0∼-100

No.1 12 : Tested in Toshiba.
No.13 23 : Tested in Hitachi.

* No.1 12:Solution conductivity ≦ 0.1 μS/cm
No.13 23:Solution conductivity = 0.3 μS/cm

** IGSCC ratio = $\frac{\text{(IGSCC fracture area)}}{\text{(Whole fracture surface area)}}$

< > calculated concentration at test specimen's location.

( ) concentration at the inlet of test autoclave.

Table 4. Results of creviced SSRT for Alloy 600 and Alloy 182.

No.	Mater.	Test environment*			Corrosion potential	SCC** ratio
		O_2 (ppb)	H_2O_2 (ppb)	H_2 (ppb)	(mV SHE)	(%)
1	Alloy 600	200	0	0	-65	0
2		200	10	0	-55	0
3		750	0	0	101	0
4		1	0	100	-548	0
5	Alloy 182	18000	0	0	200	85
6		2000	0	0	10	40
7		1000	0	0	30	<1***
8		100	0	180	-100	0***
9		100	0	0	-200	0***

* Solution conductivity≤ 0.1 μS/cm

** IGSCC ratio= $\frac{\text{(SCC fracture area)}}{\text{(Whole fracture surface area)}}$

*** Test was terminated at ε=5%

Table 5. Results of UCL, Creviced U-bend, and CBB test.

No.	Test	Matr.	Test environment*			Corrosion Potential	Test time	SCC** fre-quency
			O_2 (ppb)	H_2O_2 (ppb)	H_2 (ppb)	(mV SHE)	(h)	
1	UCL	600 /182	200	<1	<1	-65	4000	0/12
2			<10	<1	100	-548	3200	0/12
3	Crev. U-bend	600 /182	200	<1	<1	-65	4300	0/20
4			<10	<1	100	-548	4300	0/20
5	CBB	Alloy 182	18000	0	0	250	500	5/10
6			2200	0	0	110	500	1/10
7			50	0	0	60	500	0/10
8			<10	0	100	-300	500	0/10
9			<10	0	200	-450	372.5	0/10

* Solution conductivity ≤ 0.1 μS/cm

** SCC frequency= $\frac{\text{(SCC observed specimen)}}{\text{(Specimen number)}}$

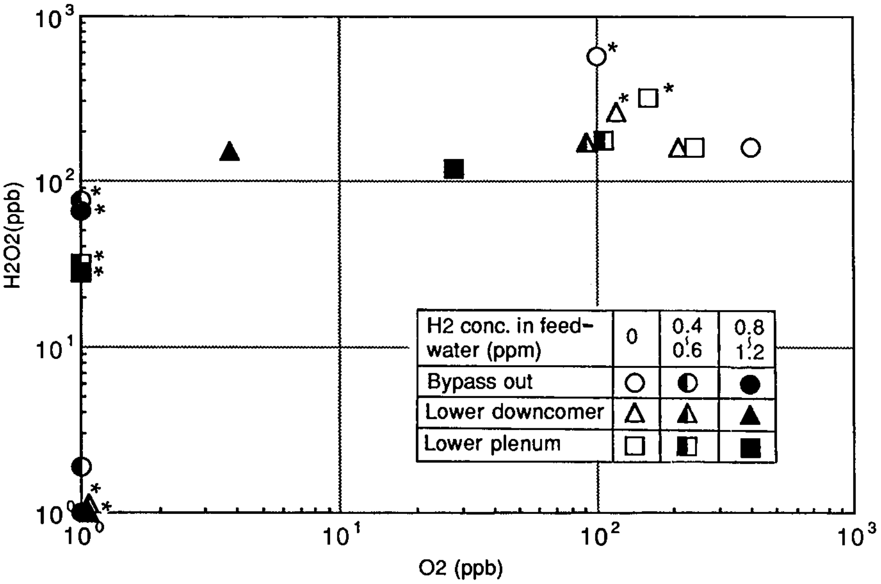

Fig. 1 An example of BWR in-reactor water chemistry estimation for 1100 MWe BWR.
*:calculated in Hitachi(2)
others:calculated in Toshiba(1)