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Stress Corrsion Cracking of Austenitic Stainless Steels in High Temperature Water and Alternative Stainless Steel

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Abstract: In order to clarify the effect of SFE on SCC resistance of austenitic stainless steels and to develop the alternative material of Type 316LN stainless steel for BWR application, the effect of chemical composition and heat treatment on SFE value and SCCGR in oxygenated high temperature water were studied. The correlation factors between SFE values for 54 heats of materials and their chemical compositions for nickel, molybdenum, chromium, manganese, nitrogen, silicon and carbon were obtained. From these correlation factors, original formulae for SFE values calculation of austenitic stainless steels in the SHTWC, SHTFC and AGG conditions were established. The maximum crack length, average crack length and cracked area of the IGSCC for 33 heats were evaluated as IGSCC resistance in oxygenated high temperature water. The IGSCC resistance of strain hardened non-sensitized austenitic stainless steels in oxygenated high temperature water increases with increasing of nickel content~~s~~ and SFE values. From this study, it is suggested that the SFE value is a key parameter for the IGSCC resistance of non-sensitized strain hardened austenitic stainless steels. As an alternative material of Type 316LN stainless steel, increased SFE value material, which is high nickel, high chromium, low silicon and low nitrogen material, is recommendable.

Keywords: *Intergranular Stress Corrosion Cracking, Stacking Fault Energy, Sensitization, Strain Hardening, Crack Growth Rate*

I. INTRODUCTION

In nuclear power plants, austenitic stainless steels are widely applied to many kinds of components, such as vessels, pipes, tubes, valves, etc., due to their excellent properties, for instance, corrosion resistance in various corrosive environment, high strength in high temperature environment, non low temperature embrittlement, high ductility under high neutron-irradiation environment, etc. But, in 1965, the intergranular stress corrosion cracking (IGSCC) was detected in the welded heat affected zone of primary loop for re-circulation (PLR) pipes and emergency core cooling system (ECCS) line pipes made of Type 304 stainless steel of the Dresden No.1 (first BWR)[1].

The root cause of this IGSCC was clarified as the sensitization of austenitic stainless steel pipes and high electrochemical potential of high temperature water environment. The sensitization was caused by high carbon content of austenitic stainless steels and large heat input at the time of welding. The high electrochemical potential of high temperature water environment was caused by the high oxygen content level (higher than 100ppb) in PLR pipelines and water radiolysis due to high gamma ray irradiation near reactor vessel[2]. This IGSCC was detected in many BWRs in a world, in early 1970's [3].

In Japan, Type 316LN stainless steel as the new alternative austenitic stainless steel was developed for PLR pipes and other pipes

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as the one of the countermeasure for this type IGSCC accident [4]. This Type 316LN stainless steel contains low carbon content to avoid sensitization at the time of welding, and also contains high nitrogen content to maintain the strength level of conventional Type 316 stainless steel, in spite of low carbon content.

Type 316LN stainless steel has been widely used for pipe for BWRs in a world. (In United States, this type stainless steel is called as Type 316 NG (nuclear grade) stainless steel [5]).

But, in 2002, SCC in PLR pipes made of non-sensitized Type 316LN stainless steel was also reported in many Japanese BWRs[6], that SCC was initiated from strain hardened (ground before operation) surface exposed to high temperature water, and propagated along the strain hardened region which were highly strained by welding. The hardness of strain hardened area was higher than Hv 250 and the crack depth of the IGSCC was identified thicker than 3mm [6].

It is wellknown that the strain hardening increases with decreasing of the stacking fault energy (SFE) [7]. So, the author of this study idealized that the SCC of Type 316LN stainless steel in high temperature water might be caused by the high strain hardening due to low stacking fault energy (SFE) of this stainless steel. Because, it is wellknown that the SFE value decreases with increasing of nitrogen content [8].

Then, the author has studied on the effect of chemical composition and heat treatment on the SFE value and SCC resistance of austenitic stainless steels in oxygenated high temperature water (accelerated BWR water)[9, 10], to clarify the effect of SFE on SCC resistance of austenitic stainless steels and also to develop the alternative austenitic stainless steel of Type 316LN stainless steel for BWR application.

This paper summarizes the results of the author and co-worker’s comprehensive studies on the effect of cold working and SFE value on SCC resistance of Type 316 stainless steel in oxygenated high temperature water environment to evaluate the performance of Type 316 stainless steel.

II. EXPERIMENTAL PROCEDURES

The SCC resistance of austenitic stainless steels in oxygenated high temperature water was studied for laboratory melted 32 austenitic stainless steels and commercial Type 310S stainless steel by the SCC growth rate (SCCGR) measurement tests. And SFE value measurement tests were conducted for laboratory melted 52 austenitic stainless steels and commercial Types 310S and 316M stainless steels, to clarify the mechanisms on IGSCC for the non-sensitized and strain hardened austenitic stainless steel in high temperature water.

Materials

In order to evaluate the effects of chemical compositions and heat treatment conditions on SFE values for austenitic stainless steels, three kinds of heat treated materials were used for 52 laboratory-melted heats and two commercial heats (Types 310S and 316M : totaling 54 heats), in this study. The three heat treatments were; solution heat treating at 1,050ºC for one hour and then water cooling (labeled SHTWC); furnace cooling after solution heat treating (labeled SHTFC); and, finally, ageing at 650ºC for two hours after SHTWC (labeled AGG).

For evaluation of SCC resistance for austenitic stainless steels, 32 laboratory-melted heats and one commercial heat (Type 310S) were applied to SCCGR measurement test in oxygenated high temperature water.

Table I. Chemical compositions and test matrix of test materials

No.	No.	Features	Chemical Composition by Product Analysis (Wt%)								SFE Measured Value (mJ/m2)						SCCGR Tested Oxygenated	
			C	N	Si	Mn	Ni	Cr	Mo	Others	SHTWC	STD	SHTFC	STD	AGG	STD	HT A	HT B
41	L41	High Purity 316 Standard	0.004	0.003	0.020	0.03	15.60	17.5	2.5		49.6	1.22	50.6	0.98	51.6	0.74		○
42	L42	Al, Nb, Ti, -316	0.020	0.009	0.030	0.03	15.60	17.6	2.5		50.8	1.36	51.3	1.56	54.6	1.30		○
43	L43	LowSi, Mn, N, -316	0.020	0.002	0.010	0.03	14.00	17.1	2.4		46.6	1.22	47.3	0.78	50.3	1.16		○
44	L44	LowC-N-Si, HighNi-Cr, -316	0.005	0.001	0.010	0.19	15.60	17.7	2.6		49.8	1.40	51.2	0.64	52.8	0.68		○
45	L45	Med. N-Mn, -304	0.026	0.038	0.100	1.18	11.20	18.9	0.3		34.5	0.94	34.7	0.50	35.2	0.94		○
46	L46	LowC-N, Med. Si-Mn, -304	0.016	0.008	0.100	0.85	10.80	19.0	0.3		33.5	0.80	34.1	0.88	35.0	0.82		○
51	L51	High Purity 316L Standard	0.003	0.004	0.014	0.02	12.10	17.0	2.6		40.2	0.68	41.0	0.68	42.0	0.62		
52	L52	Effect of C	0.009	0.003	0.016	0.03	12.20	17.0	2.7		40.8	0.82	41.2	1.14	42.5	0.92		
53	L53	Effect of C	0.018	0.004	0.014	0.03	12.00	16.9	2.7		39.8	1.24	41.0	0.96	42.1	1.12		
54	L54	Effect of C	0.046	0.004	0.030	0.03	11.90	16.7	2.7		39.3	0.88	40.4	0.80	41.8	1.96		
55	L55	Effect of C	0.075	0.003	0.030	0.03	12.00	17.0	2.6		39.5	0.78	40.4	0.74	41.8	1.08		
56	L56	Effect of N	0.003	0.013	0.015	0.03	12.00	16.9	2.6		38.7	0.62	40.0	1.12	41.4	1.12		
57	L57	Effect of N	0.003	0.023	0.019	0.03	12.00	16.8	2.7		39.0	1.46	40.2	1.52	41.6	0.68		
58	L58	Effect of N	0.003	0.061	0.018	0.03	12.10	17.1	2.6		38.5	0.78	39.9	0.96	41.2	1.02		
59	L59	Effect of N	0.003	0.087	0.029	0.03	11.80	16.8	2.5		36.9	1.18	38.1	1.34	39.7	0.64		
60	L60	Effect of Mn	0.004	0.004	0.024	0.21	12.20	17.1	2.7		39.1	1.48	40.4	0.72	41.1	0.64		
61	L61	Effect of Mn, N	0.003	0.041	0.020	0.21	12.00	16.7	2.7		38.6	1.44	39.5	1.12	41.1	0.60		
62	L62	Effect of Mn	0.004	0.004	0.024	0.78	12.00	16.6	2.7		40.8	0.92	41.2	0.60	41.7	0.64		
63	L63	Effect of Mn, N	0.003	0.042	0.020	0.8	11.90	17.0	2.6		38.8	0.86	39.7	1.16	41.1	0.84		
64	L64	Effect of C, Mn	0.055	0.003	0.041	1.37	12.00	17.1	2.7		41.9	1.00	42.7	0.84	43.0	1.00		
65	L65	Effect of Mn, C	0.004	0.046	0.020	1.46	12.10	17.2	2.5		40.6	1.00	41.5	1.02	42.2	0.98		
66	L66	Effect of Mo	0.003	0.002	0.022	0.02	12.00	16.9	0.9		36.1	0.72	36.8	0.72	37.3	0.74		
67	L67	Effect of Mo	0.003	0.001	0.020	0.02	12.00	16.85	0.32		35.5	0.78	36.3	0.62	36.7	0.00		
71	L71	High Purity High Ni, Cr, 316	0.0006	0.001	0.010	0.02	15.32	17.7	2.45		49.0	0.94	49.7	1.38	50.3	0.00		
81	L81	High Purity High Ni, Cr, 316	0.002	0.0011	0.03	0.02	15.75	16.95	2.28		49.7	0.52	50.3	0.66	51.3	0.00		
82	L82	Effect of Mn	0.002	0.0043	0.03	3.95	15.72	17.13	2.29		52.0	0.86	52.5	1.02	53.6	0.00		
83	L83	Effect of Cr	0.003	0.0071	0.02	0.03	15.4	13.09	2.29		46.8	0.56	48	0.74	48.9	0.00		
84	L84	Effect of C	0.074	0.004	0.03	0.02	15.65	17.02	2.28		48.9	0.62	49.8	0.82	50.9	0.00		
85	L85	Effect of N	0.002	0.0974	0.03	0.01	15.56	16.95	2.29		46.3	0.84	48.0	1.10	49.4	0.00		
86	L86	Effect of Si	0.003	0.0069	1.82	0.03	15.51	13.35	2.31		43.4	0.72	44.0	0.92	46.5	0.00		
310S	C310S	Commercial 310S	0.050	0.042	1.08	1.83	19.85	24.11	0.04		53.1	2.12	53.6	1.14	55.5	0.00	○	
316M	C316	Commercial 316	0.05	0.04	0.52	1.81	13.11	16.08	2.11		43.1	0.58	44.0	0.56	44.5	0.00		
1	N1	Lab.Melt 316LN Standard	0.018	0.097	0.49	0.83	12.50	16.46	2.30		39.5	0.84	41.1	0.90	41.7	0.00	○	○
2	N2	Effect of Cr	0.020	0.099	0.49	0.83	12.57	18.09	2.33				42.3	0.90			○	
3	N3	Effect of Cr	0.020	0.097	0.48	0.80	12.70	20.07	2.34				45.5	0.76			○	
4	N4	Effect of Cr	0.021	0.109	0.49	0.83	12.48	24.82	2.34				47.5	1.46			○	
5	N5	Effect of Cr, Ni	0.022	0.108	0.50	0.84	18.57	25.08	2.32				53.2	2.48			○	
6	N6	Effect of Cr, Ni	0.021	0.085	0.48	0.80	14.84	22.68	2.40				48.3	1.34			○	
7	N7	Effect of Si	0.019	0.105	0.21	0.84	12.58	16.48	2.42				42.1	1.10				
8	N8	Effect of Si	0.017	0.101	0.06	0.80	12.58	16.35	2.30				41.9	1.38			○	
9	N9	Effect of Si, Mn	0.018	0.127	0.04	1.01	12.53	16.47	2.34				41.9	0.78			○	
11	N11	Effect of Zr	0.019	0.101	0.05	0.80	12.57	16.42	2.40	Zr:0.005							○	
13	N13	Effect of O	0.015	0.111	0.50	0.80	12.30	16.36	2.29	O:0.008							○	
15	N15	Effect of Al, Ti	0.020	0.0011	0.52	0.87	12.50	16.37	2.32	Al:0.19 Ti:0.21							○	
16	N16	Effect of Nb	0.020	0.0015	0.47	0.87	12.49	16.36	2.30	Nb:0.19							○	
17	N17	Effect of V	0.019	0.0023	0.49	0.85	12.56	16.40	2.33	V:0.20							○	
18	N18	Effect of Ni	0.019	0.107	0.50	0.83	14.78	16.42	2.31				48.9	0.66			○	
19	N19	Effect of Ni, Cr, Low N, Si	0.021	0.001	0.01	0.74	11.11	17.95	2.26				37.6	0.90			○	
20	N20	Effect of Mn	0.019	0.114	0.50	1.95	10.08	16.28	2.30				37.5	1.36			○	
21	N21	Effect of Mn	0.019	0.094	0.50	0.02	12.64	16.43	2.29				41.5	0.78				
22	N22	Effect of Mo	0.018	0.087	0.50	0.84	12.58	16.44	0.95				41.6	0.76			○	
23	N23	Effect of Ni, Cr, Mo, Low N, Si	0.018	0.001	0.02	0.74	14.87	22.89	1.01				50.0	1.36			○	
24	N24	Effect of Ni, Cr, Low N, Si	0.020	0.002	0.02	0.75	25.23	23.01	2.33				66.0	2.52			○	
25	N25	Effect of Ni, Cr, Low N, Si	0.017	0.002	0.00	0.74	20.18	24.61	2.34				55.5	1.70			○	
26	N26	Effect of N	0.018	0.033	0.49	0.87	12.63	16.30	2.27				40.9	1.14			○	
27	N27	Effect of N	0.018	0.003	0.49	0.75	12.78	16.48	2.27				40.5	1.02			○	
31	N31	Effect of C	0.024	0.0034	0.02	0.83	14.67	17.41	2.31				49.5	1.26			○	
32	N32	Effect of C	0.030	0.0006	0.01	0.82	15.97	18.07	2.30				50.4	1.26			○	
33	N33	Effect of C	0.023	0.006	0.02	0.85	13.93	16.85	2.33				47.9	1.42			○	
S	S	Effect of C	0.068	0.002	0.02	0.01	13.77	17.89	2.23								○	

🟪 : Type 316LN Stainless Steel

🟥 : Sensitized Stainless Steel

🟨 : Objective Element for Studying on the "Effect of Element on SCCGR"

🟦 : Candidate Alternative Stainless Steel

STD : 95% Confidence Interval

HT A : Forged + SHT (1,050℃ x1h WC) + Sensitized (650℃ x 2h) + 15% Cold or Warm Rolled

HT B : Forged + SHT (1,050℃ x1h WC) + 15% Cold or Warm Rolled

HTC : Forged + SHT (1,050℃ x1h WC) + 15% or 25% or 30% Cold Rolled

The chemical compositions of these test materials and test matrix of this study were shown in Table 1(open circle marked heats were applied to SCCGR measurement test). These laboratory-melted heats were 30 kg vacuum induction melted (VIM) and cast in a vacuum atmosphere or 30 kg vacuum arc re-melted after VIM with high purity raw materials and cast in a vacuum atmosphere. All laboratory melted heats and commercial Types 310S and 316M heats were forged for remove casting structure, solution-annealed at 1,050ºC for one hour, water cooled, aged at 650ºC for 2 hours, or cold- or warm- rolled 15 % (7.5% each, cross rolled) to 25mm thick plate. 15 % cross rolling at room temperature (cold working), or cold rolled 15 % or 25% or 30% to 25mm thick plate. 15 % cross rolling at room temperature (cold working) was applied to the material which had lower Md_{30} value (deformation martensite transformation temperature) than 0 ºC, but 15 % cross rolling at 200ºC (warm working) was applied to the material which had a higher Md_{30} value than 0 ºC.

Sensitization was detected in some aged materials by the Strauss Test (intergranular corrosion test in boiling copper- 5.5% copper sulfate- 16% sulfuric acid solution,) and elecrochemical reactivation (EPR) test. Sensitized material is shown as pink colored heats in Table 1. But, sensitization was not found in other aged materials.

In these test materials, one materials (No.1) are identified to be used to simulate the cracked PLR pipe Type 316LN stainless steel. It may be helpful to identify the materials to be used for each objective in the bullets. Other test materials were selected from the following view points:

- Effect of nickel, chromium, molybdenum, silicon, manganese, nitrogen, carbon content.
- Effect of minor elements addition: zirconium, aluminum, titanium, vanadium etc.,
- To check the carbon, nitrogen stabilizing effect: aluminum, titanium, niobium, vanadium, etc.,

The effects of various elements on IGSCC resistance in this study were mainly compared for yellow colored heats, as shown in Table I.

SFE Value Measurement

In this study, SFE values for all heats were directly measured by Transmission Electron Microscope (TEM), to precisely grasp the correlation between the SCC resistance and SFE values of test materials. The mini-tensile type specimens (diameter of parallel region was 3mm) were machined from the test coupon of each heat which was solution heat treated at 1,050ºC and furnace cooled. Thin disks were cut at 45 degree of tensile axis in parallel region of the mini-tensile specimens after 2% pre-straining, and thinned down by electro-polishing in a Tenupol-5 electro-polishing unit. These thin foils were observed in a JEOL 2000 EX TEM. The isolated extended dislocations in these thin foils were observed by the TEM, under dark-field weak-beam with g-3g diffracting conditions, as shown in Fig. 1. The dark field images about the isolated extended dislocations were taken into highly sensitive negative film, Kodak Electron Image Film SO-163. The betha angle and width of the isolated extended dislocations on the negative films were measured by image analyzer, as shown in Fig. 2. The SFE value for each test material was calculated from the following equation, based on the data of the betha angle $\boldsymbol{\beta}$ and width Δ_d of the isolated extended dislocations.

$$\gamma = \frac{\mu b_p^{2}(2-\upsilon)}{\Delta_d 8\pi(1-\upsilon)}\left(1-\frac{2\upsilon\cos2\beta}{2-\upsilon}\right) \qquad (1)$$

γ: SFE value

β : Angle between the dislocation and Burgers vector

Δ_d : Width of isolated extended dislocation

μ : Shear modulus

b_p : magnitude of Burgers vector

υ : Poisson's ratio

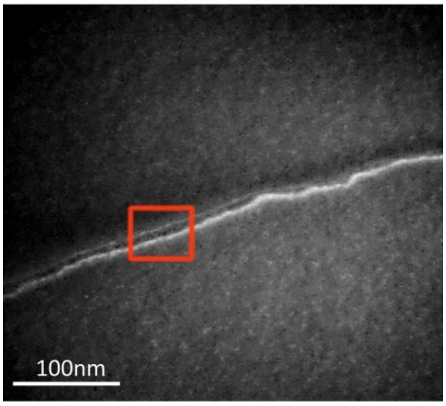


Fig.1. Typical photograph of an isolated extended dislocation for a SHTFC heat treated test material.

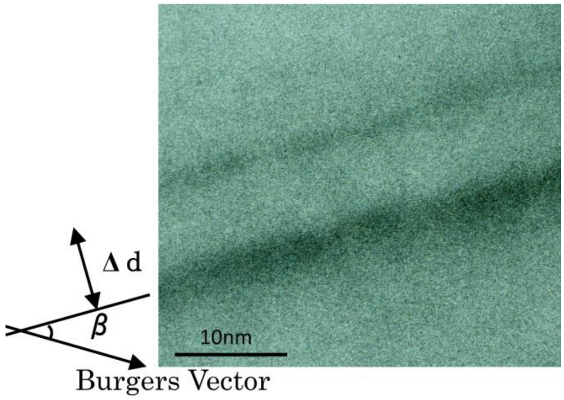
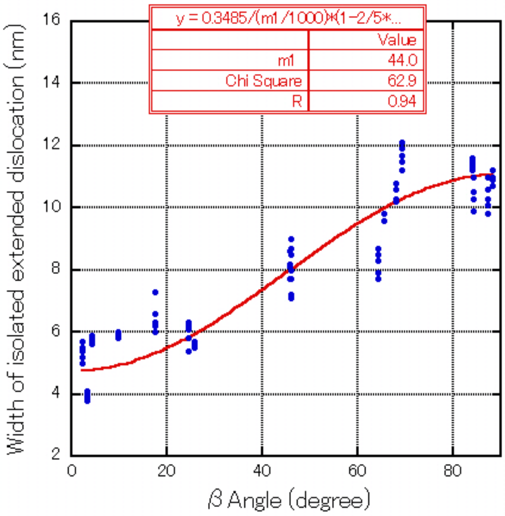
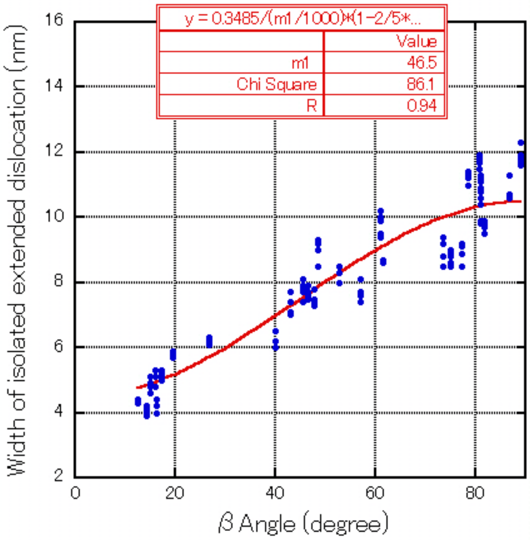


Fig.2. Typical measured parameters for Δ_d and β of an isolated extended dislocation for a SHTFC heat treated test material.

Fig.3 shows the typical data for statistical analysis for the SFE value of the test material (SHTFC and AGG for No.L86) from the Δ_d and β measurements.



a) SHTFC for No.L86



b) AGG for No.L86.

Fig.3. Typical data for statistical analysis for the SFE value of the test material from the Δ_d and β measurements. a) SHTFC for No.L86 and b) AGG for No.L86.

SCC Tests

In this study, a multiple-specimen test system was originally designed and fabricated to evaluate the stress corrosion cracking resistance for many specimens at the same time. In this autoclave, 20 compact tension (CT) specimens can be tested at the same time for SCCGR measurement. All specimens were loaded by the outer load cell. Each specimen can be continued for testing by the connecting tool, if other specimens were cracked and broken. The total displacement for 20 specimens was monitored during SCC test. Electro- chemical potentials (ECP) of specimens were measured for the top and bottom specimens.

In order to evaluate the SCC resistance for test materials in oxygenated (accelerated) BWR water, the SCCGR measurement tests were conducted using 0.7T compact tension (CT) type specimens at 288°C under 200 mV of ECP with addition of oxygen (about 32 ppb DO), less than 5 ppb of chloride and sulfate, less than 0.2 μS/cm of outlet and inlet conductivity, about 6 m^3/h of flow rate. The SCCGR measurement test was conducted during about 1,500 hours for each test run, under periodic unloading condition (R=0.7, holding time=30hours, K value≒30MPa√m).

The SCC resistance for each test material was compared by evaluation of the maximum crack length, average crack length and cracked area of the IGSCC, from the fractography after SCC test. The average crack length was calculated from the observed cracked area of IGSCC divided by the integrated crack initiation length at the front end of fatigue pre-crack, as shown in Fig. 4.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Effect of Chemical Compositions and Heat Treatment on SFE Value for Austenitic Stainless Steels

Fig. 5 shows the correlation between the SFE values of each heat treatment of the test materials, for the SHTWC and SHTFC in Fig.5a), for the SHTWC and AGG in Fig. 5b), for the SHTFC and AGG in Fig.5c). From this figure, it was observed that the SFE value for austenitic stainless steels were clearly affected by the heat treatment conditions, used in this study. In the formulae derived for calculating SFE values in this paper, the factors are determined to be negative for nitrogen and carbon contents and increase in the following order: SHTWC > SHTFC > AGG. It is seen that the SFE values increase with increasing holding time in the temperature range from 400 °C to 750 °C during the heat treatment. It is considered that the solute nitrogen in the austenite matrix must be precipitated as chromium nitrides at the lower temperatures of solution heat treatment such as from 400 °C to 750°C so that the solute nitrogen in the austenitic matrix is reduced after SHTFC and AGG compared to SHTWC.

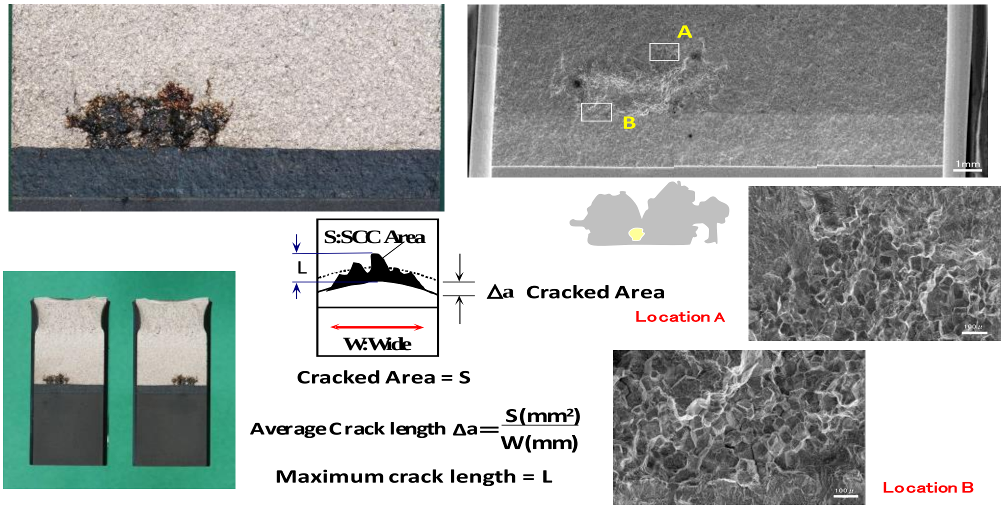
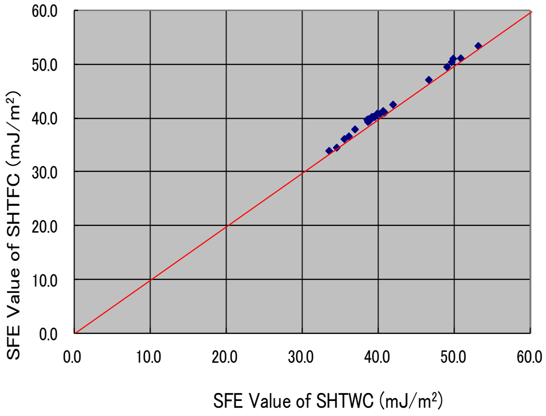
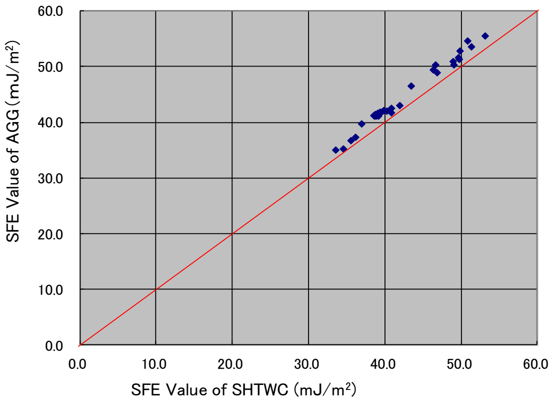


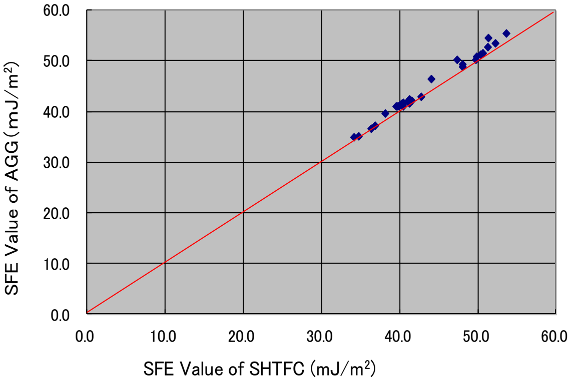
Fig. 4. Typical SCC fracture surface of specimen ($E_{corr.}$=200mV, at 288°C, 1,500 hours)



a) SHTWC and SHTFC



b) SHTWC and AGG



c) SHTFC and AGG

Fig. 5. Comparison of SFE values between a) SHTWC and SHTFC, b) SHTFC and AGG, c) SHTWC and AGG materials after solution heat treatment.

The width and angle of the Burgers' vector of isolated extended dislocations were observed for 56 heats of austenitic stainless steel using a high resolution transmission electron microscope. From these data, the correlation between SFE values and their chemical compositions (nickel, molybdenum, chromium, manganese, nitrogen silicon and carbon) were obtained.

At first, the correlation between nickel content and SFE value was obtained, as shown in Fig.6. The factor for nickel is 2.8, regardless of heat treatment condition in this case. The effect of nickel content on SFE value are very large. So, if there is even small difference in nickel content in each test material, the SFE value could still appear significantly. So, to evaluate the correlation of each element and the SFE value, each measured SFE value was corrected by nickel content. The correlation between molybdenum, chromium, manganese, silicon, nitrogen, carbon content and SFE values corrected by nickel content was gained respectively.

Fig. 7 shows the typical correlation data between SFE values and nitrogen content corrected by nickel content. From this kind of correlation data, the correlation factors for nickel, chromium, molybdenum, silicon, manganese, carbon and nitrogen were obtained.

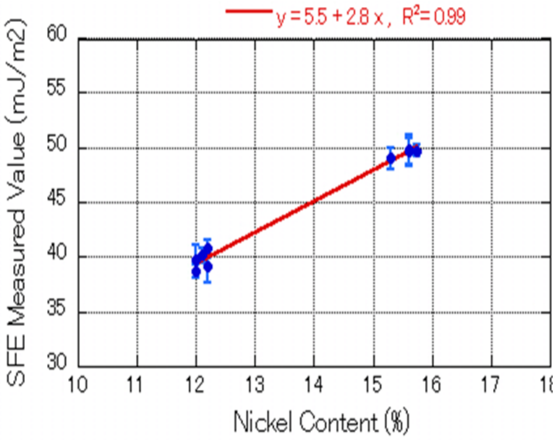


Fig. 6. Correlation between nickel content and SFE measured values for test materials No.41,44,51,52, 53,56,60, 71 and 81 of SHTWC

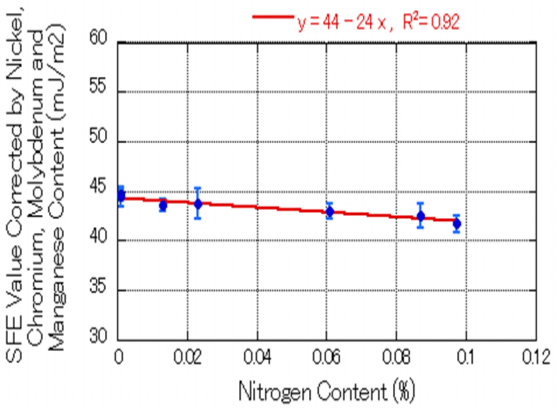


Fig.7. Correlation between nitrogen content and SFEmeasured values corrected by nickel for test materials No.56, 57, 58, 59, 71, 81 and 85 of SHTWC

From these correlation factors, more reliable formulae for calculating the SFE values from the chemical compositions of austenitic stainless steels and their heat treatment conditions have been established [11]. These SFE calculation formulae are applicable to the composition ranges from 10 to 16% nickel, from 13 to 18% chromium, from 0 to 3% molybdenum, from 0 to 2% silicon, from 0 to 4% manganese, from 0 to 0.08% carbon, and from 0 to 0.1% nitrogen. (The figures of chemical compositions are in weight percent).

The calculation formula derived for the SFE values of austenitic stainless steels in the SHTWC condition is as follows:

SFE = -7.1 +2.8 x Ni(%) +0.49 x Cr(%) +2.0 x Mo(%) -2.0 x Si(%) +0.75 x Mn(%) -5.7 x C(%) -24 x N(%) (2)

The calculation formula derived for SFE values for austenitic stainless steels in the SHTFC condition is, as follows:

SFE = -4.8 + 2.8 x Ni(%) +0.44 x Cr(%) +2.0 x Mo(%) -2.0 x Si(%) +0.75 x Mn(%) -2.1 x C(%) -17 x N(%) (3)

Lastly, the calculation formula for SFE values for austenitic stainless steels in the AGG condition was determined to be:

SFE = -4.0 +2.8 x Ni(%) +0.39 x Cr(%) +2.2 x Mo(%) -2.0 x Si(%) +0.75 x Mn(%) -0.47 x C(%) -12 x N(%) (4)

And also, in order to check the reliability of the factors for different elements in these formulae, the effects of nickel, chromium, molybdenum, silicon, manganese, nitrogen and carbon contents on the SFE values for austenitic stainless steels were also evaluated using a first-principles approach based on Density Functional Theory (DFT). The calculations were conducted using the CASTEP code from Accelrys. For the calculation of the exchange correlation functional in the DFT, a non-local density approximation (generalized gradient approximation) was used considering spin polarization, as proposed by Perdew [12].

Thus, from the above thermodynamic analyses, the factors for the elemental trends of the new calculation formulae for SFE for austenitic stainless steel were basically confirmed, except for the case of carbon [11].

To clarify the effect of carbon on the SFE calculation formulae for austenitic stainless steels, more data are needed for materials with various carbon contents.

The Effect of Chemical Compositions on IGSCCGR

In order to evaluate the effect of metallurgical factors on IGSCCGR for cold- or warm- rolled (not hot rolled) austenitic stainless steels, the IGSCCGR for all aged test materials was compared with the carbon content for each material, as shown in Figure 8. In case of the aged test materials, the IGSCCGR roughly increases with increasing of carbon content. But in this figure, specific tendency was observed. It is that the sensitized materials which were identified by the Strauss Test and EPR test, showed remarkably larger IGSCCGR than that of the non-sensitized materials. So, the sensitization must be distinguished from the other metallurgical factors, to evaluate the effect of metallurgical factors on IGSCCGR for cold worked austenitic stainless steel.

The effect of chemical compositions on IGSCCGR for aged materials before cold- or warm- rolled were evaluated from the maximum crack length, average crack length and cracked area after IGSCC test. The IGSCCGR for low silicon stainless steels decreased with increasing of nickel content, and increasing of SFE value should be effective for improving of the IGSCC resistance for strain hardened stainless steels. The effects of minor element, e.g. nitrogen, carbon, molybdenum contents, on the IGSCC resistance were not certain.

The effects of nickel, chromium, molybdenum, nitrogen, silicon, manganese contents and nickel equivalent value on IGSCCGR were compared for the non-sensitized low carbon austenitic stainless steels. Fig. 9 shows the effects of nickel content and all Type 316 stainless steels on the maximum crack length, cracked area and averaged crack growth rate for the non-sensitized materials. From this figure, it is seen that the IGSCCGR decreases with increasing of nickel content for non-sensitized Type 316 stainless steels except low silicon, nitrogen and manganese Type 316 stainless steels. The IGSCCGR of low silicon, nitrogen and manganese Type 316 stainless steels is basically smaller than that of high silicon or nitrogen or manganese 316 stainless steels. But in this study, the effect of silicon, nitrogen and manganese contents were not so certain quantitatively, due to the limited number of test materials. And the specific tendency for the chromium, molybdenum contents and nickel equivalent value on IGSCCGR could not be identified from this study.

As seen from Fig.9 that the averaged SCCGR for non-sensitized Type 316 stainless steels are strongly affected by nickel content, and SFE value is strongly affected by nickel content for Type 316 stainless steel, as mentioned above. So, it is suggested that the averaged SCCGR for non-sensitized Type 316 stainless steels may be affected by SFE.

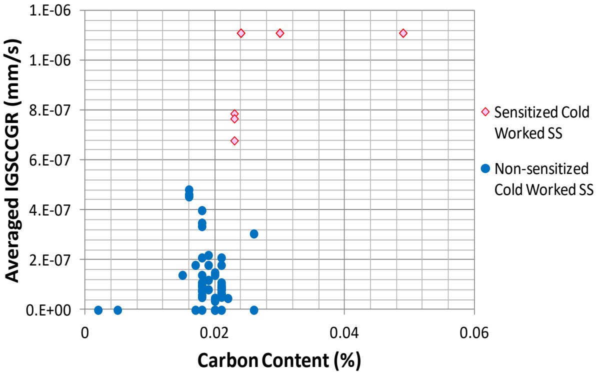
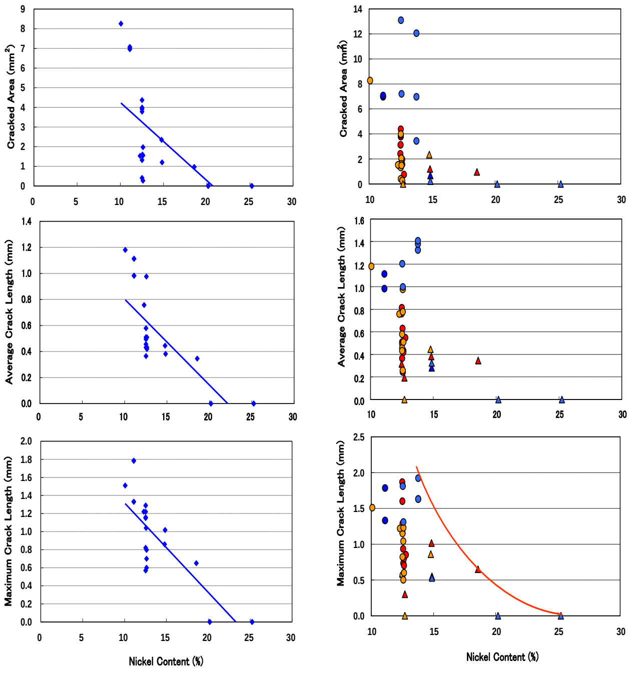


Fig. 8. The effect of canbon content and sensitization on averaged SCCGR in oxygenated high temperature water for aged and cold worked austenitic stainless steel.



Non-sensitized low carbon nickel varied materials

All test materials

Fig.9. The effect of nickel content on SCCGR in oxygenated high temperature water.

The Effect of SFE Value on IGSCCGR

The effect of measured SFE value on IGSCCGR for non-sensitized materials and the effect of calculated SFE value from the above formulae on IGSCCGR for all materials are shown in Figs 10 and 11, respectively. IGSCCGR increases with increasing of SFE value in these figures. The tendency in Fig. 16 was clearer than that in Fig. 10. In these figure, the IGSCCGR of sensitized material is not related to the SFE value. It is wellknown that the sensitization is the key metallurgical factor for IGSCCGR of non cold worked austenitic stainless steel in oxygenated high temperature water. But, from figures 10 and 11, also suggested that the sensitization is distinguished from the other metallurgical factors, to evaluate the effect of metallurgical factors on IGSCCGR for cold worked austenitic stainless steel, and the SFE value is a key parameter for the IGSCCGR and IGSCC resistance of the non-sensitized and strain hardened low carbon austenitic stainless steels.

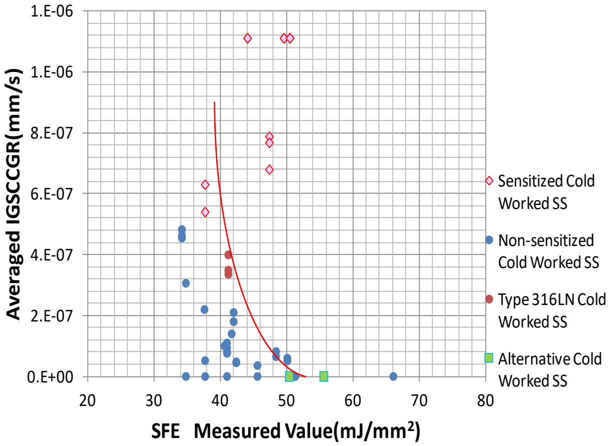


Fig. 10. The effect of measured SFE value on IGSCCGR in oxygenated high temperature water for non sensitized cold worked austenitic stainless steel.

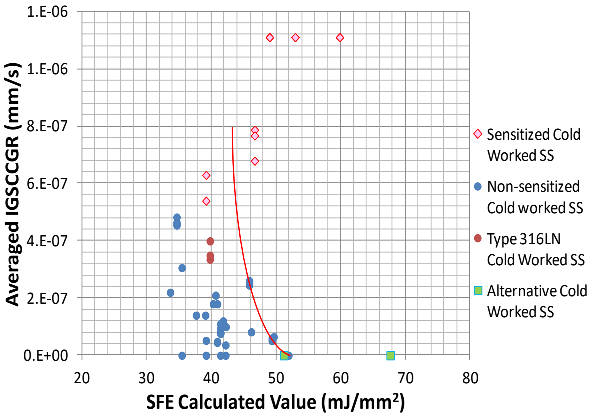


Fig. 11. The effect of calculated SFE value on IGSCCGR in oxygenated high temperature water for non sensitized cold worked austenitic stainless steel.

From the above test results, the authors suggest that the high SFE Type 316 stainless steel is the basic concept for the alternative austenitic stainless steel within JIS or ASTM material standard specified chemical composition range. And also, the author speculated that the SFE estimation formulae are very important for maintaining the quality of the IGSCCGR and IGSCC resistant non-sensitized strain hardened stainless steels.

From these test results, increasing SFE value material, which is of high nickel, high chromium, but low silicon and low nitrogen material, is recommendable, as an alternative austenitic stainless steel of Type 316LN.

IV. CONCLUSIONS

In order to clarify the effect of SFE on SCC resistance of austenitic stainless steels and to develop the alternative austenitic stainless steel of Type 316LN for BWR application, the effect of chemical composition and heat treatment on the SFE value and SCCGR in oxygenated high temperature water were conducted.

From these comprehensive studies, following new findings were obtained.

1) The correlation between SFE values for test

materials and their chemical compositions for nickel, molybdenum, chromium, manganese, nitrogen, silicon and carbon were obtained.

2) From these correlation factors, the original calculation formulae were proposed for SFE values of austenitic stainless steels in the SHTWC, SHTFC and AGG conditions.

3) The maximum crack length, average crack length and cracked area of the IGSCC for all test materials were evaluated as IGSCC resistance in oxygenated high temperature water, using originally designed multi-specimen type autoclave.

4) The IGSCC resistance of strain hardened low carbon austenitic stainless steels in oxygenated high temperature water increases with increasing of nickel content~~s~~ and SFE values, for non-sensitized materials before strain hardening.

5) The effects of the molybdenum and manganese contents on the SCC resistance for non-sensitized materials were not so pronounced in this study.

6) It is suggested that the SFE value is a key parameter for the IGSCC resistance of non-sensitized strain hardened austenitic stainless steels.

7) As an alternative austenitic stainless steel of Type 316LN, increased SFE value material, that is high nickel, high chromium, low silicon and low nitrogen material, is recommendable.

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