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by

W. J. Shack, T. F. Kassner, P. S. Maiya,
J. Y. Park, and W. E. Ruther

Materials and Components Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

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ABSTRACT

This paper presents results on (a) the influence of simulated BWR environments on the stress-corrosion-cracking (SCC) susceptibility of Types 304, 316NG, and 347 stainless (SS), (b) fracture-mechanics crack-growth-rate measurements on these materials and weld overlay specimens in different environments, and (c) residual stress measurements and metallographic evaluations of conventional pipe weldments treated by a mechanical-stress-improvement process (MSIP) as well as those produced by a narrow-gap welding procedure. Crack initiation studies on Types 304 and 316NG SS under crevice and non-crevice conditions in 289°C water containing 0.25 ppm dissolved oxygen with low sulfate concentrations indicate that SCC initiates at very low strains (<3%) in the nuclear grade material. Crack growth measurements on fracture-mechanics-type specimens, under low-frequency cyclic loading, show that the Type 316NG steel cracks at a somewhat lower rate (~40%) than sensitized Type 304 SS in an impurity environment with 0.25 ppm dissolved-oxygen; however, the latter material stops cracking when sulfate is removed from the water. Crack growth in both materials ceases under simulated hydrogen-water chemistry conditions (<5 ppb oxygen) even with 100 ppb sulfate present in the water. An unexpected result was obtained in the test on a weld overlay specimen in the impurity environment, viz., the crack grew to the overlay interface at a nominal rate, branched at 90° in both directions, and then grew at high rate (parallel to the nominal applied load). Residual stress measurements on MSIP-treated weldments and those produced by a narrow-gap welding procedure indicate that these techniques produce compressive stresses over most of the inner surface near the weld and heat-affected zones.

Introduction

Cracking in sensitized austenitic stainless steel (SS) piping and associated components in boiling water reactors (BWRs) has been observed since the mid-1960s. Proposed remedies include (1) procedures that produce a favorable residual stress state in the weld regions, (2) replacement of the piping with materials that are more resistant to stress corrosion cracking (SCC), and (3) modification of the reactor coolant environment. During this year, studies have been carried out that have important implications for all three classes of proposed remedies. These studies include fracture-mechanics crack-growth-rate tests on Type 316NG SS and weld overlay specimens in impurity and high-purity environments, metallographic and residual stress studies on weldments treated by the mechanical-stress-improvement process (MSIP) developed

by O'Donnell and Associates, constant-extension-rate-tensile (CERT) tests on the German Nuclear Grade Type 347 SS and other steels to determine the influence of reactor coolant impurities (e.g., SO_4^{2-} , Cu^{2+}) on SCC susceptibility. In addition, the effect of gamma radiation of simulated reactor-coolant environments on the corrosion potential of stainless steel is being investigated. Together with related studies on the characterization of the SCC behavior of irradiated stainless steels (in another program) these results will permit a better assessment of the potential for irradiation-assisted SCC of materials in the reactor core.

SUMMARY OF RESEARCH PROGRESS

SCC of Type 316NG Stainless Steel

(a) Fracture-Mechanics Crack Growth Tests

Fracture-mechanics crack-growth-rate tests under less severe mechanical loading have been performed on Type 316NG SS to confirm the susceptibility to transgranular SCC (TGSCC) observed in CERT tests. In different phases of the tests, the water-chemistry conditions were varied from a reference condition of 0.25 ppm dissolved oxygen plus 0.1 ppm sulfate (as H_2SO_4) to lower oxygen concentrations at this sulfate level as well as higher and lower sulfate concentrations at a fixed dissolved-oxygen concentration in the feedwater. The tests included a lightly sensitized ($\text{EPR} = 2 \text{ C/cm}^2$) Type 304 SS control specimen. Most of the tests were carried out with a maximum stress intensity of $\sim 30 \text{ MPa m}^{1/2}$, a load ratio R of 0.95, and a frequency of 0.08 Hz, i.e., a nearly constant load with a small superposed cyclic ripple.

The crack growth rates for each specimen under the different water chemistry conditions, i.e., (1) through (6) are shown in Fig. 1. The open-circuit corrosion potential of a Type 304 SS electrode and the conductivity of the feedwater for each phase of the test are shown in the insert panel of the figure, where the region above the curve defines the region of susceptibility for intergranular SCC (IGSCC) based on CERT data. With cyclic loading conditions, both materials cracked under the reference chemistry [conditions (1) and (3)]; the crack growth rates were $\sim 40\%$ higher in the sensitized specimen. In a high-purity environment with 0.25 ppm dissolved oxygen [condition (2)], crack growth ceased in the Type 304 SS specimen, but in the Type 316NG specimen it continued at almost the same rate as in the impurity environment. Under condition (4), the dissolved-oxygen concentration of the feedwater was decreased to 0.002 ppm with 1.2 ppm hydrogen and 0.1 ppm sulfate. Under these conditions the electrochemical potential of Type 304 SS decreased from +140 to -630 mV(SHE), and crack growth ceased in both specimens, even with sulfate present. In the next phase of the test [condition (5)], sulfate was not added to the low-oxygen environment, and the conductivity of the effluent water was reduced to 0.1 $\mu\text{S/cm}$. As expected, no crack growth occurred in either specimen during the transition to the high-purity environment. When the environment was then changed to a simulated, high-purity BWR environment with 0.25 ppm dissolved oxygen [condition (6)], crack growth resumed in the Type 316NG SS specimen at a rate similar to that observed under conditions (1) and (3), while the crack remained dormant in the sensitized Type 304 SS specimen. After $\sim 500 \text{ h}$, the loading was changed to constant load ($R = 1$) conditions. The crack growth rate in the Type 316NG SS specimen decreased by an order of magnitude compared with

that observed under the $R = 0.95$ load, while the crack growth rate in the sensitized specimen increased to a level close to that observed in the Nuclear Grade specimen under the $R = 0.95$ load.

Fig. 1. Effect of Several Simulated BWR Water Chemistries, Within and Outside of the IGSCC Regime for Sensitized Type 304 SS, on the Crack Growth Rates of a Compact-Tension Specimen of This Material and a Type 316NG SS Specimen under Low-Frequency, Moderate-Stress-Intensity, and High- R Loading Conditions at 289°C.

Since the test is still in progress, no fractographic information on the mode of cracking is available. However, in previous tests with sensitized and solution-annealed Type 304 SS, where the behavior of the solution-annealed specimen was similar to that observed in the Type 316NG SS specimen in this test, the sensitized specimen cracked intergranularly under these conditions, as expected, while the solution-annealed specimen cracked transgranularly.

(b) Crack Initiation Studies

In CERT tests, our previous work has shown that Type 316NG SS is susceptible to TGSCC in oxygenated water with sulfate additions.^{1,2} The sulfate concentration required to produce cracking decreases very rapidly with strain rate, as shown in Fig. 2, and at a strain rate of $2 \times 10^{-5} \text{ s}^{-1}$ is less than 25 ppb. The CERT test results also suggest that once a crack initiates, the crack growth rate is only weakly dependent on the concentration of sulfate as shown in Fig. 3. Although the CERT tests involve large plastic strains, the general trends predicted from these tests are consistent with the results of our fracture-mechanics crack-growth-rate tests. These results have prompted a study of the effects of impurities on crack initiation. In an earlier work,³

Fig. 2. Variation of Critical Concentration of Sulfate (Required for SCC) with Strain Rate.

Fig. 3. Effect of Impurity Concentration on Average Crack Growth Rate for Type 316NG SS at 289°C and a Strain Rate of $2 \times 10^{-7} s^{-1}$. Environment: 0.25 ppm oxygen plus 0.025 to 0.1 ppm sulfate.

interrupted CERT tests performed on Type 316NG SS showed that crack initiation (defined in terms of cracks 50–200 μm in length) occurs at relatively low strains. A more sensitive technique involves a CERT specimen in which a small diameter (0.86 mm) through-hole is drilled in the center of the gage length. This geometry localizes the specimen region in which crack initiation occurs and enables the detection of very small cracks by scanning-electron microscopy (SEM). The test is interrupted at low nominal strains, the specimen is then cross-sectioned as shown in Fig. 4, and the surface of the hole examined by SEM. The strain concentration of ~ 8 for this geometry has been estimated by Neuber's rule and finite-element calculations. The nominal strains can be accurately determined by measurement of the distance between two gage marks before and after the test.

Fig. 4. Cross Sectional View of CERT Specimen Around the Hole Used for Crack-Initiation Studies.

Figures 5 and 6 show micrographs that illustrate the degree of cracking of Type 316NG SS in an impurity environment as a function of the nominal strain. These results suggest that crack initiation occurs at actual strains between 1.5-3% (assuming a strain concentration factor of 8) at a strain rate of $\sim 2 \times 10^{-4} \text{ s}^{-1}$. By comparison, results from similar tests on solution-annealed Type 304 SS, which are shown in Fig. 7, indicate that crack initiation occurs at strains greater than 3.0% for the same environments and strain rate.

CERT tests were also performed on Type 316NG SS in environments with and without impurities under artificially produced crevice conditions. The specimen geometry is similar to that used for the initiation studies, except that two holes were drilled only halfway through the specimen and Type 304 SS pins (0.84 mm diameter) were inserted in the holes. Comparison tests were performed without the pins. Test results in high-purity water and in an impurity environment are shown in Fig. 8. Without the pins, the specimens failed in a completely ductile fashion in high-purity water, but with the pins in place, SCC occurred both in high-purity water and in sulfate environments. Additional tests on solution-annealed Type 304 SS and a very resistant heat of Type 316NG SS (Heat No. 4679580) also demonstrated that SCC occurred under crevice conditions in environments where no SCC was observed under non-crevice conditions. Since the electrochemical conditions at the tip of a SCC may be similar to those in a crevice of the same composition, these results are consistent with our fracture-mechanics test results in which cracks propagate under environmental conditions where no cracking was observed in smooth specimen tests.

Fig. 5. Micrographs of the Region within the Diametral Holes in Type 316NG SS CERT Specimens for Crack Initiation Studies at a Strain Rate of $2 \times 10^{-7} \text{ s}^{-1}$ in 289°C Water with 0.25 ppm Dissolved Oxygen and 0.1 ppm Sulfate. Nominal plastic strains in the specimen are indicated; localized strains in hole region are a factor of 8 higher.

Fig. 6. Micrographs of the Region within the Diametral Hole in a Type 316NG SS CERT Specimen after a Nominal Plastic Strain of 0.35% at a Strain Rate of $2 \times 10^{-7} \text{ s}^{-1}$ in 289°C Water with 0.25 ppm Dissolved Oxygen and 0.1 ppm Sulfate. Localized strain in the hole region is a factor of ~ 8 higher.

Fig. 7

Micrographs of the Region within the Diametral Hole in Solution-Annealed Type 304 SS CERT Specimens for Crack Initiation Studies at a Strain Rate of $2 \times 10^{-7} \text{ s}^{-1}$ in 289°C Water with 0.25 ppm Dissolved Oxygen and 0.1 ppm Sulfate. Nominal plastic strain in the specimens are indicated; localized strain in the hole region is a factor of ~ 8 higher.

Fig. 8

Micrographs of the Hole Region of Type 316NG SS CERT Specimens after Straining at a Rate of $2 \times 10^{-7} \text{ s}^{-1}$ at 289°C under (a) Non-crevice and (b) Crevice Conditions in High-Purity Water with 0.25 ppm Dissolved Oxygen, and (c) Crevice Conditions in Water with 0.1 ppm Sulfate at This Oxygen Level.

(c) Effect of Weld-Induced Plastic Strains on SCC of Type 316NG SS

Although no mechanism has been established, it has been reported⁵ that cold work (5-20%) promotes intergranular crack initiation in nonsensitized Type 316NG SS. Recent results from a U.S. NRC-sponsored research program at PNL⁶ show that during welding, large amounts of plastic strain occur on the inner surface of large diameter pipes at relatively low temperatures. Since the EPRI/GE pipe test qualification program for Type 316NG SS was based primarily on 4-in.-diam pipe weldments⁵ in which much less plastic strain occurs during welding than in large diameter pipes, it has been suggested⁷ that the results of the pipe tests may not be conservative for all pipe sizes.

In order to test this hypothesis, a 28-in.-diam pipe weldment fabricated from Type 316NG SS was obtained from the EPRI NDE Center. CERT tests were performed to determine whether cracks would initiate preferentially in regions close to the inner surface of the pipe where the plastic strains are large and whether the mode of cracking would be intergranular. The tests were performed in an environment containing 0.25 ppm oxygen and 0.1 ppm sulfate.

The results are summarized in Table I. Transgranular cracking occurred in the tests at strain rates of $<1 \times 10^{-6} \text{ s}^{-1}$; there was no evidence of IGSCC in any test. The cracks initiated on the side of the specimen that was farthest from the inner surface of the weldment. The crack growth rates were somewhat higher than those observed in corresponding tests on our reference heat, but this variation is within the expected heat-to-heat variability. To determine more explicitly the role of the cold work accumulated during welding, comparison tests are now being performed on base material obtained well away from the welded region.

Crack Growth Resistance of Weld Overlay Material

To characterize the inherent crack growth resistance of the Type 308L SS weld metal used for weld overlay repairs, two fracture-mechanics crack-growth-rate tests are being performed on specimens fabricated from a 10-in.-diam pipe with a weld overlay applied by NUTECH Engineers and GAPCO Welding in accordance with their standard practice for overlay repairs. The

Table I. Effect of Strain Rate on the Crack Growth Rate of Type 316NG SS from CERT Tests in 289°C Water Containing 0.25 ppm Dissolved Oxygen and 0.1 ppm Sulfate

Strain Rate, s^{-1}	28-in.-diam. (0.11 wt.% N_2)	ANL Ref. Heat ^a (0.068 wt.% N_2)
$\dot{a}_{av}, m \cdot s^{-1}$		
1×10^{-6}	No SCC	1.51×10^{-9}
4×10^{-7}	2.06×10^{-9}	9.74×10^{-10}
2×10^{-7}	1.52×10^{-9}	7.35×10^{-10}

^aHeat No. P91576.

pipe was furnace sensitized before the overlay was applied. The 1TCT specimens were fabricated such that cracks will propagate through the furnace sensitized base material into the weld overlay. One specimen is being tested in a high-purity environment with 0.2 ppm dissolved oxygen, the other in a similar oxygenated environment with 0.1 ppm sulfate. The tests are being performed at 289°C under high-R (0.90-0.95), cyclic loads with maximum stress intensity factor of 28 to 37 MPa m^{1/2}.

In the ongoing test in the high-purity environment, the crack tip is apparently just at the interface between the pipe and the overlay. No change in compliance, which would indicate either crack growth thorough the overlay or crack growth along the interface, was observed during a test period of 840 h at a maximum stress intensity factor of 30 MPa m^{1/2} or during a subsequent 1296-h test period with a maximum stress intensity factor of 33 MPa m^{1/2}. This may be indicative of an inherent resistance of the weld overlay material to stress corrosion crack growth in this environment.

In the impurity environment compliance measurements indicated that the crack was growing through the overlay. However, as shown in Fig. 9, posttest examination revealed that the crack grew to the overlay, branched at 90° along the weld interface, and grew ~12 mm in each direction along the interface parallel to the applied load. Based on the assumption that the compliance data can be used to determine when the crack reached the overlay, the average crack growth rate along the interface is $\sim 6 \times 10^{-10}$ m s⁻¹. This is almost an order of magnitude higher than the crack growth rate for the initial crack in the furnace sensitized material normal to applied load (8×10^{-11} m s⁻¹). Although bending loads are rather high in CT specimens (we have not yet computed the stress intensity factors at the tips of the branched cracks), it seems intuitive that the stress intensity factors for the branched crack should be substantially lower than those for the crack normal to the applied load, which is contradictory to the apparent high crack growth rate. A future test is planned in which the CT specimen is designed for crack growth along the interface.

Metallographic and Residual Stress Studies of MSIP

The mechanical-stress-improvement process (MSIP) is a proprietary development of O'Donnell and Associates, Inc. (OAI). Like induction-heating-stress improvement (IHSI) it is intended to produce a more favorable state of residual stress on the inner surface of pipe weldments especially in the vicinity of heat-affected-zones (HAZs). Although the two processes have similar objectives, MSIP is a purely mechanical process. The favorable residual stresses are induced by the plastic compression of the weldment produced by a split-ring-like tool mounted on the pipe. The plastic strain imposed on the pipe is controlled by the opening between the split-rings, which is adjusted by inserting appropriate shims.

Two pipe-to-pipe weldments treated by the MSIP process were examined. The process did produce favorable residual stress states in both 12- and 28-in.-diam weldments. Unlike most residual stress improvement processes, the effectiveness of MSIP does not appear to be a strong function of pipe diameter (or thickness), although the peak compressive axial stresses in the smaller pipe weldment are somewhat higher. The 12-in.-diam weldment had been exposed to boiling MgCl₂ at the EPRI NDE Center before being sent to Argonne. Although no cracking was reported by the NDE Center after the MgCl₂ test, metallographic

CRACK GROWTH IN A TYPE 304 SS WELD OVERLAY SPECIMEN
LOW FREQUENCY, CYCLIC LOADING AT 289°C

Fig. 9. Micrographs of a Compact-Tension Specimen of Sensitized Type 304 SS with an ER 308L Weld Overlay That Show Crack Growth along the Interface of the Overlay (Parallel to the Nominal Applied Stress) after Low-Frequency, Moderate-Stress-Intensity, and High-R Loading in 289°C Water Containing 0.2-0.3 ppm Dissolved Oxygen and 0.1 ppm Sulfate.

studies at Argonne did reveal some cracking which we attribute to highly localized tensile stress regions that are susceptible to chloride induced SCC. No cracks were observed in the 28-in.-diam weldment that was subjected to higher plastic strains during MSIP, but was not exposed to MgCl_2 .

The residual stresses on the inner surface of the MSIP-treated weld in the 12-in.-diam specimen were measured at two azimuthal locations. The stresses at the two azimuths did not differ significantly and the average stresses for a given axial position are summarized in Table II. Both the axial and hoop stresses are compressive at all locations. No control welds were prepared, but calculations and measurements suggest that the axial stresses in the HAZs of such welds will typically be tensile with a magnitude of $\sim 20-30 \text{ ksi}$. Finite-element analyses by OAI predict tensile stress regions on the portion of the inner surface directly beneath the tool after MSIP. However, in this case the measured stresses were compressive in this region.

Throughwall axial residual stress measurements were made at one azimuth. In the regions near the HAZs, the stress distributions are almost linear across the thickness except near the outer surface, and are similar to the distributions in weldments treated by IHSI. In the region directly under the tool, the profiles are more nonlinear. The compressive stresses produced by MSIP in the HAZs persist through a substantial portion ($\sim 50\%$) of the pipe wall. This indicates that the process can provide significant benefits even in the presence of small flaws that may not be detected by nondestructive examination.

Table II. Average Measured Residual Stresses on the Inner Surface of a 12-inch-diameter Pipe Weldment Treated by the Mechanical Stress Improvement Process

Location	Gage Position	Distance From Weld Centerline (in.)	Axial Stress (ksi)	Hoop Stress (ksi)
Tool Side				
HAZ	1	-0.20	-31	-34
	2	-0.59	-35	-33
	3	-0.99	-26	-13
	4	-1.77	-16	-17
Under Tool	5	-2.57	-15	-17
	6	-3.35	-14	-15
	7	-4.14	-17	-13
Across Weld HAZ	8	0.20	-34	-36
	9	0.59	-48	-31

The results of the strain-gage residual stress measurements on the 28-in.-diam weldment are summarized in Table III. There are high compressive stresses in the regions near the weld and heat-affected zones. The stresses do become tensile on the inner surface in the region under the tool (i.e., ~3-8 in. from the weld centerline) in agreement with the finite-element analyses performed by OAI, but the magnitudes of the stresses are relatively low (~5-10 ksi) compared to the analytical predictions.

Throughwall residual stresses measurements were performed at one azimuth on the 28-in.-diam weldment. As in the case of the 12-in.-diam weldment, the compressive stresses produced by MSIP in the HAZs persist through a substantial portion (~50%) of the pipe wall.

Table III. Average Measured Residual Stresses on the Inner Surface of a 28-inch-diameter Pipe Weldment Treated by the Mechanical Stress Improvement Process

Location	Gage Position	Distance From Weld Centerline (in.)	Axial Stress (ksi)	Hoop Stress (ksi)
Tool Side				
HAZ	1	-0.08	-24	-53
	2	-0.55	-36	-30
	3	-1.34	-22	-15
Under Tool	4	-2.52	-12	2
	5	-3.70	-1	8
	6	-6.06	6	8
	7	-8.42	6	-15
Across Weld HAZ	1	0.08	-22	-50
	2	0.55	-36	-36
	3	1.34	-40	-25

MSIP appears to be an appropriate technique for improvement of the residual stress state of piping system weldments and is effective for both large and small diameter pipes. The associated plastic strains are unlikely to have detrimental effects either through the production of brittle phases (e.g., martensite) or other mechanisms that increase susceptibility to stress corrosion cracking.

Studies on Modified Type 347 Stainless Steel

(a) Stress Corrosion Tests

Type 347 SS has been widely used in Germany as a piping material and as a weld clad in PWRs and BWRs with no reports of IGSCC. The steel has a low carbon concentration (0.04 wt% max) and the main alloying elements are adjusted to give a nominal ferrite number of 4 to 8. The maximum Nb content is limited to 0.55 wt% to promote weldability. To evaluate the SCC susceptibility of this steel, CERT tests have been performed on two heats of material. The materials were obtained as weldments fabricated with matching filler materials at the EPRI NDE Center. CERT tests were performed on material in the as-welded condition and after an additional heat treatment (500°C/24 h) over a range of strain rates in 289°C water with 0.25 ppm dissolved oxygen in both high-purity water and with sulfate additions ranging from 0.025 to 0.1 ppm. The results for the two heats of material are summarized in Tables IV and V. For both heats of material TGSCC occurs at strain rates of $< 5 \times 10^{-7} \text{ s}^{-1}$ in impurity environments. Even for strain rates as low as $2 \times 10^{-7} \text{ s}^{-1}$, no cracking is observed in the high-purity environment. The critical strain rate required to produce TGSCC in these materials appears to be slightly lower than those required to produce TGSCC in similar tests on Type 316NG SS. However, the average crack growth rates are approximately the same. No evidence of knife-line attack has been observed, and failure always occurs in the base metal. No effect of the additional heat treatment was observed. As shown in Fig. 10, the strain rate and average crack growth rate are related by a power law with an exponent of $\sim 1/3$, which is consistent with the behavior of Type 316NG and solution-annealed Type 304 SS and the model we have developed to describe strain rate effects on various parameters in CERT tests.¹⁰

Preliminary examination of six Type 347-Type 347 and Type 347-Type 304 SS 10-in.-diam weldments received from the New York Power Authority has been completed. The weldments were prepared using either the German narrow-gap welding process without an insert or the more conventional welding procedure developed at the EPRI NDE Center, which uses an insert. Before shipment to Argonne the weldments were radiographed and examined ultrasonically; the welds were found to be of high quality with relatively few potential defects. Metallographic examination of a narrow-gap weldment at ANL [Fig. 11(a)] has confirmed the high quality of the weld indicated by the nondestructive examinations. One small defect, which is less than 5 mm long and $\sim 30 \mu\text{m}$ deep, was noted. A cross section of the defect is shown in Fig. 11(b). The defect was observed by dye penetrant examination after the initial sectioning of the weldment. A dye penetrant test before sectioning did not show an indication. The defect appears to have occurred during normal welding operations, i.e., there is no evidence of weld repair in this region.

Table IV. Effect of Strain Rate and Environment (0.25 ppm Dissolved Oxygen and 0 to 0.1 ppm Sulfate)^a on the SCC Susceptibility of Type 347 SS in 289°C Water

Sulfate, ^b ppm	Heat Treatment	$\dot{\epsilon}$, s ⁻¹	t_f , h	ϵ_f , %	$\Delta A/A_o$, %	σ_{max} , MPa	Failure Mode	$\dot{a}_{av}$, m·s ⁻¹
0.1	c	1×10^{-6}	77.5	27.9	62	435	Ductile	-
0.1	d	1×10^{-6}	65.5	23.6	65	432	Ductile	-
0.1	c	5×10^{-7}	136.6	24.6	51	428	TGSCC	1.40×10^{-9}
0.1	d	5×10^{-7}	114.5	20.6	47	417	TGSCC	1.63×10^{-9}
0.05	d	5×10^{-7}	126.3	22.7	70	435	Ductile	-
0.1	c	2×10^{-7}	328.5	23.7	41	434	TGSCC	1.00×10^{-9}
0.1	d	2×10^{-7}	301.5	21.7	40	448	TGSCC	1.10×10^{-9}
0.05	d	2×10^{-7}	280.7	20.2	47	458	TGSCC	8.31×10^{-10}
0.1	d	2×10^{-7}	313.5	22.6	78	442	Ductile	-
0.1	c	1×10^{-7}	676.5	24.4	41	443	TGSCC	1.05×10^{-9}
0.1	d	1×10^{-7}	574.5	20.7	47	451	TGSCC	7.58×10^{-10}

^aSteady-state open-circuit corrosion potential: ~ 30 mV (SHE).

^bHeat No. 174100.

^cAs-welded.

^dAs-welded plus 500°C/24 h.

Table V. CERT Test Results for Type 347NG SS at 289°C (Heat No. 170162)

Test No.	Oxygen, ppm	Sulfate, ppm	SS-Potential, mV (SHE)	$\dot{\epsilon}$, s ⁻¹	t_f , h	ϵ_f , %	$\Delta A/A_o$, %	σ_{max} , MPa	$\dot{a}_{av}$, m·s ⁻¹
301	0.25	0.1	84	1×10^{-6}	55.7	20.1	76	427	0
305	0.25	0.1	91	5×10^{-7}	114.1	20.5	67	430	b
297	0.26	0	22	2×10^{-7}	253.8	18.3	80	444	0
310	0.25	0.1	22	2×10^{-7}	250.5	18.0	61	471	5.5×10^{-10}
299	0.005	0.025	-609	2×10^{-7}	243.2	17.5	54	438	3.5×10^{-10}
304	0.005	0.05	-580	2×10^{-7}	231.8	16.7	69	442	4.6×10^{-10}

^aEvidence of initiation, but the crack length is too short to estimate a velocity.

Fig. 10. Average Transgranular Crack Growth Rate as a Function of Strain Rate for Type 347 SS in 289°C Water with 0.25 ppm Dissolved Oxygen and 0.1 ppm Sulfate.

Fig. 11

(a) Cross Section of 10-in.-diam Modified Type 347 SS Pipe Weldment Prepared by German Narrow-Gap Welding Process.

(b) Small Defect near Weld Fusion Line on the Inner Surface.

Residual stress measurements were made on one of the narrow-gap weldments. The axial and circumferential residual stresses in the vicinity of the weld are shown in Figs. 12 (a) and (b), respectively. The stress distributions are substantially different from those associated with conventional welding techniques.^{8,9} Tensile stresses are observed only in the axial direction in a very narrow zone near the weld, and the magnitude of these stresses is low. Over most of the inner surface the stresses are as compressive as those generally obtained after a residual stress improvement process like MSIP or IHSI.

Water Chemistry Effects on the SCC of Sensitized Stainless Steels

The effect of various ions on the stress corrosion cracking behavior of sensitized Type 304 SS is being investigated. Particular attention is given to both anion and cation impurities that provide alternative cathodic reduction reactions to dissolved oxygen. Although not all impurities affect stress

Fig. 12. Axial (a) and Circumferential (b) Residual Stresses Associated with a Narrow-Gap Welding Procedure.

corrosion cracking through this particular mechanism, it does appear important for several impurity species present in reactor coolant water (e.g., sulfate and copper ions). Such impurities are potentially damaging even in low-oxygen environments associated with the hydrogen-water chemistry in BWRs and secondary-system water in PWRs.

The influence of the impurities, on SCC of sensitized Type 304 SS was investigated in CERT tests in 289°C water at a low dissolved-oxygen concentration (<5 ppb). In these experiments, the crack growth behavior of the materials was correlated with the type and concentration of the impurities and the electrochemical potentials of Type 304 SS and platinum electrodes in the environment.

The CERT results indicate that the crack growth rate of these steels is largely controlled by the rate of cathodic reduction of oxyanions [e.g., SO_4^{2-} , NO_3^- , PO_4^{3-} , ClO_4^- , AsO_4^{3-} , which have a central atom (S, N, P, Cl, and As) that can assume different oxidation states] as well as by cations (e.g., Cu^+ , Cu^{2+}) that can undergo similar reduction (to metallic Cu). The observation that BO_3^{3-} or Zn^{2+} , Mg^{2+} , or Na^+ (added as chloride salts), which cannot undergo cathodic reduction like the other species, do not promote SCC in the low-oxygen environments, as demonstrated by the test results shown in Fig. 13, provides further evidence in support of this mechanism. As in the case of dissolved oxygen, the reduction of these species couples with anodic dissolution or oxidation at the crack tip following film rupture. Since cathodic reduction of the various species occurs simultaneously, these impurities contribute to crack growth in a manner determined by their concentrations and the relative rates of the reduction reactions. The CERT results also indicate different threshold concentrations for each of the species; that is, when their concentrations are below a specific level, which may depend on the strain rate, neither transgranular nor intergranular cracking occurs in high-temperature water.

Fig. 13. Effect of Several Salts at a Chloride Concentration of 10 ppm in Low-Oxygen (<5 ppb) Water on the Time to Failure of Sensitized Type 304 SS CERT Specimens at 289°C.

Effects of Irradiation on the Corrosion Potential of Stainless Steel in BWR-Like Environments

Experiments to characterize the effect of high gamma radiation on the corrosion potential of SS have been carried out using a 90K Ci cobalt source. A standard reference electrode was modified to operate satisfactorily in the gamma environment. The effect of the gamma dose rate and total dose on the open-circuit potential of Type 304 SS and the redox potential of a platinum electrode was measured in conventional BWR-like environments with 0.2-0.3 ppm dissolved oxygen and in deoxygenated water (<0.005 ppm oxygen). The gamma radiation causes a significant increase (~ 200 mV) in the corrosion potential of the Type 304 SS, but no significant changes were noted in the potential of the platinum electrode. No influence of gamma dose on the potentials was found over the range from 0.08 to 10 Mrad.

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